Modeling Multi-Reservoir Hydropower Systems in the Sierra Nevada with Environmental Requirements and Climate Warming

By

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DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Water Resources Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2011

Acknowledgements

I first would like to thank my committee members Drs. Jay Lund, Joshua Viers, and Geoffrey Schladow for their invaluable support of my academic and professional goals at UC Davis, in particular for helping me to think about and describe resource management problems in fundamentally different, yet complementary, ways. Thanks to my major professor, Jay Lund, for his ceaseless stream of ideas, his invaluable ability to help me say more with less, and, of course, his paella parties. I worked most closely with Josh Viers, who provided constant advice and constructive criticism, and, importantly, helped me keep one foot firmly planted in global freshwater conservation efforts. Several other professors have also helped along the way: Miguel Marino, Richard Howitt, Jeffrey Mount, and Bassam Younis at UC Davis, and John Dracup at UC Berkeley.

I am grateful for the friendship of colleagues near and far, past and present. In completely random order, I especially thank Rachael Hersh-Burdick, Nate Burley, Rob Lusardi, Christina Buck, Kaveh Madani, Josue Azuára-Medellín, Marcelo Olivares, David Rosenberg, Julien Harou, Patrick Ji, Rachel Ragatz, Matt Seitzler, Prudentia “Gugu” Zikalala, Gerhard Epke, Sarah Null, Scott Ligare, Sarah Yarnell, and Laleh Rastagarzadeh. I am also indebted to my former colleagues at the World Wildlife Fund for, perhaps unkowingly, shining the light for my path: Bernhard Lehner, Robin Abell, Michele Thieme, Nikolai Sindorf, Rebbecca Ng, and Carissa Wong.

Other people and organizations deserving particular mention for their advice, research support, and guidance include: the Stockholm Environment Institute, including Jack Seiber, David Purkey, Charles Young, and Vishal Mehta; Mike Deas of Watercourse Engineering; Gary Reedy of the South Yuba River Citizens League; Bob Center of American Whitewater; Michael Kiparsky at the University of Idaho; and Jaime Pittock at the Australian National University.

My work at UC Davis, including more than this dissertation, was funded by the Resources Legacy Fund Foundation, the California Energy Commission, and the California Department of Water Resources, to whom I am grateful.

I thank above all my vast family, Lowell and Jun Rheinheimer, Edith and Philip Bragdon, and my siblings Lisa, Jason, Wendell, Francis, Zenobia, Laura, Owen, and Leyla. I am indebted to you all for your love and encouragement. Thanks also to my aunt and uncle Carol and Andy Sawyer for their warm welcome to Sacramento and the Sierra Nevada, their majestic backyard.

Abstract

Hydropower systems and other river regulation often harm instream ecosystems, partly by altering the natural flow and temperature regimes that ecosystems have historically depended on. These effects are compounded at regional scales. As hydropower and ecosystems are increasingly valued globally due to growing values for clean energy and native species as well as and new threats from climate warming, it is important to understand how climate warming might affect these systems, to identify tradeoffs between different water uses for different climate conditions, and to identify promising water management solutions.

This research uses traditional simulation and optimization to explore these issues in California's upper west slope Sierra Nevada mountains. The Sierra Nevada provides most of the water for California's vast water supply system, supporting high-elevation hydropower generation, ecosystems, recreation, and some local municipal and agricultural water supply along the way. However, regional climate warming is expected to reduce snowmelt and shift runoff to earlier in the year, affecting all water uses. This dissertation begins by reviewing important literature related to the broader motivations of this study, including river regulation, freshwater conservation, and climate change. It then describes three substantial studies.

First, a weekly time step water resources management model spanning the Feather River watershed in the north to the Kern River watershed in the south is developed. The model, which uses the Water Evaluation And Planning System (WEAP), includes reservoirs, run-of-river hydropower, variable head hydropower, water supply demand, and instream flow requirements. The model is applied with a runoff dataset that considers regional air temperature increases of 0, 2, 4 and 6 °C to represent historical, near-term, mid-term and far-term (end-of-century) warming. Most major hydropower turbine flows are simulated well. Reservoir storage is also generally well simulated, mostly limited by the accuracy of inflow hydrology. System-wide hydropower generation is reduced by 9% with 6 °C warming. Most reductions in hydropower generation occur in the highly productive watersheds in the northern Sierra Nevada. The central Sierra Nevada sees less reduction in annual runoff and can adapt better to changes in runoff timing. Generation in southern watersheds is expected to decrease. System-wide, reservoirs adapt to capture earlier runoff, but mostly decrease in mean reservoir storage with warming due to decreasing annual runoff.

Second, a multi-reservoir optimization model is developed using linear programming that considers the minimum instream flows (MIFs) and weekly down ramp rates (DRRs) in the Upper Yuba River in the northern Sierra Nevada. Weekly DRR constraints are used to mimic spring snowmelt flows, which are particularly important for downstream ecosystems in the Sierra Nevada but are currently missing due to the influence of dams. Trade-offs between MIFs, DRRs and hydropower are explored with air temperature warming (+0, 2, 4 and 6 °C). Under base case operations, mean annual hydropower generation increases slightly with 2 °C warming and decreases slightly with 6 °C warming. With 6 °C warming, the most ecologically beneficial MIF and DRR reduce hydropower generation 5.5% compared to base case operations and a historical climate, which has important implications for re-licensing the hydropower project.

Finally, reservoir management for downstream temperatures is explored using a linear programming model to optimally release water from a reservoir using selective withdrawal. The objective function is to minimize deviations from desired downstream temperatures, which are specified to mimic the natural temperature regime in the river. One objective of this study was to develop a method that can be readily integrated into a basin-scale multi-reservoir optimization model using a network representation of system features. The second objective was to explore the potential use of reservoirs to maintain an ideal stream temperature regime to ameliorate the temperature effects of climate warming of air temperature. For proof-of-concept, the model is applied to Lake Spaulding in the Upper Yuba River. With selective withdrawal, the model hedges the release of cold water to decrease summer stream temperatures, but at a cost of warmer stream temperatures in the winter. Results also show that selective withdrawal can reduce, but not eliminate, the temperature effects of climate warming. The model can be extended to include other nearby reservoirs to optimally manage releases from multiple reservoirs for multiple downstream temperature targets in a highly interconnected system.

While the outcomes of these studies contribute to our understanding of reservoir management and hydropower at the intersection of energy, water management, ecosystems, and climate warming, there are many opportunities to improve this work. Promising options for improving and building on the collective utility of these studies are presented.

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Chapter 1:
Introduction

Problem statement

Environmental flows and water temperature are important for conserving freshwater ecosystems. However, many river systems are highly regulated with infrastructure, such as dams and diversions, often harming native instream ecosystems. Though most types of river regulation affect freshwater ecosystems, hydropower systems are particularly important as a nexus between water, environment, and energy. Hydropower dominates other water management uses in the Sierra Nevada, California, the geographic region considered here. Globally, demand for renewable energy is increasing, and hydropower has a major role in meeting new energy demands. In California, recent shifts in policy (e.g., California Assembly Bill No. 32) have emphasized developing and maintaining hydropower as part of efforts to curb greenhouse gas emissions. This trend is observed elsewhere. China, for example, is currently undertaking an unprecedented expansion in hydroelectric capacity.

Confounding this renewed focus on hydropower as a source of clean and inexpensive energy, long-term hydrologic regimes, which are the basis for current hydropower operations, are no longer stationary. In California, the major water systems depend on timely and predictable snowmelt from the Sierra Nevada. However, regional climate warming is expected to reduce snowmelt and shift runoff to earlier in the year, when energy demands are lower. These changes will affect planning and operations and the potential need for adaptation.

Given the importance of hydropower for supplying clean energy and the major effects of hydropower and other water management systems on freshwater ecosystems, a better understanding of the effects of existing management schemes on ecosystems, including tradeoffs between water for the environment and other uses, is needed to make better water management decisions. Some general questions that arise include: What are the quantitative effects of water management on the abiotic and biotic character of rivers and streams? What are the tradeoffs between competing water management objectives? How will global climate warming likely affect water management? Though these questions pervade water management efforts globally, addressing these questions for specific systems or regions, such as California's Sierra Nevada, is needed. Computer models are essential to understanding the effects of existing operations and to anticipate the effects of changing conditions on operations. To use computer models effectively, however, we also ask: How can freshwater ecosystem objectives be better included in water planning and management models?

This dissertation develops and uses simulation and optimization to explore climate change effects on hydropower management in the Sierra Nevada, California, the tradeoffs between environmental releases and hydropower generation and how climate warming might alter these competing interests, and the management of thermal pools in reservoirs to meet downstream temperature objectives. The remainder of this chapter provides more general background to this work, including river regulation, freshwater conservation, hydropower, and global climate change. It also outlines the following chapters and summarizes important contributions to the body of knowledge.

River regulation and freshwater conservation

The broad motivation for this research stems from a global trend of rapid recent losses in freshwater biodiversity and ecosystem services due to general development and river regulation (Mace et al. 2005; Nel et al. 2008; Postel and Carpenter 1997; Richter et al. 1997; WWF 2004) and calls for greater efforts to better understand and manage rivers for freshwater ecosystems and ecosystem services (Abell 2002; Arthington et al. 2010; Costanza et al. 1997; Jewitt 2001; Johnson et al. 2001; Nel et al. 2008; Postel and

Carpenter 1997; Richter et al. 2003). There is an ongoing need for research tools and knowledge from the reservoir operations modeling community to aid water resources system managers in addressing these challenges locally and regionally (Jager and Smith 2008; Jewitt 2001; Poff 2009). A second motivation is the general recognition that the assumption of stationarity of the hydrologic record is unjustifiable given the broad consensus that global climate warming will result in substantial changes to hydrologic regimes (Milly et al. 2008), necessitating the consideration of future global and regional climate changes in freshwater conservation planning and management (Abell 2002).

Water resources planning and management efforts can address freshwater ecosystem objectives in multiple environmental and management domains (e.g., Bratrich et al. 2004) and multiple spatial scales. Existing or promising practices for better management of rivers for ecosystems and ecosystem services broadly include regional water planning and management (Abell et al. 2007; Nel et al. 2008; Viers and Rheinheimer 2011), better operations of regulating infrastructure (Richter and Thomas 2007), environmentally-friendly design of regulating infrastructure (e.g., fish passage structures at dams), and local physical interventions such as management of habitat morphology (Brookes and Shields Jr. 1996; Wheaton et al. 2004). Continual monitoring and adaptive management (Holling 1978; Lee 1999; Pahl-Wostl 2007; Walters 1986; Walters and Holling 1990) are needed across all management domains (Richter et al. 2003). At the watershed scale, researchers addressing freshwater ecosystem conservation highlight the need to integrate riverine conservation plans with water resources management due to the long-range, longitudinal nature of riverine ecosystems (Nel et al. 2008; Roux et al. 2008; Viers and Rheinheimer 2011). Though some researchers highlight the need for and utility of “protected areas” in freshwater conservation efforts (Abell et al. 2007; Roux et al. 2008), the large spatial range and importance of longitudinal connectivity of freshwater systems generally precludes developing terrestrial protected areas large enough to include all or even most regional freshwater systems, especially in systems that are already heavily regulated. However, “conservation areas”, which could include a combination of management strategies, would likely be suitable for most river systems with high existing or potential conservation value (Nel et al. 2008). Effective planning and management of water resources for freshwater conservation and other water uses at the regional scale requires a better understanding of baseline and potential future operations for existing systems. This need motivates Chapter 2, which describes a hydropower-centric water resources management model spanning the upper west slope of the Sierra Nevada in California. Chapter 3 and Chapter 4 focus on better operations of regulating infrastructure.

Hydropower

Many rivers are regulated for hydropower, with substantial local and regional effects on freshwater ecosystems, as described below and in the following chapters. To understand how hydropower systems affect ecosystems, it is important to understand the physical and operational characteristics of hydropower systems. We focus on river regulation from hydropower because of its ubiquity in many developed regions of the world and its growing importance globally, because the ecosystem effects of some features of hydropower facilities apply to other river regulation mechanisms, and because hydropower is particularly important in the upper Sierra Nevada, the geographic region of interest here.

Hydropower facilities convert the potential energy of impounded water into electricity. The potential energy is used to rotate turbines at high rotational velocities, generating electricity. Water used to generate electricity in a hydropower facility is usually directly from rivers and is either used for immediate hydropower generation or stored for later release. Because hydropower production uses water from rivers, which replenish naturally, hydropower is considered renewable and inexpensive to produce.

The energy equation for a hydropower plant is:

$$E = \gamma h Q \eta \tag{0.1}$$

where γ is the specific weight of water ($\gamma = \rho g$, where ρ is the density of water and g is the gravitational constant), h is effective head on the turbine, Q is the flow rate of water through the turbine, and η is the turbine efficiency. Turbine efficiency varies with flow rate and head, but is often considered constant in planning studies. That hydropower generation depends on flow rate has important ecological implications. Energy output objectives, which are driven by both energy supply needs on an electricity grid and a portfolio of electricity supplies, result in hydropower flow releases that, from an energy demand perspective, should match electricity grid needs rather than ecosystem needs.

Several hydropower facility configurations and operating purposes exist, where the configuration constrains operational possibilities. There are several common hydropower system configurations:

- *Conventional (variable head)* – Conventional hydropower plants derive their energy from the potential energy of water stored in an impoundment just upstream of the powerhouse. Because the powerhouse is at the base of the impoundment, which may have variable storage, variations in head can be large compared to average head. Water sent through the powerhouse is released into the river directly below the dam. Facilities with large storage capacity can substantially alter the downstream flow regime, as discussed below.
- *Run-of-river (low head)* – Run-of-river (ROR) hydropower plants have little to no reservoir capacity to store energy. Because there is little storage, their head is relatively constant. ROR plants depend on water flowing in the river or released from an upstream reservoir to generate electricity. The little storage in ROR facilities is often operated for energy use peaks (see below). Their small reservoir capacity reduces their ability to significantly alter the seasonal timing of downstream flows.
- *Run-of-river (high head)* – High head ROR plants also do not depend on a large reservoir for potential energy, but are located some distance from the dam, at a much lower elevation than the dam. Water is diverted from a river, possibly from a large reservoir, via a canal, flume, tunnel, or pipe to a forebay, which is used to maintain a constant, high head. Forebays for high head ROR plants are typically small, but may be large enough for short-term storage from the water source. High head run-of-river configurations are common in high elevation hydropower schemes due to the high potential energy but (often) low flows relative to areas with low elevation gradients.
- *Pumped-storage* – Finally, *pumped-storage* hydroelectric schemes use potential energy from stored water to generate electricity during times when electricity demand (price) is high and pump the released water back into the storage reservoir when demand and pumping costs are low. Pumped storage is therefore profitable, though a net energy loss. Pumped storage facilities are considered environmentally advantageous as they can be located off-stream and can re-use the same water to reduce effects on instream flows (Richter and Thomas 2007).

Hydropower facilities operate to serve a larger electricity grid, which is usually supplied by several electricity generation plants. The electricity grid distributes energy generated to meet local energy demands. However, because electricity in a regional grid is not stored, supply must exactly match demand. Electricity system operators are therefore always balancing energy demand and supply. While much demand is predictable, and can be planned for well in advance, there are frequently short-term fluctuations in energy demand and unexpected changes in supply. Three operating roles of electricity producers reflect these demand characteristics:

- *Base load* – Base load supply is used to meet fixed demand that can be planned for well in advance. Powerplants that provide base load are typically left on and shut down only for scheduled maintenance. Plants that are slow to start and shut down (e.g., nuclear and coal-fired plants) are typically always used for base load, but any plant that can provide a reliable and stable supply can be used. Hydropower is often used for base load in wetter years and in areas where hydropower dominates grid supplies, in which case hydropower releases are stable and predictable. ROR hydropower plants without significant upstream storage are typically used for base load.

- *Load following* – Load following plants are used to meet demand that is fairly predictable but intermittent. For example, diurnal periods of high residential demand in the late afternoon and evenings are typically met with load following supply. Because load following is typically planned for a day in advance, any plant that can start or stop in hours or less can be used for load following. Hydropower is often used for load following due to its ability to start and stop quickly and its high generation efficiency.
- *Peaking* – Peaking operations are used to meet the many short-term fluctuations in energy demand. This includes, in particular, short periods of high demand during hot summer days when air conditioners are used. Whereas thermal facilities such as nuclear powerplants are unable to alter output on such short notice, hydropower plants are typically well suited for peaking operations. Hydropower plants used for peaking operations can respond, often within seconds, to changes in energy demand, with a variety of control mechanisms. However, this “hydropeaking” causes rapid fluctuations in flows downstream of the plant, which can have disastrous ecological consequences.

Not all electricity generation plants can fulfill these roles. However, hydropower plants, depending on the physical configuration of the facility, can fill some or all of these roles. As a result, hydropower is an unusually valuable electricity supply. Hydropower often is used to meet base load, especially in countries with a high percentage of energy consumption from hydropower (REN21 2011). In California, hydropower is used to meet peak load demand, for example on hot summer days, when energy prices are high, and to accommodate fluctuations in demand.

Globally, about 16% of total energy production is from hydropower (REN21 2011); in California, hydropower averages about 15% of the state’s electricity supply (California Energy Commission 2008). Demand for electricity is increasing globally due to increases in population and per capita consumption, particularly in developing nations such as India and China (U.S. Energy Information Administration 2011). Demand for energy, including electricity, in developed nations is also expected to rise with climate warming in areas, including California, where increases in electricity demand for summer cooling (air conditioners) are expected to exceed decreases in electricity for winter heating (Franco and Fagundes 2005; Hadley et al. 2006).

Demand for renewable electricity sources, such as hydropower, over fossil fuel plants to help mitigate greenhouse gas emissions also is increasing (Kosnik 2008). For example, California has emphasized developing and maintaining hydropower to help curb greenhouse gas emissions (e.g., California Assembly Bill No. 32). Though hydropower reservoirs emit greenhouse gases (Rosenberg et al. 1997), and could contribute as much as 15% of other documented anthropogenic greenhouse gas sources with anticipated future developments (St. Louis et al. 2000), in temperate regions such as the United States, atmospheric greenhouse gases from hydropower are much less than from fossil fuel plants (Bratrich et al. 2004).

Environmental effects of hydropower

While beneficial for a power supply system, hydropower systems disrupt aquatic ecosystems in a variety of ways. Hydropower effects vary spatially and temporally, from local to landscape scales and from minutes and hours to decades and longer time periods. Major effects of hydropower facilities include changes to the flow regime (Bunn and Arthington 2002; Poff et al. 1997; Poff et al. 2007); alterations to the sediment regime, which affects habitat substrate quality (Gordon and Meentemeyer 2006; Ligon et al.

1995); changes to water quality such as stream temperature, dissolved oxygen, and other quality characteristics due to reservoir water quality dynamics (Gordon and Higgins 2007); and habitat fragmentation due to dams (Dynesius and Nilsson 1994). These primary effects commonly coincide with complex and cascading cumulative effects on ecosystems. For example, a highly altered flow regime might encourage invasive species, which could further affect already stressed native species

Changes to a river's flow patterns affect channel forming processes and physical habitat complexity, diminishing biotic diversity; lateral and longitudinal connectivity; life history patterns such as spawning and recruitment; and the growth of invasive species populations (Bunn and Arthington 2002). Though downstream effects of altered flows (and water quality) occur over large spatial and temporal scales (Nel et al. 2008; Rosenberg et al. 1997), the effects often diminish downstream of impoundments as the influence of tributaries other water sources (e.g., groundwater) restore natural river conditions (Stanford and Ward 2001; Ward and Stanford 1983). Concepts used to better characterize and manage river flows for freshwater ecosystems are discussed below. Operations for better flow management are explored in Chapter 3.

Because energy output from a hydropower plant is directly proportional to hydropower turbine flow, the electricity supply from a hydropower plant directly affects downstream flows and, consequently, downstream ecosystems. However, because there are many possible hydropower system configurations, different kinds of flow regulation effects can occur in different parts of a regulated river system. In the Upper Yuba River watershed (Chapter 3), for example, flow patterns below the main storage reservoirs are completely different from flow patterns below the hydropeaking powerhouses, which are located in the Bear River watershed.

Geomorphic characteristics of a river greatly affect riverine ecosystems. In general, clean, sorted gravel in a river bed that is periodically replenished, supports a range of habitat niches, from primary producers to vertebrates (Milhous 1998; Osmundson et al. 2002; Peterson 1996; Yarnell et al. 2010). Hydropower dams reduce the availability and quality of sediment needed for fish substrate habitat. Specific geomorphic features of riverbeds and their characteristics, such as channel bars and the river bed, are determined by the local flow regime, sediment supply, and geological conditions (slope and bed materials) (Ashworth 1996). Large rainfall and snowmelt events mobilize and transport sediment for later redistribution downstream (Madej 1999). In snowmelt-dominated flow regimes, the natural gradual reduction in flows during the spring snowmelt period creates heterogeneous distributions of sediment in the river and in channel bars (Yarnell et al. 2010). Dams block downstream movement of sediment and reduced flows can reduce or eliminate sediment supplied from erosion of floodplain deposits in new channels (Ligon et al. 1995). This results in simplification of channels, with fewer and lower quality channel bars, channel incision, and generally greater river stability (Ligon et al. 1995), all of which decrease the range of physical habitats needed to support a healthy river ecosystem.

Hydropower facilities also affect water quality. Reservoirs in temperate regions often thermally stratify during the warm season (Chapra 1997). Many hydropower plants have a single intake from the reservoir, so the temperature of the hydropower release is the reservoir temperature at the intake location. This can make downstream releases too cold or too warm for downstream ecosystems, possibly both over the course of a year. Dams can also cause eutrophic reservoir conditions, reducing dissolved oxygen concentration in the hypolimnion and accumulating sediment-bound nutrients that may later be released (Gordon and Higgins 2007). Managing reservoir releases to meet downstream temperature objectives is the topic of Chapter 4.

The barrier of dams to flows of water, material, energy, and biota also often have major ecosystem effects (Johnson et al. 1995; Vannote et al. 1980). As a barrier to upstream and downstream fish migration, hydropower and other dams fragment habitat, cutting off species from their original habitat range, causing genetic isolation (Heggenes and Røed 2006; Neraas and Spruell 2001; Pringle 1997). Fish that successfully pass through a reservoir outlet or turbine can become temporarily vulnerable to predation (Jepson et al. 1998). Though some dams have fish passage facilities, the many dams that need to be passed reduces overall species population size (Dynesius and Nilsson 1994; Poff and Hart 2002).

Local effects of global climate change

Mean global temperatures are expected to increase by about 5 °C above historical levels by 2100 with business-as-usual greenhouse gas emissions (IPCC 2007); in California the increase is likely to be higher (Hayhoe et al. 2004). These changes will affect water resources, such as stream runoff and stream temperature regimes (Kundzewicz et al. 2007), and ecosystems (Fischlin et al. 2007). In dry mid-latitude regions, including Mediterranean regions, the western United States, and much of the Middle East, runoff will decrease. In California in particular, where major rivers are dominated by snowmelt, increases in temperature will decrease precipitation storage as snow, thereby increasing rainfall runoff and decreasing snowmelt runoff, shifting flows to earlier in the year (e.g., Hayhoe et al. 2004; Vicuna and Dracup 2007). Anticipated mean annual runoff in California will decrease, primarily from increased evapotranspiration, though precipitation is expected to decrease somewhat (e.g., Dettinger et al. 2004; Hayhoe et al. 2004).

Increases in global temperatures also will affect stream temperatures, partly from stream warming and partly from changes in the flow regime. In California's Sierra Nevada, snowmelt provides a steady supply of cold water. The combined effect of changing flows and temperatures will affect river ecosystems in several ways, including by altering habitat suitability and organism metabolism, ultimately changing the abundance and distribution of freshwater species (Poff et al. 2002). Of particular importance, warming is likely to drastically reduce the availability of habitat for cold water fisheries in the western Sierra Nevada (Null et al. in review), a motivation for the study described in Chapter 4.

Global and regional climate warming therefore threatens the long-term viability of native freshwater ecosystems, in addition to current and future stressors from river regulation, described above. However, though threats to freshwater ecosystems from river regulation and climate warming have been studied there is little research related to the vulnerabilities of freshwater ecosystems to the combination of river regulation and climate warming. Studies described in this dissertation address water resources management issues that should be considered when planning for local and regional freshwater conservation in the context of global and regional climate warming.

Though the global and California-specific trends of impacts on hydrologic regimes have been widely reported (Kundzewicz et al. 2007; Vicuna and Dracup 2007), detailed water management models for climate impacts studies require higher spatial and temporal resolutions than is typically done. In particular, to translate the results from global-scale models to hydrologic (and other) changes in specific locations is challenging, and requires several modeling steps using physical models, statistical analyses, or both. To estimate the local hydrologic effects of anticipated global climate changes, future flows can be 1) explicitly modeled using either assumed or modeled changes in meteorological conditions, possibly informed by General Circulation Model (GCM) results, or 2) estimated by using perturbation ratios to perturb data from a hydrologic dataset that represents historical conditions. With an explicit model, changes in local meteorological conditions are first estimated and then used in a statistically- or physically-based hydrology model that considers local hydrologic processes (Gleick 1986; Wood et al. 1997). Local meteorological conditions can be estimated by using modified local data ('hypothetical scenarios') or by using downscaled results from GCMs (Vicuna and Dracup 2007). More commonly, GCMs are used either directly or down-scaled, using a variety of techniques (Wood et al. 2004), to estimate local meteorological conditions. Vicuna and Dracup (2007) list many examples for California.

Once local meteorological parameters are estimated or otherwise assumed, a range of hydrologic models, either physically-based or statistically-based, can be used to estimate local runoff and other hydrologic conditions. Physically-based models determine hydrologic conditions based on an understanding of fundamental hydrologic processes in a locality and are frequently used (Vicuna and Dracup 2007). Because physically-based models rely on fundamental physical processes, they can be used with meteorological scenarios outside the range of historical conditions, though they require the estimation of many parameters, which may be difficult. Statistically-based hydrologic models use empirical statistical relationships between meteorological conditions (e.g., precipitation and temperature) and, for example, runoff. Such models are simple to develop, but may not be accurate outside the range of historical conditions. While physically-based hydrology models have provided useful insights, Vicuna and Dracup (2007) note that physical watershed parameters that drive hydrologic responses, such as vegetation cover, are left constant in climate impact studies, whereas they would likely change with long-term warming.

The perturbation ratio method to incorporate GCM results into local runoff for climate impact studies avoids the need to estimate or otherwise assume future meteorological conditions at a smaller spatial resolution than is available from the GCM grid cells (e.g., Vicuna et al. 2008). Ratios between flows from an arbitrary future time period of interest and from the historical time period are developed using runoff data developed with a GCM at the GCM grid scale. This method can also be used to utilize GCMs for their estimation of relative changes from historical conditions, in instances when representation of historical hydrologic conditions using GCMs is substantially different from observed conditions (Tanaka et al. 2006; Vicuna et al. 2007). In California, several recent studies of climate warming impacts on water resources have used the perturbation ratio method (e.g., Madani and Lund 2010; Tanaka et al. 2006; Vicuna et al. 2008).

A wide range of combinations of the above methods have been used to estimate the effects of global warming on water resources in California, as documented by Vicuna and Dracup (2007). The work described in the following chapters uses results from the work of Young et al. (2009), who used the Water Evaluation and Planning software (WEAP) (Yates et al. 2005), a physically-based lumped hydrology model, to develop a runoff dataset for the western Sierra Nevada. The model of Young et al. (2009), described in further detail in Chapter 2, was applied using historical meteorological data with ‘hypothetical scenarios’ consisting of uniform increases in temperature of 0, 2, 4, and 6 °C to represent temperature increases through the end of the century. Temperatures used in Chapter 4 are also based on this model.

Outline of chapters

Chapter 2 describes the development and implementation of a multi-purpose water management simulation model that spans the western slope of the Sierra Nevada, from the Feather River in the north to the Kern River in the south. The model includes reservoirs, hydropower plants, instream flow requirements, diversions, water supply demand, and some flood regulation. The model is applied using a 20-year, weekly time step runoff dataset that includes historical climate conditions and uniform regional atmospheric warming of +2, 4 and 6 °C to assess the warming impacts on hydropower generation at the watershed scale.

In Chapter 3, an optimization model is developed that includes a weekly time step down ramp rate requirement below reservoirs in a multi-reservoir system to prevent the sudden decrease in flow that typically occurs at the end of the spill season. The model is applied to a hydropower system in the upper Yuba River in the northern Sierra Nevada to assess the trade-offs between hydropower generation/revenue, minimum instream flow requirements, down ramp rate requirements, and regional climate warming, using the same inflow dataset used in Chapter 2.

Chapter 4 explores another important ecosystem concern, management of temperatures released from reservoirs. An optimization model for operation of selective withdrawal to manage releases from thermal layers in a multi-reservoir system is developed and applied to Lake Spaulding, a seasonally-stratified reservoir in the upper Yuba River.

Finally, Chapter 5 concludes by discussing the importance of the work and prospects for future research. In particular, Chapter 5 describes how the studies in each previous chapter could be integrated to assess regional-scale impacts of warming with environmental flows to help prioritize water resources management efforts both in the Sierra Nevada and elsewhere.

Summary of contributions

This dissertation includes several novel contributions to the body of knowledge related to water resources management at the nexus of hydropower operations, freshwater ecosystem management and climate warming. These include:

- A multi-sector water management simulation model of the western Sierra Nevada, including two new methods to approximate hydropower operation by integrating historical energy demand and with changes in inflow hydrology.
- A watershed-scale assessment of regional effects of climate warming on hydropower generation to help identify watersheds where hydropower generation is most at risk.
- A multi-reservoir linear programming model that explicitly includes maximum rates of decrease below reservoirs to restore spring snowmelt flows, applied to the Upper Yuba River, California.
- An optimization model to optimize releases from a thermally stratified reservoir at the weekly scale and in a node-arc model framework.
- A method to optimize releases for hydropower in a traditional simulation model with limited energy price information.

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Chapter 2:
Simulating the Water Resources of the Upper West Slope Sierra Nevada

Abstract

Climate warming is expected to affect the beneficial uses of water in the Sierra Nevada, affecting residents throughout California. To improve understanding of how regulated flows in the Sierra Nevada may be vulnerable to climate warming and to help develop adaptation strategies to manage water resources for competing demands, we developed a weekly time step water resources management model for the west slope Sierra Nevada spanning the Feather River watershed in the north to the Kern River watershed in the south. The model, developed with the Water Evaluation And Planning system (WEAP), includes management of reservoirs, run-of-river hydropower plants, water supply demand locations, conveyances, and instream flow requirements. The model is applied with runoff from a rainfall-runoff model that considers regional air temperature increases of 0, 2, 4 and 6 °C warming to represent historical, near-term, mid-term and far-term (end-of-century) warming. Most major hydropower turbine flows are simulated well. Reservoir storage is also generally well simulated, mostly limited by the accuracy of inflow hydrology. System-wide hydropower generation is reduced by 9% with 6 °C warming. Most reductions in hydropower generation occur in the highly productive watersheds in the northern Sierra Nevada. The central Sierra Nevada sees less reduction in annual runoff and can adapt better to changes in runoff timing. Generation in southern watersheds is expected to decrease. System-wide, reservoirs adapt to capture earlier runoff, but mostly decrease in mean reservoir storage with warming due to decreasing annual runoff. We highlight important model limitations and recommend improvements, including the use of alternative inflow hydrology data to represent a broader range of climate warming scenarios and a more refined hydropower simulation method.

Introduction

Climate warming is expected to affect the beneficial uses of water in California’s Sierra Nevada mountains, including hydropower, water supply, ecosystem benefits, and flood control, directly affecting nearly every resident of California. However, no single model or tool is available to assess potential regional vulnerabilities to climate change across a range of water use sectors in sufficient detail to inform management decisions. To help fill this management information gap, we developed a watershed scale, weekly time step simulation model of regulated flows for 15 watersheds in the upper west slope of the Sierra Nevada (Figure 2-1), called the Sierra Integrated Environmental and Regulated Rivers Assessment (SIERRA) model.

SIERRA is an operations simulation model of major water management infrastructure and operations in the upper watersheds of the west slope of the Sierra Nevada (WSSN). Modeled features include reservoir operations, hydropower generation, water demand, and instream flow requirements. Young et al. (2009) used WEAP to model the unimpaired hydrology of 15 major watersheds in the western Sierra Nevada. SIERRA spans the same geographic region, uses the same set of climate change scenarios (+0, 2, 4 and 6 °C warming), and the same temporal resolution (weekly time steps). Subsequently, Mehta et al. (2011) developed a water management simulation model using WEAP to study the effects of climate change on hydropower in the Cosumnes, American, Bear and Yuba River watersheds using the runoff results of Young et al. (2009). SIERRA builds on the work of Mehta et al. (2011) with improved simulation methods.

This chapter describes the model methods, calibration, a subset of results, and a summary of model limitations and recommendations for improvement. Results from a model as comprehensive as SIERRA are extensive. Here, results focus on hydropower generation, the dominant management objective in the upper Sierra Nevada. Focusing on hydropower also allows for comparisons of results with other regional hydropower models.

Water resources in the Sierra Nevada

The Sierra Nevada mountains, located in eastern California, span 650 km (400 mi.) from north to south and rise from about 100 m to 4,000+ m in the south and to +2,500 m in the north. The west slope includes 15 watersheds that range in size from 730 to 9,412 km^2 , totalling of 47,700 km^2, and that drain a total of approximately 26.2×10^9 m^3 per year (Null et al. 2010). Water infrastructure in the upper Sierra Nevada, defined as elevations above about 350 m (1000 ft), is managed mostly for hydropower, but also for municipal and agricultural water supply, environmental releases, and recreation. California's in-state hydropower generation supplies from 10-20% of the state's total energy use, about 12% on average (California Energy Commission 2009; Franco and Fagundes 2005), produced primarily from more than 150 reservoirs in the Sierra Nevada higher than 350 m above sea level (Franco and Fagundes 2005). There are about 134 hydropower facilities in the west slope Sierra Nevada with a collective capacity of approximately 8,800 MW. Total storage in reservoirs greater than 1.2×10^6 m^3 (1,000 AF) is approximately 24.6×10^9 m^3 in the western Sierra Nevada (Null et al. 2010), which includes the large low-elevation multi-purpose reservoirs mostly excluded in this study, or about 94% of the total annual runoff.

While the majority of high-elevation reservoirs are not explicitly managed for water supply or flood regulation, they implicitly have water supply and flood regulation roles at the watershed scale by providing inflows to the major water projects of the Central Valley and by providing incidental flood storage space at the watershed scale.

Global climate warming will alter hydrology on global, regional, and local scales (Bates et al. 2008). Climate warming is expected to reduce snowpack, decrease mean annual flow, and lead to earlier spring snowmelt runoff in the western United States, including the Sierra Nevada (Dettinger et al. 2004; Hayhoe et al. 2004; Tanaka et al. 2006; Vicuna et al. 2007).

Hydrologic changes in the Sierra Nevada will affect hydropower production, urban and agricultural supply, recreation and other beneficial uses such as aquatic and terrestrial ecosystems (Hayhoe et al. 2004; Ligare et al. 2011; Madani and Lund 2010; Medellín-Azuara et al. 2008; Null et al. 2010; Tanaka et al. 2006). Though it is widely understood that warming will affect hydrology-dependent systems in the Sierra Nevada, few models quantify effects on specific systems. These models are discussed below.

Regional water resources management models

Several water resources management models exist that include some aspect of watershed-scale water resources in the upper Sierra Nevada. All models of upper Sierra Nevada water systems are single-purpose (i.e., flood regulation, hydropower, and water supply). Existing models that include most of the upper Sierra Nevada are temporally coarse, generally monthly-scale, and also single-purpose. Some local models have greater temporal resolution (e.g., Vicuna et al. 2008). Models of California's major water supply systems such as CALVIN (Medellín-Azuara et al. 2008; Tanaka et al. 2006) and CalSim II (Draper and Darabzand 2003) exclude most high-elevation water systems above the large, low-elevation, multi-purpose reservoirs, yet rely on runoff from the Sierra Nevada as boundary inflows; changes in upstream inflow patterns from changing hydrology and changing management could affect large reservoir operating constraints.

Two single-purpose reservoir management models have been developed that span most of the western Sierra Nevada. Hickey et al. (2003) included 73 flood reduction reservoirs, including 40 high-elevation Sierra Nevada reservoirs, in a *HEC-5* (U.S. Army Corps of Engineers (USACE) 1998) synthetic flood hydrograph simulation model for California's Central Valley. Madani and Lund (2009) modeled monthly hydropower generation in California for elevations higher than 300 m (1000 ft.), including most hydropower reservoirs in the Sierra Nevada, by describing reservoir storage in energy units and using the Energy-Based Hydropower Optimization Method (EBHOM) and assuming no annual spill. As these models are tailored to addressing specific water use purposes, they do not enable estimating regulated flows in specific locations.

Numerous models have been developed for operations planning for individual watersheds or systems in the western Sierra Nevada for flood control, hydropower, and water supply. For instance, the Pacific Gas & Electric Company (PG&E) uses an optimization model that incorporates probabilistic inflows to help plan operations of its hydropower systems (Jacobs et al. 1995), which span a substantial portion of the western Sierra Nevada.

Several models have been developed to study potential impacts of climate change on hydropower systems with local case studies (Mehta et al. 2011; Vicuna et al. 2009; Vicuna et al. 2008) and to study broad impacts across the Sierra Nevada at the monthly scale (Madani and Lund 2010). Using a range of downscaled climate conditions from two emissions and six global climate model (GCM) scenarios, Vicuna et al. (2009) estimated decreases in energy production of 12.2% in the Upper American River Project (UARP) system and 10.4% in the Big Creek System (San Joaquin River watershed) by end-of-century, when averaged across emissions and GCM scenarios. These results are from corresponding decreases in mean annual runoff of 10.1% in the UARP system and 17.8% in the Big Creek System.

Mehta et al. (2011) developed a weekly scale model of the Cosumnes, American, Bear, and Yuba (CABY) watersheds in the western Sierra Nevada using WEAP (Yates et al. 2005) to simulate changes in water management with regional climate warming. Assuming uniform air temperature increase of 0, 2, 4, and 6 °C (Young et al. 2009), a decrease in hydropower generation of almost 20% in the Yuba-Bear/Drum-Spaulding project in the upper Yuba River and Bear River watersheds and 22% in the Middle Fork Project in the American River watershed. These correspond to decreases in annual runoff of just 4.4% in the upper Yuba River and 6.6% in subwatersheds contributing to the Middle Fork Project. The model described here builds on the work of (Mehta et al. 2011), with key model improvements.

At the system-wide scale, Madani and Lund (2010) applied EBHOM (Madani and Lund 2009) to estimate effects of warming, with wet, dry, and warming-only conditions, on high-elevation hydropower generation. With warming-only—i.e., a change in runoff timing to earlier in the year, but with no change in total annual runoff—Madani and Lund (2010) estimated a decrease in energy generation California-wide by a much more modest 1.3% using hydrology from 1985-1988. With drier conditions (less runoff), they estimated decreases of almost 20%.

These studies demonstrate that annual generation is much more positively dependent on total annual runoff than on changes in runoff timing and that by end-of-century, hydropower production will likely decrease substantially due to decreased average annual runoff. This is due to the ability of hydropower systems to adapt, at least partially, to changes in runoff timing. Most regional climate change adaptation models inherently adapt to changes in timing because they use optimization methods; it is therefore essential to incorporate system adaptive capacity in a rule-based simulation model.

These anticipated impacts on hydropower generally mean that changing climate conditions need to be considered in long term, regional planning of water resources in the Sierra Nevada, as water users will be under ever greater pressure to maintain services and revenues by continuing to operate in ways that potentially harm other water users, including the environment.

While previous studies have greatly contributed to the body of knowledge both in terms of methods (e.g., Madani and Lund 2009) and findings, they are collectively limited in geographic scope, management domain, and/or temporal scope. The goal of this work was to fill some of these gaps by including most of the water management infrastructure in the western Sierra Nevada in multi-reservoir simulation model framework and by using a finer temporal resolution.

Methods

The primary objective of this work was to create a model that simulates the operations all major upper west slope Sierra Nevada water management in a way that is sensitive to climate changes and that can be readily improved for future studies. The model scope and the physical characteristics and operational logic of modeled features are described.

Geographic and temporal scope

From north to south, modeled watersheds include the Feather, Yuba, Bear, American, Cosumnes, Mokelumne, Calaveras, Stanislaus, Tuolumne, Merced, San Joaquin, Kings, Kaweah, Tule, and Kern River watersheds (Figure 2-1). Though the Calaveras and Merced watersheds lack major regulating infrastructure above their terminal dams, they were included for completeness.

Most major infrastructure elements in each watershed are included, except for most of the major terminal "rim" dams, as described below. The modeling goal was to simulate dominant operations of major water management infrastructure, including reservoirs, diversions, hydropower, and water supply, with air temperature a primary variable for operations. Though operations become increasingly complex at smaller time steps, the weekly time step is used.

Infrastructure

The SIERRA model includes 58 reservoirs, 102 hydropower plants, 126 conveyances (canals, flumes, tunnels, and pipelines), and 25 water supply demands, and 109 instream flow requirement locations, a total of 420 managed features (Table 2-1), though water demand is omitted from a few small features pending further development. A complete list of modeled infrastructure and their characteristics is included in Appendix 2-A.

Modeled reservoirs range in size from the 415 m^3 (0.6 AF) Rock Creek Reservoir in the Bear River watershed to the 1.45×10^9 m^3 (1.18×10^6 AF) Lake Almanor in the Feather River watershed. Though some small reservoirs are included in the CABY region, most small reservoirs such as diversion reservoirs and forebays are excluded. Generally, reservoirs listed by the California Data Exchange Center (CDEC) were included, while others were excluded. The large, low-elevation, multi-purpose reservoirs of the Sierra Nevada are not included—with the major exception of Folsom Lake and Lake Isabella—due to the added complexity of modeling flood regulation and water deliveries to the Central Valley, their primary purposes. Hydropower projects range from the 0.4 MW San Joaquin 1A project in the San Joaquin River watershed to the 1,200 MW Helms pumped-storage facility in the Kings River watershed. Small, private hydropower plants were generally omitted, with the exception of Kanaka Powerplant (Feather River watershed). Water supply demands were included where data were available or where a diversion for water supply clearly exists. Diversions for water supply are limited in the Sierra Nevada relative to water supply for the Central Valley. The majority of features, parameter values, and operational logic of the American, Bear and Yuba (ABY) watersheds included in the SIERRA model are directly from the ABY regional model described by 2011), except for hydropower operations logic, as described below.

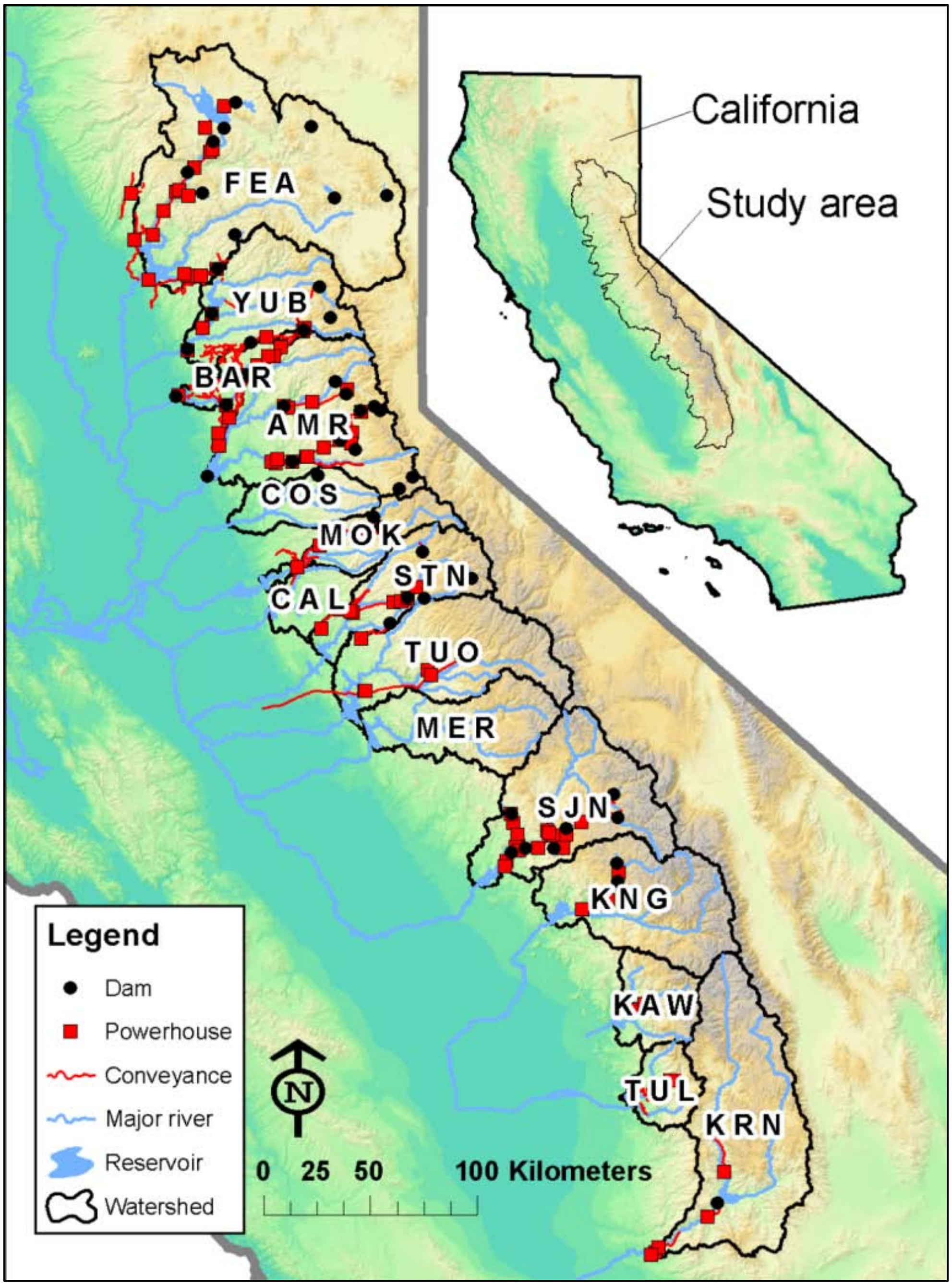

Figure 2-1. Study area: the upper west slope Sierra Nevada.

Table 2-1. Count of modeled features in SIERRA (ordered north to south).

Model code	Watershed	Outlet location (Exclusive/Inclusive)	Run-of-river hydro	Variable head hydro	Reservoirs	Supply demands	Instream flow req't	Conveyance	Total
FEA	Feather River	Lake Oroville (Exc.)	16	2	10	3	18	20	69
ABY	Yuba River / Bear River	DaGuerre Point Diversion (Inc.) / Camp Far West Lake (Inc.)	17	5	12	11	20	23	88
	American River	Folsom Lake (Inc.)	9	5	13	3	15	17	62
	Cosumnes River	Michigan Bar (Inc.)			1		1	1	3
MOK	Mokelumne River	Pardee Reservoir (Exc.)	4	1	2	2	7	9	25
CAL	Calaveras River	New Hogan Lake (Exc.)							0
STN	Stanislaus River	New Melones Lake (Exc.)	8	2	6		11	12	49
TUO	Tuolumne River	Don Pedro Lake (Exc.)	3		3	1	3	6	16
MER	Merced River	Lake McClure (Exc.)							0
SJN	San Joaquin River	Millerton Lake (Exc.)	15	1	8		19	21	64
KNG	Kings River	Pine Flat Reservoir (Exc.)	4		2		5	5	16
KAW	Kaweah River	Lake Kaweah (Exc.)	3				4	5	12
TUL	Tule River	Lake Success (Exc.)	2			5	1	2	10
KRN	Kern River	Kern R. below Rio Bravo PP (Inc.)	5		1		5	5	16
		Total	86	16	58	25	109	126	420

SIERRA was developed and applied using weekly time steps. For this study, SIERRA uses weekly inflow data from Water Year (WY) 1981-2000, as developed by Young et al. (2009). This time span is useful because it includes a wide range of recent historical climatic and discharge conditions typical of the region, including an extended drought (1987-1992), the wettest year on record (1983), and the flood year of record (1997).

The Water Evaluation and Planning System (WEAP)

SIERRA uses the Water Evaluation and Planning System (WEAP) software, a water resources modeling platform that integrates a 2-soil layer, 1-dimensional rainfall-runoff hydrology model with a priority-based water resources management model (Yates et al. 2005). SIERRA uses WEAP's water management module, with runoff (inflow) represented as exogenous variables.

To simulate operations accurately, WEAP requires physical and management parameters, operating rules, and management priorities in the form of written expressions (Figure 2-2). Expressions can vary from a single integer value to a call to an external script; they can include mathematical operators, logical functions, and a range of built-in modeling functions. Though SIERRA mostly relies on expressions to define input data, external lookup tables and scripts are also used. Major inputs to the regulated model, including classes of modeled features and feature attributes, are listed in Table 2-2. The following sections describe the methods used for each feature attribute, including data sources.

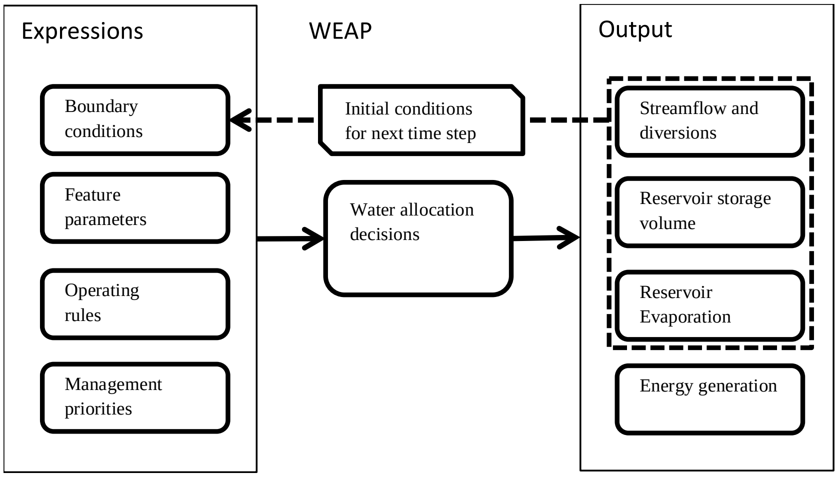

Figure 2-2. WEAP model process.

Table 2-2. Modeled features and attributes.

Feature	Model input attribute
Universal parameters	Water year indices Project-specific water year types
Reservoirs	Storage capacity Initial storage Volume-elevation curve Reservoir pool operations Storage priority Meteorological data for evaporation
Hydropower	Maximum turbine flow Generating efficiency Energy demand Energy priority
Water supply demand	Annual water use rate Weekly variation Water supply demand priority
Diversions	Maximum diversion
Instream flow requirements	Instream flow requirement (“IFR”) IFR priority
Calibration gages	Stream flow data Reservoir data

Inflow hydrology

SIERRA represents inflows as headwater flows in artificial tributaries to real river locations. The SIERRA model was originally designed to use the rainfall-runoff model results of Young et al. (2009), described below. Artificial inflow tributaries are therefore coincident with the locations where Young et al. (2009) estimated runoff from subwatersheds. However, SIERRA can readily accommodate other inflow datasets.

Young et al. (2009) developed a weekly scale rainfall-runoff simulation model of the western Sierra Nevada watersheds using WEAP, assuming no regulating infrastructure. WEAP uses a spatially explicit, 1-dimensional, 2-soil layer rainfall-runoff method, which simulates surface runoff and other hydrologic responses by explicitly accounting for overland flow, snow accumulation and melt, soil moisture storage, and evapotranspiration losses (Yates et al. 2005). Young et al. (2009) divided each watershed into subwatersheds, defined by locations—called "pour points"—of management interest or where there was sufficient observed data. They intersected each subwatershed with 250-m elevation bands, resulting in “catchments” that each had homogeneous physical characteristics such as meteorological conditions, soil conditions, and mix of land use cover.

Using weekly time steps, 2009) modeled twenty one water years (1980-2001) using interpolated DAYMET climate data for historical precipitation, air temperature, and vapor pressure deficits. Watersheds were characterized using U.S. Geological Survey (USGS) 10 m digital elevation models (DEM), soil surveys from the Natural Resource Conservation Service (NRCS), and land cover from the USGS National Land Use Classification Database (NLCD). Simulated flows were calibrated at unregulated stream flow locations using data from USGS stream gages, and at some regulated sites using estimates of unimpaired hydrology from the California Department of Water Resources (DWR).

The unimpaired runoff models were calibrated for monthly flows at the outlets of 13 of the 15 watersheds—the Bear River and Calaveras River watersheds were omitted for lack of observed data—and for snow water equivalent (SWE) at 15 high-elevation locations (Young et al. 2009). This is an important consideration when assessing model results, which are sensitive to boundary inflows.

Universal parameters

Universal parameters, called “key assumptions” in WEAP, can be used across the physical or management domain as primary or intermediary parameters to simplify expressions. For example, instream flow requirements often depend on a Water Year Type (WYT) that is regional in scope rather than associated with a single managed feature. A WYT defined as a key assumption can be used in operating rules for several instream flow requirement locations. Key assumptions are discussed in the relevant methods sections below, primarily for hydropower generation and instream flow requirements.

Reservoirs

Storage capacity

Reservoir storage capacities were mostly obtained directly from the California Data Exchange Center (CDEC).

Initial storage

The beginning of the modeling period is October 1, 1980. Initial storage values were mostly from CDEC, but also from USGS gauges. Where only monthly reservoir storage data were available, storage values from October 1980 are used, as storage values from CDEC are for beginning-of-month. Where daily reservoir storage data were available, storage values from on October 1, 1980 were used. If historical storage was unavailable for October 1980 and a relationship between previous water year type and October storage was observed, then the average October storage for Wet water years on record was used, since Water Year 1980 was Wet under both the Sacramento and San Joaquin Valley Water Year Type definitions. If no relationship between water year type and October storage was apparent, then a simple average of storage levels for all Octobers on record was used, rounded to the nearest 100 AF (1.2×10^5 m^3).

Volume-elevation curves

Volume-elevation data for most reservoirs are from annual reservoir reports published by the U.S. Geological Survey. For reservoirs where such reports did not exist or did not include volume-elevation data, volume-elevation curves were created using a second-order polynomial fit using historical volume and elevation data reported by CDEC. Mountain Meadows Reservoir (North Fork Feather River) had neither a USGS report nor historical volume and elevation data from CDEC; a linear volume-elevation curve for this reservoir was assumed. A linear volume-elevation curve was also used for many small reservoirs included in the original CABY model; these curves were retained.

Reservoir zone operations

Reservoir operations for recreation, water supply, and flood control are defined by setting requisite volumes for the inactive zone, buffer zone, and conservation zone of a reservoir ("zones" are also known as "pools").

Inactive zone – The inactive zone of a reservoir is the level, in elevation or storage, below which water cannot be withdrawn, for physical or operational reasons. An inactive zone storage volume was included for most reservoirs based on observed historical minimum levels.

Buffer zone – The buffer zone is the volume or elevation below which water allocations are curtailed, but not ceased. To help guide reservoir operations during the refill (wet season) period, an increasing buffer zone was defined in some reservoirs during a defined refill period.

Conservation and flood zones – The conservation zone is the volume available to store water above the inactive and buffer zones to meet downstream demand. A maximum conservation zone level, or rule curve, is used to create flood space in flood control reservoirs. Rule curves were included for Folsom Lake (American River), New Bullards Bar Reservoir (North Fork Yuba River), and Lake Isabella (Kern River), though they were not fully developed. Several reservoirs in the CABY region were assigned conservation zone rule curves based on historical observations or public documents; these rule curves were retained from Mehta et al. (2011).

Lake evaporation

A lake evaporation model using a modified form of the Penman equation (Penman 1948) as described by Dingman (2002) was applied to reservoirs. The Penman equation, modified by Van Bavel (1966) and Kohler and Parmele (1967), expresses lake evaporation as a function of:

- air temperature,
- incoming solar radiation,
- relative humidity,
- wind speed,
- cloudiness fraction, and
- reservoir surface area.

Each of the meteorological conditions (the first five inputs) is readily available from the rainfall-runoff model of Young et al. (2009). We use meteorological data from the lowest catchment in the subwatershed contributing directly to the reservoir. In the unimpaired hydrology model, air temperature is from DAYMET; relative humidity is calculated from observed vapor pressure, which was from DAYMET; average weekly wind speed is used; and a cloudiness factor of 1 is assumed. Solar radiation is calculated internally in WEAP. Reservoir area in one time step is derived from storage area at the end of the previous time step. We developed approximate volume-surface area relationships directly from volume-elevation relationships.

In real reservoirs, inflows and outflows transfer energy to/from the lake, affecting evaporation. We included neither these transfers. We also assumed convective heat transfer to/from the ground via groundwater to be negligible.

Hydropower

The goal in this study was to model dominant operational characteristics of hydropower systems and to represent historical mean weekly and mean annual hydropower turbine flows. Two methods were used to define demand for hydropower. The first method, called the Water Year Index method (WYIM), is based on energy demand and is used to simulate historical reservoir releases to hydropower plants. The WYIM uses historical observations to approximate operating rules. The second method, called the "spill demand" method (SDM), is based on water demand rather than energy demand and is used to simulate the operating goal of operators to minimize spill, which usually represents lost revenue. Energy demand is modeled explicitly (WYIM) only for powerhouses that receive water directly from a large reservoir; all reservoirs, however, use the spill demand method (SDM). These two methods are described.

Water Year Index method

Energy demand (E) for a powerhouse can be represented with an expression that includes percent (α) of energy generation capacity (E^{max}) as a key temporally variable parameter:

$$E_t = \alpha_t \cdot E^{max} \tag{0.2}$$

Energy generation capacity (E^{max}) is assumed constant in all high-head hydropower plants, such that:

$$E^{max} = \gamma \cdot h \cdot \eta \cdot Q^{max} \tag{0.3}$$

where γ is the specific weight of water, h is fixed hydropower head, η is plant efficiency (assumed 90%), and Q^{max} is the hydropower turbine flow capacity. The purpose of the energy demand modeling method is to define α_t. The Water Year Index method (WYIM) does this by relating weekly hydropower demand to annual water availability as a coarse approximation of actual demand.

Mehta et al. (2011) demonstrated that mean weekly hydropower operations can be adequately represented by establishing a relationship between water year type (WYT) and water demand for hydropower during any given week. For each week and each powerhouse, Mehta et al. (2011) used three regional water year types (dry, normal, and wet) and determined the respective non-exceedance percentiles of historical hydropower turbine for that week. A single non-exceedance percentile value was then chosen to specify a minimum diversion amount during simulation. For example, for a particular week, hydropower turbine flow demand might be the 10% non-exceedance value of historical flows for that week in dry years, 50% non-exceedance in normal years, and 90% non-exceedance in wet years. Mehta et al. (2011) adjusted these values during calibration.

The Water Year Index method (WYIM) modifies this approach. The WYIM assumes a continuous, linear response of turbine flow to regional water availability, as defined by a water year index, instead of the discrete, non-linear response to water year types of the CABY model.

For each week and each powerhouse, a linear relationship between water year index (WYI)—a continuous function of regional mean annual runoff—and hydropower turbine flow is established using historical observations. The equation parameters of the resulting linear fit—slope and intercept—are then used to determine hydropower turbine flow demand percent (α) given WYI:

$$\alpha_t = \frac{m_t \cdot WYI + b_t}{Q^{max}} \tag{0.4}$$

where m_t is the slope of the line, b_t is the intercept during week t for any given powerhouse, and Q^{max} is the maximum turbine capacity. In implementation, (2.3) is modified as needed to ensure that $0 \leq \alpha_t \leq 1$.

The slope and intersect of (2.3) are readily determined from historical data and WYI for each powerhouse. For pumped storage facilities, which can have reverse flows, (2.3) is used without modification.

In the SIERRA model, the California Department of Water Resources (DWR) Sacramento Valley WYI was used for the northern watersheds (Feather through American) and the San Joaquin Valley WYI was used for the southern watersheds (Mokelumne through Kern). DWR WYIs are continuous and have units of million acre-feet (MAF) per year. The Sacramento Valley WYI is defined as:

> $WYI_{SacValley}$ = 0.4 * Current Apr-Jul Runoff Forecast (in MAF) + 0.3 * Current Oct-Mar Runoff in (MAF) + 0.3 * Previous Water Year's Index (if the Previous Water Year's Index exceeds 10.0, then 10.0 is used) (CDEC, 2010)

where “Runoff” is the sum of runoff from Sacramento River at Bend Bridge, Feather River inflow to Lake Oroville, Yuba River flow at Smartville, and American River inflow to Folsom Lake (CDEC 2010). The latter three quantities can be computed directly from the unimpaired hydrologic models. To include the Sacramento River, we used a simple linear regression to correlate monthly flows in the Sacramento River at Bend Bridge with historical monthly Full Natural Flow (FNF) calculated by DWR for the Feather River. Using linear regression results, and assuming no change in relationship between the flows with warming, we calculated monthly Sacramento River flows for each climate warming scenario using simulated Feather River flows.

The San Joaquin WYI is defined as:

> $WYI_{SJValley}$ = 0.6 * Current Apr-Jul Runoff Forecast (in MAF) + 0.2 * Current Oct-Mar Runoff in (MAF) + 0.2 * Previous Water Year's Index (if the Previous Water Year's Index exceeds 4.5, then 4.5 is used) (CDEC, 2010)

where “Runoff” is the sum of Stanislaus river inflow to New Melones reservoir, Tuolumne river inflow to New Don Pedro reservoir, Merced river inflow to Lake McClure, and San Joaquin river inflow to Millerton Lake, each of which is available from the unimpaired hydrologic models (CDEC, 2010).

$WYI_{SacValley}$ and $WYI_{SJValley}$ are calculated for each atmospheric warming scenario using simulated runoff for the scenario. Since each WYI depends partly on WYI from the previous year, an initial WYI is required. To do this for warming scenarios, we established a linear regression between ΔT and WYT for each water year in the study period (i.e., WY 1981-2000). The slope of that linear relationship from a year with a WYI historically similar to that of WY 1980 was used to estimate WYI for WY 1980 for each warming scenario. Because initial rough estimates of WYI for WY 1980 were needed to determine the WYI-ΔT slopes, we excluded the first four Water Years from the slope calculations to eliminate the lag influence of WYI from one year to the next.

Figure 2-3 demonstrates this method for hydropower flow demand for Big Creek No. 1 powerhouse (San Joaquin watershed) for weeks with strong (July 25-31) and weak (Nov. 7-13) relationships between the San Joaquin Valley WYI and hydropower turbine flow. As with most powerhouses, the linear relationship is stronger in wetter weeks and weaker during drier weeks (Figure 2-3). In wet weeks, hydropower and other uses can generally take as much as is available, even in drier years. During dry weeks, however, water users must be more selective about when they use water and base their decisions on factors other than annual availability (e.g., energy prices, peaking operations, and agreements with other users); these factors are much more stochastic in nature and not represented in the WYIM. Any hedging that occurs in the wet season will depend on water year type, which is generally proportionally related to weekly flow during the wet season, though not always.

The advantage of basing demand on a continuous water year index instead of a water year type, as used by Mehta et al. (2011), is greater sensitivity to changes in water availability, as measured by a water year index. This is consistent with hydropower operations being limited by real water availability rather than discrete water year type designations, even though some operational decisions may be affected by water year type (e.g., instream flow requirements). However, the continuous response function of the WYIM used here should not be a basis for assuming greater accuracy over the discrete method; The WYIM is comparable in model performance to that of Mehta et al. (2011).

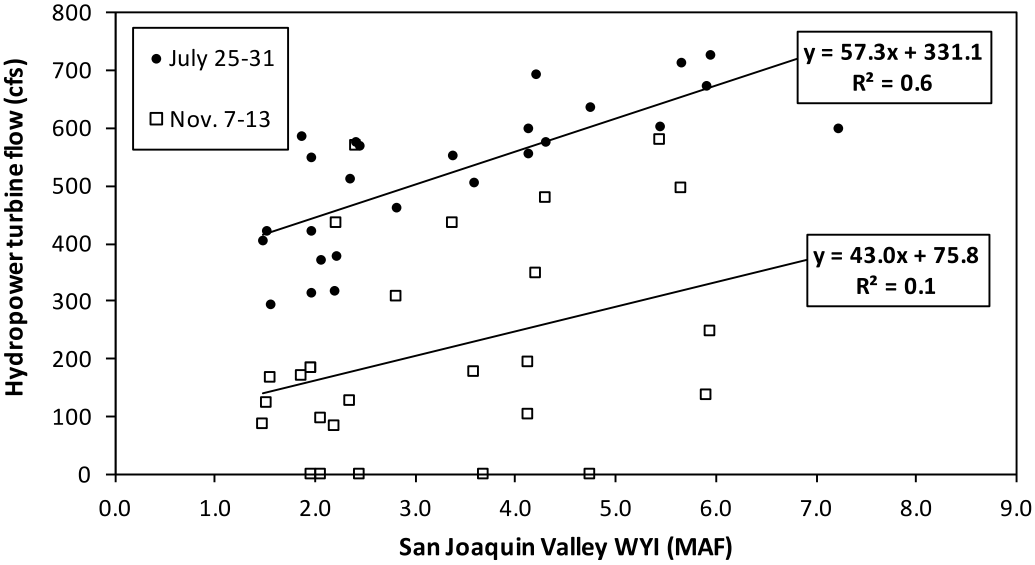

Figure 2-3. Historical San Joaquin Valley Water Year Index (WYI) and Big Creek No. 1 powerhouse turbine flow for the weeks of July 25-31 and November 7-13.

The WYIM is fundamentally a time-series analysis approach to estimating energy demand. However, because the WYIM assumes perfect foresight of the WYI and, hence, total inflows, for the water year, it implicitly uses the pack rule (Bower et al. 1966), which minimizes spill by maximizing releases during a period given predicted inflows for the remainder of the drawdown-refill cycle and other system characteristics. The WYIM is ideally suited for rapid application to many powerhouses and adequately represents hydropower demand at coarse temporal scales. However, the method neglects much in the way of real system-wide coordination and prioritization of hydropower operations and does not incorporate fundamental drivers of energy demand such as air temperature (Franco and Sanstad 2008); it is therefore generally ill-suited for assessing energy characteristics at fine spatial and temporal resolutions. In general, this method and that of Mehta et al. (2011) are intended to estimate average abstractions for hydropower flows rather than simulate actual operations in any given week.

Another important inherent weakness in the WYIM is that weekly energy demand is a function of total annual runoff, with energy demand timing based on historical timing of releases. However, the historical timing of releases is based, in part, on the assumption that the timing of inflows is predictable. The WYIM fails, therefore, to account for the change in timing of flows caused by warming. For the same total annual runoff, greater winter precipitation-driven runoff might cause greater spill in the winter. With the WYIM, for any given WYI, a reservoir would spill instead of releasing more water to a hydropower plant.

Spill Demand Method

To minimize spill, another operating rule is defined for hydropower plants called the spill demand method (SDM). The SDM simply requires that any inflow in excess of existing demands be diverted to generate hydropower. It is a demand for any spill that would otherwise occur, and ensures that hydropower plants use, as much as possible, water that cannot be stored. The SDM is expressed mathematically as:

$$Q_{sd} = Q_{in} - \left(S_{max} - S\right) - Q_{target} - \sum_{r} Q_r \tag{0.5}$$

where Q_{sd} is the hydropower release in excess of the target release, Q_{in} is the inflow during the week, S is the reservoir storage, S_{max} is the reservoir capacity, Q_{target} is the target release to meet energy demand (e.g., as determined by the WYIM), and Q_r is release for all other purposes. Q_{sd} is constrained by: $0 \le Q_{sd} \le (Q_{max} - Q_{target})$. This is similar to the pack rule (Bower et al. 1966), though minimizes spill during the current time step only, without consideration of future inflows. Though the SDM can be expressed mathematically, implementing the SDM mathematically is challenging since many of the independent variables (storage level, inflow, and releases) are not known until the water allocation problem of the current time step has already been solved. The SDM is applied in SIERRA with an additional demand of 100% of turbine flow capacity, with a demand priority lower than upstream facilities and other local uses, if any, including meeting energy demand using the WYIM.

The SDM is applied to all powerhouses to minimize water and energy spill. There are three distinct situations where this method is useful for hydropower generation. First, this method is applied to hydropower plants that lack upstream storage. This rule ensures that this type of plant acts as a must-take plant (see Chapter 1) by diverting as much as possible, when possible, constrained only by instream flow requirements (IFRs) and facility capacities. Second, this method is applied to powerhouses operated in coordination with upstream facilities. In high-elevation hydropower systems, hydropower plants are typically configured as a series as high-head plants, with water diverted via artificial channels to maintain maximum head before release via a penstock. Lower elevation plants in such cases demand 100% of capacity, albeit with a lower priority than upstream facilities. This method will result in *de facto* coordinated operations. Finally, this method is applied to all peaking powerplants, with a hydropower priority lower than all other local priorities. This ensures that any spill—i.e., water not stored or purposefully released to meet multiple demands—is diverted for hydropower generation, within capacity limitations. The latter use of the SDM is particularly important when considering climate warming, as it guarantees that peaking facilities utilize any extra available water rather than limiting diversions to historical patterns.

Water supply demand

Water supply for urban and agriculture use is limited in most of the Sierra Nevada above the large low-elevation, multi-purpose reservoirs and is small relative to water supply for agriculture in the Central Valley. However, they can be important because they have a higher priority than hydropower generation and play a central role in some systems (e.g., the Hetch Hetchy system in the Tuolumne, among others). When water is scarcer in drier years or in warming scenarios, hydropower is reduced before water supply if there is a conflict.

Demands were generally fixed, regardless of water year type, based on historical mean weekly flows, using data provided by water agencies. A major exception is diversions for water supply to San Francisco from the Hetch Hetchy system (Tuolumne River watershed). Analysis of historical diversions to San

Francisco indicated a strong negative correlation between San Joaquin Valley WYI and annual diversions to San Francisco. This trend is consistent with the Raker Act of 1913, which governs the Hetch Hetchy system and requires the San Francisco SFPUC to prioritize local sources of water. Thus, in wetter years, demand for diversions from the Tuolumne River watershed decreases. The smallest demand modeled was the Crab-Aiken Ditch Co. in the Tule River watershed, with a maximum diversion of 6.5 ft^3/s (0.18 m^3/s), though some other, more substantial demands are excluded for lack of sufficient understanding of diversion rules (e.g., water supplied by the Utica Power Authority from the Stanislaus River).

Instream flow requirements

Instream flow requirements (IFRs) in WEAP consist of minimum instream flows (MIFs) required below dams and diversions. We included all IFRs identified in FERC licenses or from other documents if the project was not regulated by FERC (e.g., the Hetch Hetchy system). We did not include pulse flows, which some projects require to flush sediment downstream, or releases for whitewater recreation.

IFRs range from a single fixed value to values that vary by month and by water year type. IFRs that vary by month require a day-to-week conversion for month beginning and end dates. In general, we converted 30-day months to 4 weeks and 31-day months to 5 weeks. Some IFRs depend on the current state of system variables other than water year type. For example the IFR below Hetch Hetchy reservoir depends on cumulative precipitation at O'Shaughnessy Dam until the month of July, when it depends on inflow to Hetch Hetchy Reservoir. For these IFRs we used values calculated in the previous time step to determine the appropriate IFR for the current time step.

We calculated water year types (WYT) as needed for development of IFR expressions using simulated unimpaired flows from the unimpaired hydrology models. Water year type definitions are usually specific to a given hydroelectric project. Definitions can further vary within a project, such as for different IFR locations within the project. Some operations may also use spatially broader water year types such as the Sacramento and San Joaquin Valley WYT. Since water year types mostly depend on streamflow and flows change with climate changes, climate change affects operations constrained by water year types.

All water year type definitions use a combination of year-to-date flows and flow forecasts for the remainder of the water year. IFRs below Hetch Hetchy additionally depend on accumulated precipitation. For expediency, we computed water year types assuming perfect knowledge of the water year type using the unimpaired hydrology data, without forecasting. Future model improvements should include incorporating forecasting for water year type definitions and other operations.

Diversions

We included maximum diversion capacity for all diversions and assumed these to be constant over time. Maximum diversion values were obtained from a variety of publicly available documents, primarily hydropower license documents. When a maximum diversion was not available from a document, maximum flow from gage data was used. In many instances, maximum diversion values and maximum turbine flows were redundant. In the CABY region, the discrete minimum flow requirement method implemented by Mehta et al. (2011) was retained for diversions not directly leading to a hydropower plant.

Priority setting

Correctly setting priorities is crucial for accurate results in priority-based water resources management models. In WEAP, priorities are assigned to all water management purposes, including for instream flow requirements, water supply, hydropower, and reservoirs. Priorities can range from 1 to 99, where 1 represents the highest priority. We assigned priorities to each feature based on 1) location of the feature in relation to other features and 2) the feature type, with modifications as needed. We did this by developing a two-digit priority scheme, where the first digit is based on the feature's location and the second digit based on the feature type. Feature locations were generalized by grouping them by hydropower or other development project. Upstream features/projects were assigned higher priorities (lower numbers), while downstream features/projects were assigned lower priorities. Without this upstream/downstream priority assignment scheme, the model allocates water to downstream users with high priorities (e.g., a utility district) instead of allowing a lower priority upstream user to use the water first.

Features were assigned priorities based on general water rights priorities:

1. Instream flow requirements
2. Water supply demand
3. Hydropower
4. Reservoirs

Hydropower facilities immediately below a reservoir, which used the Water Year Index method to establish fixed energy demand, were assigned a priority equal to the reservoir. This worked because demand was based on historical observations. However, lower elevation hydropower plants in the same hydropower chain received a lower priority, as discussed above. Table 2-3 shows priorities for a hypothetical two-project system with each feature type represented in each project. Since allocating water among different potential uses is fundamentally driven by priority, the model is generally more sensitive to priorities than any other model parameter. Though this scheme works generally, in practice each water system is unique, necessitating a more detailed assessment of local priorities for future model improvements.

Some priorities were adjusted as needed during model calibration. In particular, some reservoirs were assigned a higher priority during the refill period and a lower priority during the drawdown period.

Table 2-3. Priority assignments for two hypothetical projects.

	Project location / priority	
Water use type	*Upstream*	*Downstream*
Instream flow req't	11	21
Water supply demand	13	23
Hydropower – WYIM	15	25
Hydropower – NSM	19	29
Reservoir storage	15	25

Interbasin transfers

Generally, an interbasin transfer is simulated in only one of the two watersheds that the transfer straddles, integrating the transfer into the watershed to which the transfer project belongs. In the watershed that does not dominate in the project, inflows to or outflows from that project are assumed based on historical or other modeled data. Several small interbasin transfers were omitted from the model for simplification (e.g., diversions from the Stanislaus to the Calaveras River watersheds). Since the CABY watersheds are integrated into one model, intra-CABY transfers did not need special consideration. Transfers from Slate creek, in the Yuba River watershed, to the South Fork Feather River project, in the Feather River watershed, for hydropower and water supply were explicitly included in the Feather watershed model. These transfers were included as a fixed weekly demand from Slate Creek in the CABY sub-model. Flows from the Stanislaus watershed to the Tuolumne watershed via Phoenix powerhouse are included in the Stanislaus model, but not in the Tuolumne watershed model.

Integrating models and data management

A significant challenge in developing the model described here was to integrate 12 independent WEAP-based models with multiple climate scenarios for ease in execution, uniformity in output, and rapid results assessment and analysis. We used the Python scripting language to develop a suite of tools to address these needs. These tools can be readily adapted, if needed, and used to easily execute the model with alternative climate warming or other scenarios.

Calibration and model assessment

The parameters and operating rules used were fixed, so a formal calibration was generally not required. However, priorities, which were assigned initial values as discussed above, required adjustment in some instances to mimic observed system behavior. This was particularly true in cases for reservoirs in series or parallel in complex systems. Also, we observed that relative priorities can change seasonally in some such systems. Calibration was therefore limited to adjusting relative priorities as needed to ensure that reservoirs operated relative to each other as close as possible to observed operations. No adjustments were made to the inflow hydrology dataset. Model improvements for specific systems will require adjusting the physical parameters of the rainfall-runoff model and contacting system operators to better understand and represent operational logic and operating priorities.

Here, we assess model performance to identify the insights and conclusions we can make when interpreting model results. Performance assessment is also critical in guiding future model improvement efforts. To assess performance of the model, we focus on powerhouse turbine flow and reservoir storage, as these operations are the most challenging to simulate accurately and because meaningful characterizations of alterations to the natural flow regime—a long-term goal—depend on a good understanding of simulation accuracy. Because modeled system behavior is sensitive to the unimpaired hydrology model, which was calibrated for flows at the watershed outlets and for snow water equivalent at only 15 high elevation locations (Young et al. 2009) model performance assessments are only considered in the context of watershed-scale or range-scale operations. Limiting model performance assessments to specific facilities is only appropriate with further calibration of the rainfall-runoff model.

To assess model performance, we calculated the following metrics for hydropower turbine flow:

- Nash-Sutcliffe model efficiency (NSME) at the seasonal and annual scales
- Root mean square error (RMSE) at the seasonal and annual scales
- Mean bias

We also compare mean total and mean seasonal observed and simulated hydropower turbine flow, energy generation, and reservoir storage as points in a scatter plot at the range and watershed scales.

The Nash-Sutcliffe model efficiency index *NSME* (Nash and Sutcliffe 1980), also called the coefficient of determination (R^2) in other contexts, is often used in hydrology studies to compare modeled flows to observations. Though useful, *NSME* alone is not a reliable metric of model predictive power, as discussed by Jain and Sudheer (2008). *NSME* is defined as:

$$NSME = 1 - \frac{\sum_{t=1}^{T}\left(Q_{o,t} - Q_{m,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{o,t} - \overline{Q_o}\right)^2} \tag{0.6}$$

where Q_o^t and Q_m^t are the observed and modeled flows, respectively, at time *t*, and *T* is the total number of observations. The Nash-Sutcliffe index describes the percentage of the variance that can be explained by the model. *E* can range from –∞ to 1. When *E* = 1, the model accurately predicts the observations; when *E* = 0, the model is no better or worse than the mean of the observations; when *E* < 0, the model is a worse predictor than the mean of the observations. Values typically become asymptotic as they approach 1 (perfect predictive power), thus large negative values should not be interpreted as equally nearing imperfection.

Root mean square error (*RMSE*) is a measure of the spread of the differences between observed and modeled data points. *RMSE* is defined as:

$$RMSE = \sqrt{\frac{1}{T} \cdot \sum_{t=1}^{T} (x_{m,t} - x_{o,t})^2} \qquad (0.7)$$

where *t* is the time step and *T* is the total number of time steps. RMSE is always positive and smaller values indicate that modeled values are consistently closer to observed values. As with *NSME, RMSE* changes with time step length. Here, *RMSE* is normalized by dividing (2.6) by the mean observed flow, such that units are in percent.

Mean bias (*mBias*) quantifies the difference between the mean of modeled values and the mean of observed values:

$$mBias = \frac{1}{T} \cdot \left(\sum_{t=1}^{T} x_{m,t} - \sum_{t=1}^{T} x_{o,t} \right) \qquad (0.8)$$

Mean bias can be either positive or negative; values closer to zero indicate greater model accuracy of mean modeled flows. As with *RMSE,* here mean bias is normalized to mean observed flow, resulting in percent units.

Hydropower turbine flow

Table 2-4 lists hydropower turbine flow model performance metrics at multiple temporal scales. 78 of the 86 run-of-river hydropower plants are included in the performance assessment, as eight plants lacked sufficient observed data to make meaningful comparisons. At all temporal scales (weekly, seasonal, annual mean flow), approximately 60 percent of modeled plants have NSME values greater than zero, indicating most are better represented with the simulation model than with their historical mean flow. More than half have NSME values of 0.18, 0.23, and 0.35 at the weekly, seasonal, and annual scales, respectively. Thus, model simulation results improve with coarser units of analysis, as one would expect. Though hydropower plants of all sizes are modeled well, the most well-modeled hydropower plants are also the ones with the greatest historical diversions (Figure 2-4) and the greatest hydropower generation. Conversely, the least well-modeled plants are smaller. Most plants under-represent hydropower turbine flow, with a median normalized mBias of -11%. The mean normalized mBias is approximately -9%. These results indicate that the more important hydropower plants are simulated well.

Table 2-4. Model performance metrics for run-of-river hydropower turbine flow.

Percentile	Weekly NSME	Seasonal NSME	Annual NSME	Seasonal RMSE (%)	Annual RMSE (%)	mBias (%)
100% (maximum)	0.76	0.80	0.92	1349	615	131
75%	0.37	0.49	0.65	320	121	1
50% (median)	0.18	0.23	0.35	243	81	-11
25%	-0.37	-0.46	-0.56	182	58	-21
0% (minimum)	-4.77	-12.46	-67.89	69	0	-70

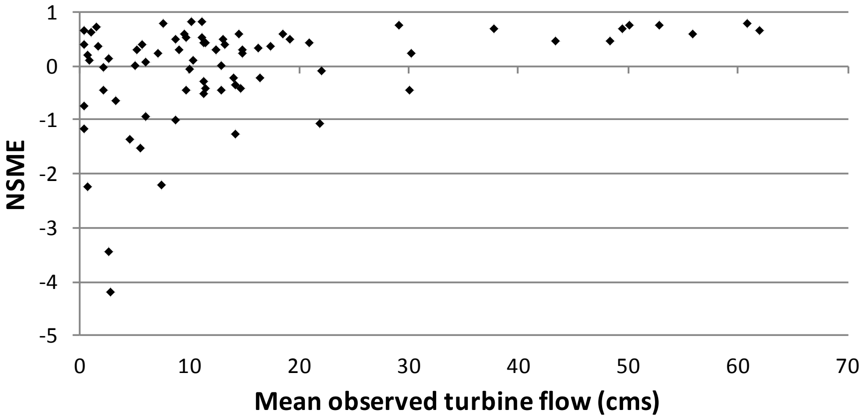

Figure 2-4. Seasonal NSME by mean observed turbine flow.

Figure 2-5 compares observed and modeled mean hydropower turbine flow in aggregate and by season (log scale). Each point in Figure 2-5 represents a single powerhouse. On average, mean hydropower flows match mean observed flows closely, though there is a tendency of the model to slightly under-predict flows, with a slope of 0.98 in Figure 2-5a. This is consistent with the negative mean bias noted above. The model tends to under-represent flows in the summer (JAS) and fall (OND), with modeled flows at 87% of observed flows for each of JAS and OND. By contrast, flows are slightly over-represented in winter (JFM) and spring (AMJ), flows 102% and 111%, respectively, of observed flows (Figure 2-5b).

Similarly, Figure 2-6 compares observed and modeled mean hydropower generation in aggregate and by season. The model generally under-predicts hydropower generation, to a slightly greater degree than hydropower turbine flow. Figure 2-7 shows that the model effectively simulates historical hydropower generation system-wide at the seasonal scale during the study period. However, consistent with the seasonal energy comparison results of Figure 2-6b, simulated energy is typically lower than observed during the summer (JAS), fall (OND), and spring (JFM).

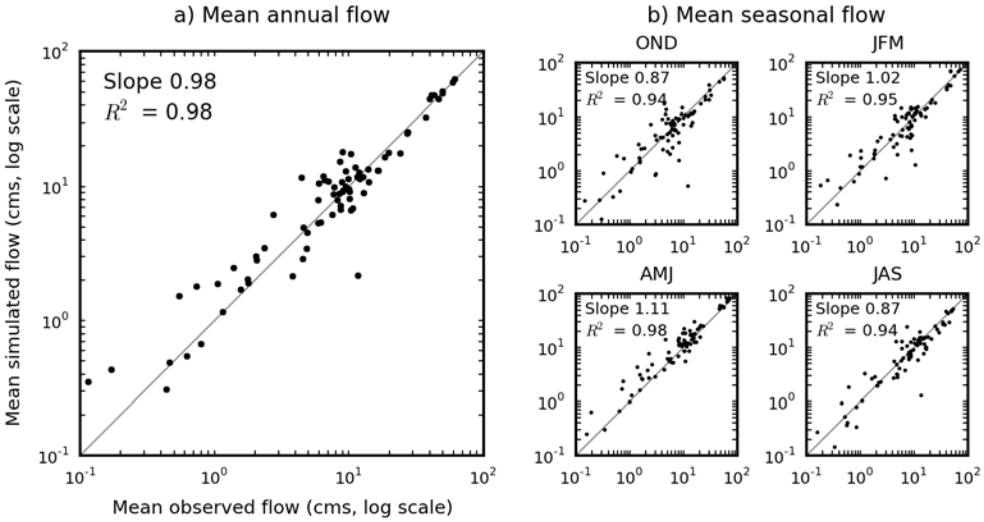

Figure 2-5. Comparison of observed and simulated mean hydropower turbine flow across all weeks (a) and by season (b).

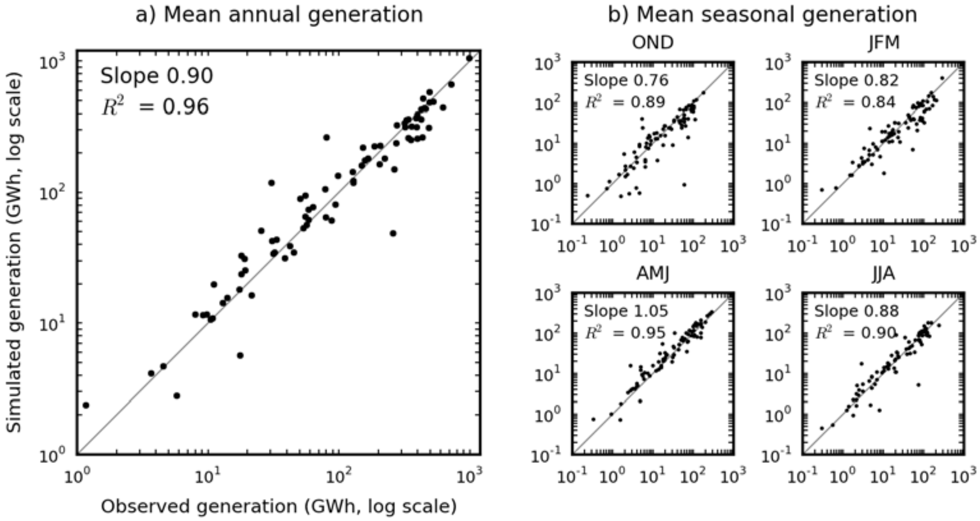

Figure 2-6. Comparison of observed and simulated mean annual (a) and seasonal (b) hydropower generation.

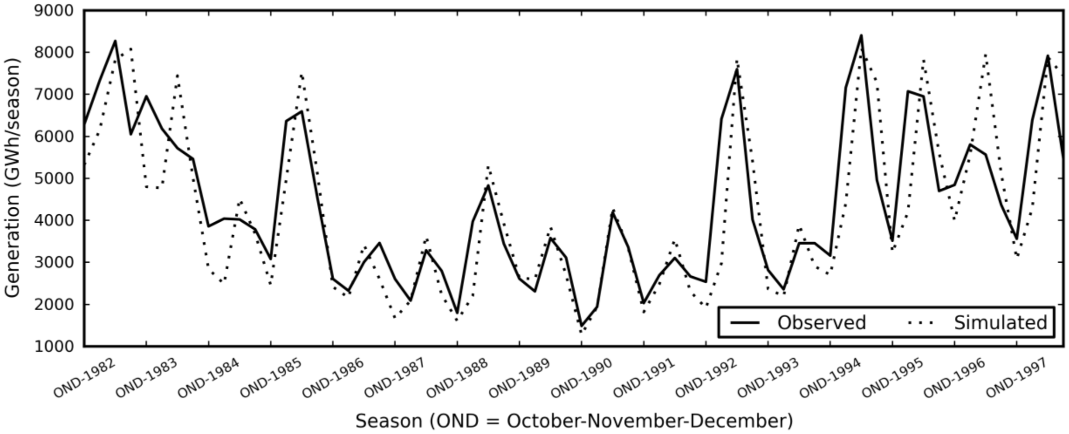

Figure 2-7. Total system-wide observed and modeled seasonal hydropower generation.

These assessment results indicate that the model effectively represents observed hydropower turbine flow and generation patterns and that the model can be used to assess system-wide and weekly, seasonal or annual time step responses to changing external drivers such as inflow hydrology. Watershed-scale assessments can be made at the seasonal or annual scale. Change response assessments for specific facilities or systems is possible for approximately one-half of the systems in the Sierra Nevada, though a more detailed assessment of each plant is needed to ensure assessments are valid. Further improvements are needed to more accurately represent specific facilities, particularly many smaller facilities. As the model is responsive to inflow hydrology, improvements in facility operations logic needs to be coupled with improvements in representation of inflow hydrology to better simulate historical operations.

Reservoir storage and evaporation

On average, modeled reservoir storage volumes (Figure 2-8) are generally modeled slightly more consistently well than hydropower flow or generation at both long term and by season. As with observed hydropower turbine flow, mean storage most closely matches observed values in the spring (AMJ), when reservoirs are typically relatively full.

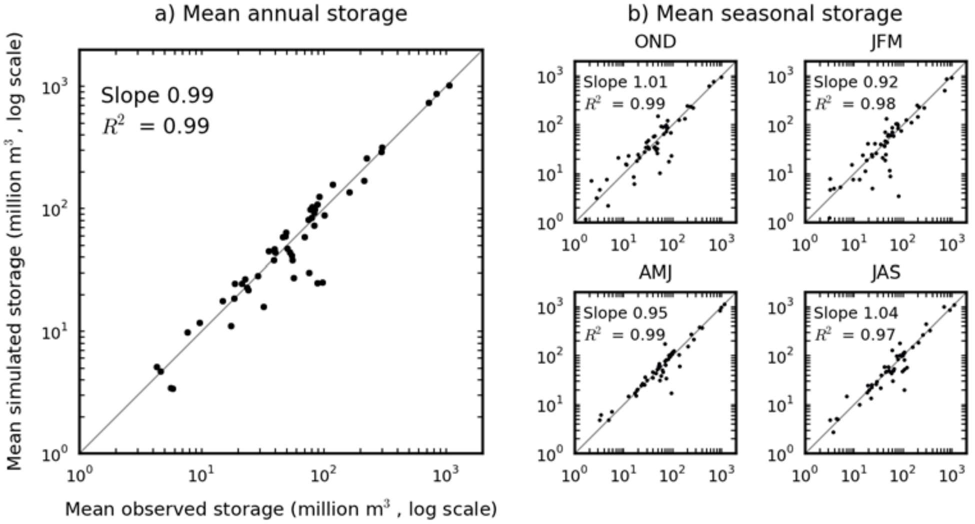

Figure 2-8. Comparison of observed and simulated mean annual (a) and seasonal (b) reservoir storage.

The California Data Exchange Center (CDEC), which publishes reservoir data, does not typically report evaporation for high elevation reservoirs. One exception is Lake Almanor (Feather River watershed), for which “observed” monthly reservoir evaporation is estimated by using a constant pan evaporation coefficient of 0.7. The model simulates the majority of L. Almanor evaporation reported by CDEC, though tends to be lower than reported during late summer through winter and higher during spring and late summer (Figure 2-9).

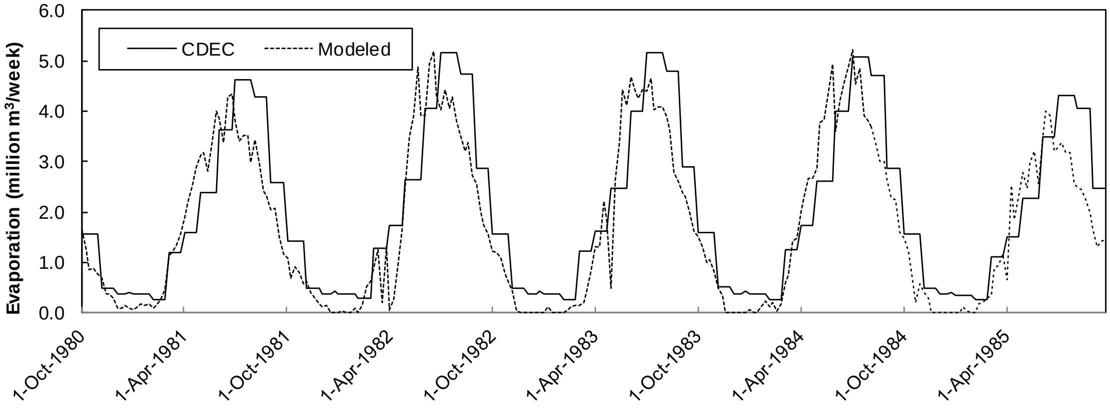

Figure 2-9. Mean (WY1981-2000) reported and modeled mean lake evaporation for Lake Almanor using observed storage data.

Results with warming

To assess effects of climate warming, we again used the rainfall-runoff data from Young et al. (2009), who applied their rainfall-runoff model with different climate warming scenarios by assuming spatially and temporally uniform increases in air temperature of 0, 2, 4, and 6 °C and no change in precipitation amount. These temperature increases broadly represent anticipated changes in the regional climate over the next 50-100 years. Historical precipitation was assumed by Young et al. (2009) because downscaled global climate models (GCMs) are less consistent in their prediction of changes in magnitude or timing of precipitation in California (Hayhoe et al. 2004).

System-wide hydropower generation

While assessments of model response to climate warming is more meaningful at coarser temporal resolutions, due to the limitations of the model operational logic and inflow hydrology calibration resolution, as discussed above, trends at the weekly time step are important to understand coarser resolution trends. Figure 2-10 shows system-wide mean weekly hydropower generation and generation changes with +0, 2, 4, and 6 °C warming. Warming decreases the system-wide mean weekly hydropower generation compared to the historical climate beginning in mid-April, when there is consistently very little change. Mean weekly generation decreases considerably thereafter—by about 40% in mid-June with 6 °C warming—until late November. Mean weekly generation consistently increases between early December and mid-April, with a maximum increase of about 40% in late February with 6 °C warming.

Sierra-wide seasonal changes are listed in Table 2-5 and shown in Figure 2-11. Although hydropower generation increases substantially during the winter (JFM), there are equally great reductions in generation in the summer (JAS). Additional reductions in the other seasons cause a net reduction in mean annual hydropower generation.

With 6 °C warming, which represents possible end-of-century climate conditions, hydropower generation decreases by 1,700 GWh or 9% compared to historical climate conditions. These results are slightly less than the results of others, discussed above. For example, Vicuna et al. (2009) estimated end-of-century generation losses of 12.2% and 10.4% for the Upper American River Project (American River) and Big Creek System (San Joaquin River), respectively. However, as discussed below, results for specific watersheds are substantially different from existing local studies.

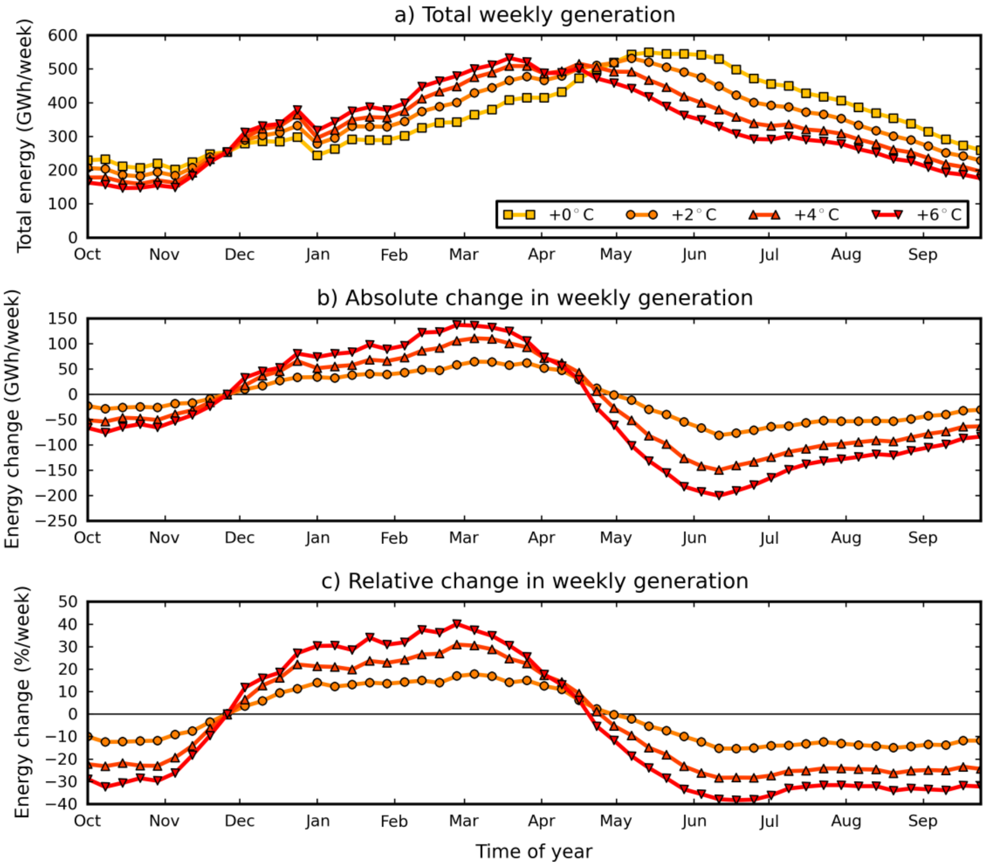

Figure 2-10. Mean weekly system-wide energy generation with warming.

Table 2-5. Seasonal and annual hydropower generation change with warming.

Generation	Warming scenario	OND (Fall)	JFM (Winter)	AMJ (Spring)	JAS (Summer)	Annual
Total (GWh)	+0 °C	3,157	4,271	6,584	4,724	18,735
	+2 °C	3,066	4,902	6,268	4,089	18,325
	+4 °C	2,969	5,334	5,785	3,548	17,636
	+6 °C	2,897	5,662	5,298	3,177	17,033
Change (GWh)	+0 °C	--	--	--	--	--
	+2 °C	-91	631	-316	-635	-410
	+4 °C	-188	1,063	-799	-1,176	-1,100
	+6 °C	-260	1,391	-1,286	-1,547	-1,702
Change (%)	+0 °C	--	--	--	--	--
	+2 °C	-3%	15%	-5%	-13%	-2%
	+4 °C	-6%	25%	-12%	-25%	-6%
	+6 °C	-8%	33%	-20%	-33%	-9%

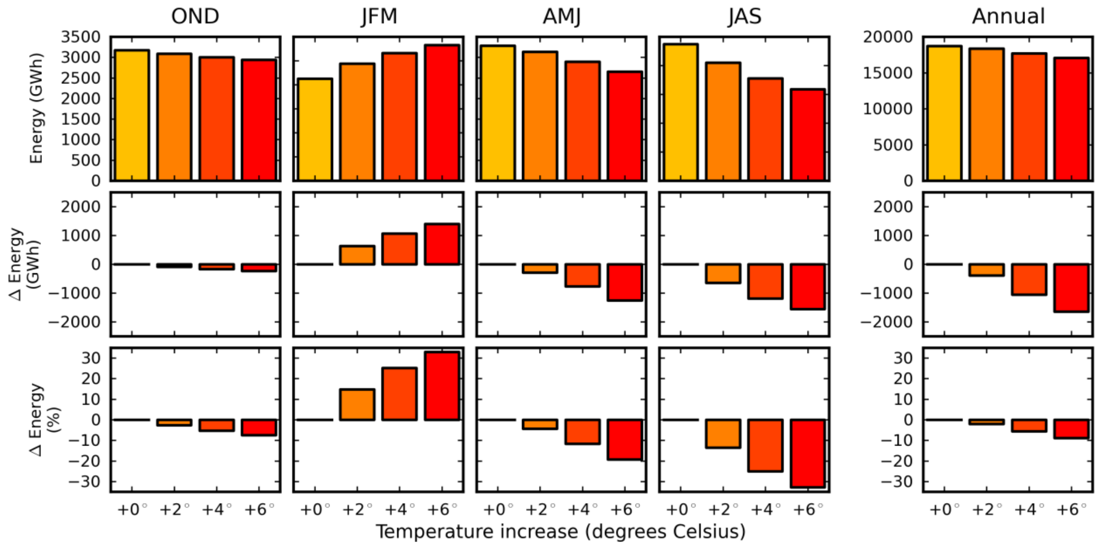

Figure 2-11. Seasonal and annual hydropower generation with warming.

Generation by watershed

The magnitudes of seasonal changes system-wide depend on the configuration and hydrologic changes of specific sub-regions. Were the aggregate results (Figure 2-11) from a single system, we might expect to see a lesser decrease in hydropower generation in the summer, as we would expect the operator to be able to store water for release later in the year, when energy prices are high. However, these results are aggregated across all systems, which are not operated as a single reservoir. Therefore, to understand these system-wide results, we need to examine individual basins and even systems within watersheds. Here, we focus on individual watersheds.

At the watershed scale, the seasonal temporal scale is the finest resolution appropriate given the limitations of the model. First, we note the seasonal shifts in hydropower generation with each warming scenario. Figure 2-12 shows seasonal changes in hydropower generation with warming for each watershed, whereas Figure 2-13 shows total annual changes in generation with warming, also per watershed. Absolute and relative change in mean annual generation values from the base historical climate to 6 °C warming are listed in Table 2-6.

Whereas hydropower generation consistently decreases Sierra-wide in the summer months (JAS), as discussed above, hydropower appears to increase in central watersheds (STN, TUO, SJN and KNG) during the winter (data not shown). By contrast, northern watersheds (FEA and ABY) do not increase much during the winter. Central watersheds are therefore able to compensate for reductions in hydropower generation lost during the summer by generating more during the winter months, when precipitation-driven runoff events are anticipated to dominate the hydrologic regime with warming. The results of these trends in seasonal shifts are seen annually in Figure 2-13. Mean annual hydropower generation substantially decreases in the highly productive northern watersheds in all warming scenarios, while generation in central watersheds change relatively little compared to the northern watersheds, and even increase somewhat with lesser warming. Generation trends with warming in the southern watersheds, which produce relatively little energy compared to northern and central watersheds, are somewhere in between—generation generally decreases, but magnitude decreases are small.

Several influences cause these trends with warming within and among watersheds: changes in runoff timing, changes in runoff magnitude, and infrastructure configuration/capacity. Additionally, model inputs and operational logic, including runoff data and priorities, affect system responses to change. Each influence is described, though a full sensitivity analysis was beyond the scope of this work.

First, throughout the Sierra Nevada there is less snowmelt-driven runoff in the late spring and early summer and greater precipitation-driven events in the winter. Even with no change in overall runoff, as this shift from snowmelt-driven events to earlier precipitation-driven events occurs, runoff becomes more evenly distributed throughout the year. Hydropower systems benefit from this increased uniformity in the near- and mid-term (+2 and 4 °C) by being able to capture more incoming water, and spilling less. Thus, the timing of runoff has a major effect on system response to warming. Hydropower generation with greater warming (+6 °C) is also influenced by changes in runoff timing, but in most cases changes in runoff magnitude dominate other influences. Warming increases evapotranspiration in the rainfall-runoff model used, which substantially reduces total annual runoff (Young et al. 2009). The combined effects of a shift to higher precipitation-driven events (high winter flows) and reduced total annual runoff results in greater earlier spill and reduces overall water available for hydropower generation with greater warming. To benefit or minimize losses from changes in runoff timing and magnitude, however, the system has to be configured and operated to allow for flexibility in operations and there has to be enough existing under-utilized hydropower capacity in earlier weeks.

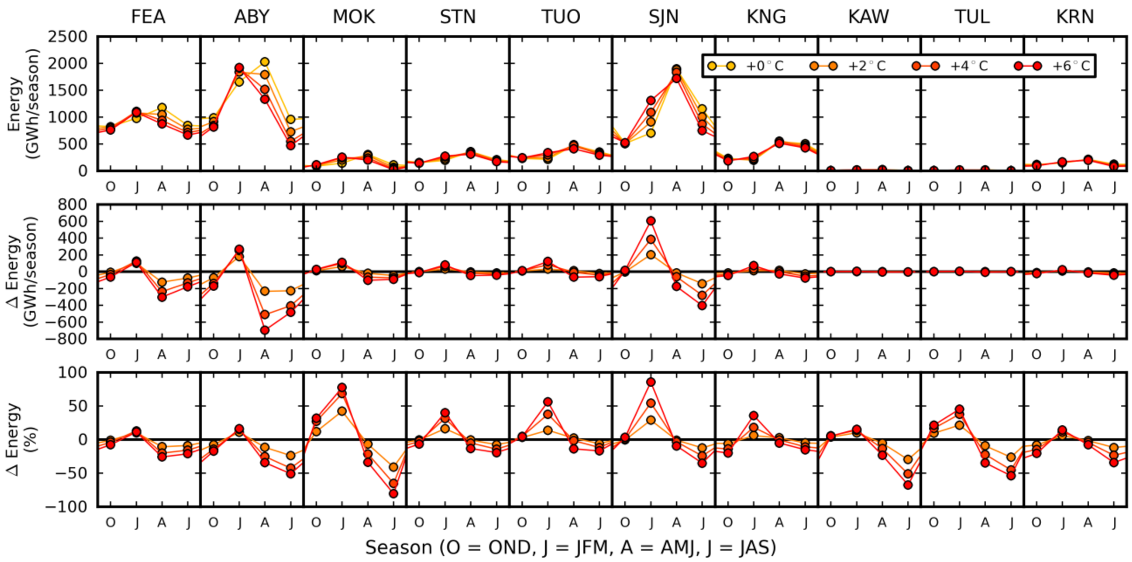

Figure 2-12. Seasonal hydropower generation change by watershed.

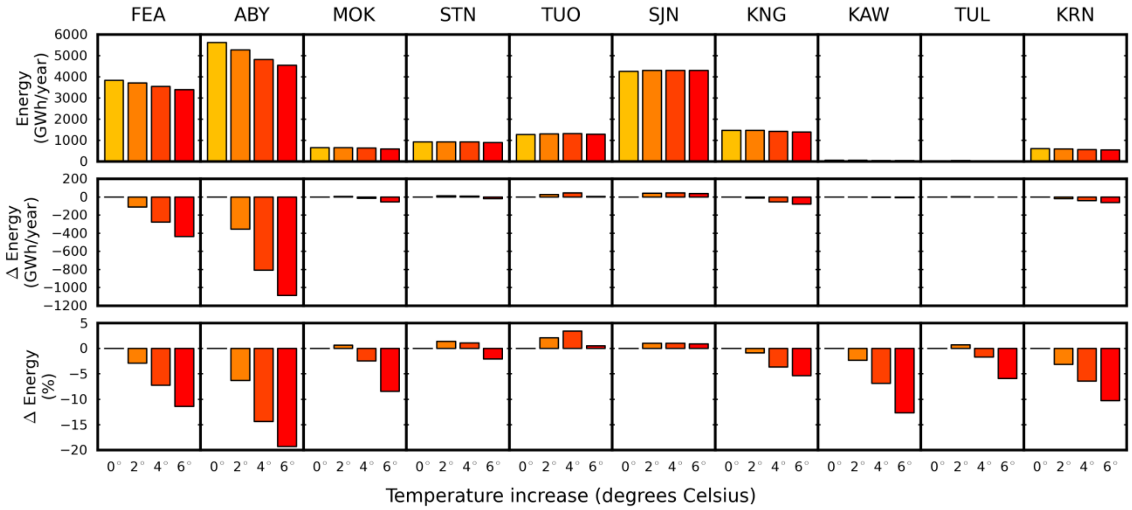

Figure 2-13. Mean annual hydropower generation change by watershed.

Table 2-6. Mean annual hydropower generation change with +6 °C warming by watershed.

Watershed	+0 °C (GWh/year)	+6 °C (GWh/year)	Change (GWh/year)	Change (%)
FEA	3,827	3,391	-436	-11%
ABY	5,629	4,541	-1,087	-19%
MOK	650	595	-55	-9%
STN	918	899	-19	-2%
TUO	1,276	1,282	7	0.5%
SJN	4,263	4,302	39	0.9%
KNG	1,475	1,396	-79	-5%
KAW	55	48	-7	-13%
TUL	38	35	-2	-6%
KRN	605	543	-62	-10%
Total	*18,735*	*17,033*	*-1702*	*-9%*

Finally, limitations of the model itself, including boundary conditions and operation logic, contribute to the observed trends in changes with warming for any particular system. The rainfall-runoff model used was calibrated to watershed outlets and a few snow gauge locations (Young et al. 2009), resulting in poorly simulated runoff in some locations within watersheds. As hydropower systems divert water from specific locations within watersheds, the quality of inflow hydrology simulation at the subwatershed scale affects the quality of system responses to warming. Under-represented inflow to a reservoir, for example, could give that reservoir more capacity to be able to compensate for changes in runoff timing. Though inflow hydrology is poorly represented in several locations, this did not appear to be a major cause of watershed-wide trends observed in Figures 2-12 and 2-13. Operational logic also affects system response to changing inflows, but was less of an issue than other influences.

Though each hydropower behavior influence described—runoff timing, runoff magnitude, system configuration/capacity, boundary condition accuracy, and operational logic—can be important, it is the combination of these influences that affects the response of any particular facility, system, or watershed to climate warming. Assuming the model is accurate, with correct operational logic and input data, the combination of system configuration, runoff magnitude, and runoff timing determine how the system behaves with historical climate and how the system responds to changes with warming. Thus, in the ABY region, substantial decreases in runoff magnitude dominate (Null et al. 2010), such that any existing additional capacity in regional systems is insufficient to substantially accommodate changes due to warming. By contrast, existing infrastructure configuration and capacity in the San Joaquin watershed, combined with minimal decreases in runoff magnitude (Null et al. 2010) with warming allows for minimal loss—gain, even—with warming. Specifically, Mammoth Pool Reservoir and powerhouse (San Joaquin River), which is historically well under capacity most of the year, can take advantage of a shift in runoff timing to reduce spill and increase generation in Mammoth Pool Reservoir. These watershed-specific trends, as reflected by spill—decreasing snowmelt spill in the American and San Joaquin watersheds with warming, yet increasing winter spill only in the American River watershed—were also noted by Vicuna et al. (2009).

Reservoir storage

To account for climate warming-induced changes in the flow regime, with less precipitation stored as snowpack, we anticipate that reservoirs will be used to store more water, filling earlier. Simulation results reflect this, with a general shift in total, watershed-wide reservoir storage to earlier in the year, as shown in Figure 2-14. The peak of total storage in the Sierra Nevada shifts from early June to mid-April. Though the timing of reservoir storage changes to replace the storage role of diminishing snowpack, total system storage decreases. Excluding Folsom Lake, storage changes from about 5.2×10^9 m^3 with a historical climate to about 5.0×10^9 m^3 with 6 °C warming, a decrease of about 4%.

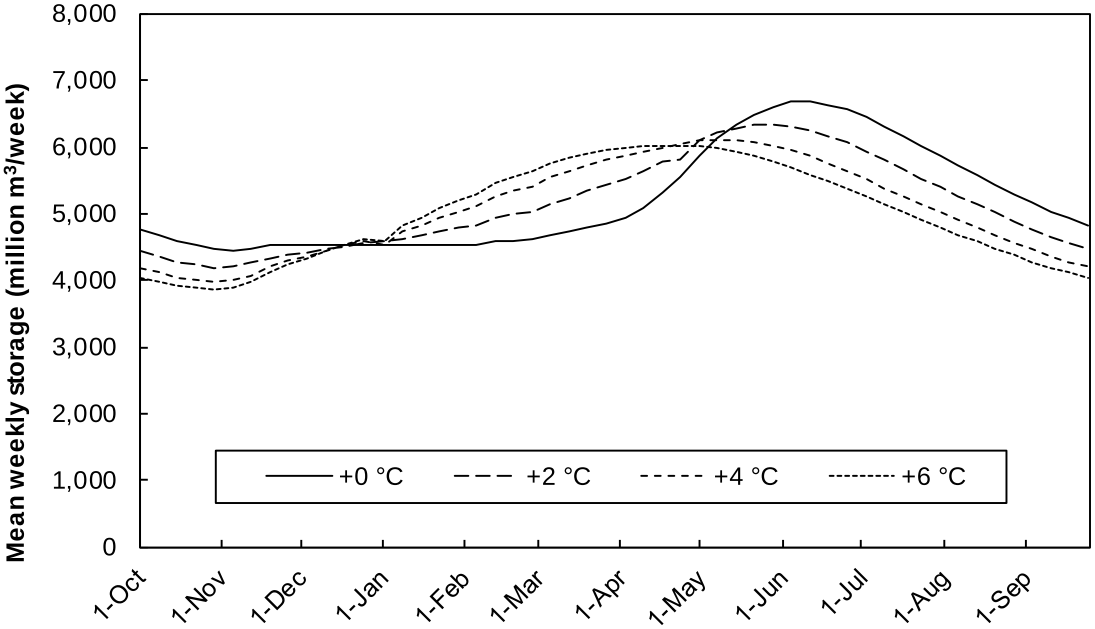

Figure 2-14. Climate warming effects on mean weekly total storage for all reservoirs except L. Folsom.

Though system-wide storage tends to decrease, the response of specific reservoirs to warming varies by reservoir size, reservoir operations, and changes in local runoff magnitude and timing. In all cases, peak reservoir storage shifts to earlier in the year. However, magnitudes of mean reservoir storage changes are more variable. With 2 °C warming, storage decreases in 63% of reservoirs compared to the historical climate, though by 6 °C warming storage decreases in 70% of reservoirs. With near- and mid-term warming, the more uniform distribution of inflows results in a more uniform distribution of storage. With long-term warming, shorter duration, precipitation-driven runoff events dominate the flow regime, but total runoff magnitude decreases (Null et al. 2010; Young et al. 2009). Further analysis would elucidate whether reductions in storage are due to inability to capture high-magnitude events in the winter or from decreases in runoff magnitude. The magnitudes of system-wide, systematic decreases in annual runoff magnitude with warming suggest that reductions are due to decreases in total annual runoff rather than changes in timing.

Figure 2-15 shows an example of a reservoir that decreases in storage with warming (Fordyce Lake, Yuba River watershed) and one that increases (Mammoth Pool Reservoir, San Joaquin River watershed). The differences in these changes are determined by local hydrologic response to warming and operations. In particular, relative priorities affect which reservoirs remain full and which empty in a multi-reservoir system. Mammoth Pool has little overall reduction in inflows and a high refill priority relative to other reservoirs. By contrast, Fordyce Lake has a much greater reduction in annual runoff with warming and has a low refill priority relative to Lake Spaulding, located just downstream. This variation in response to warming will be important in any future climate warming studies that depend on reservoir storage patterns, such as reservoir temperature simulation studies.

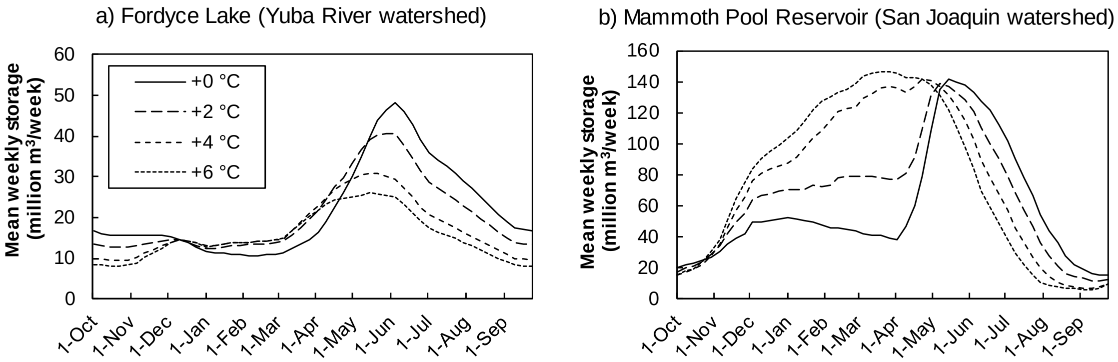

Figure 2-15. Mean weekly reservoir storage response to warming in Fordyce Lake and Mammoth Pool Reservoir.

Limitations

Spatiotemporal scope – As with all models, the SIERRA model is a simplified representation of real systems. The spatiotemporal scope of the model—weekly time step operations for most major reservoirs, hydropower plants, diversions, and instream flow requirement locations—necessitates analyses across watersheds and at the seasonal and annual time steps. Many small dams and diversions are omitted from the model for simplification, such as forebays, afterbays, and small water users that divert, store, and use water; these are currently unaccounted for. The spatiotemporal scope also affects included operations, since some hydropower generation decisions are made at the daily, hourly or shorter time step. This would affect simulation accuracy even with improved weekly-scale hydropower operations logic.

Inflow hydrology – The rainfall-runoff model accuracy is a major limitation of the model, as applied. Because the rainfall-runoff model used (Young et al. 2009) was calibrated only to the watershed outlets and to snow water equivalent at only 15 locations, inflow hydrology is under-represented in some locations and over-represented in other locations. This affects hydropower operations that depend on accurate inflows in specific locations rather than only at the watershed outlets.

Climate warming scenarios – Another important limitation of the inflow hydrology used for climate warming scenarios (Young et al. 2009) is the use of uniform and homogeneous changes in air temperature instead of location- and time-specific changes. Additionally, historical precipitation is assumed. Because some downscaled GCMs predict increased precipitation, while others predict less, it is important to assess impacts of warm-dry and warm-wet scenarios, as done by others (e.g., Madani and Lund 2010; Vicuna et al. 2008).

Climate warming effects – In the SIERRA model, warming only affects physical hydrology and lake evaporation. However, climate warming will also affect other important parameters that hydrology and water management decisions depend on. For example, atmospheric warming will likely increase energy demand; this effect is not represented in the model.

Hydropower generation – Hydropower operations here operate to a rule, whereas most hydropower systems operator for profit, responding to energy prices. The Water Year Index method works well in the long term, but does not account for weekly scale fluctuations in hydropower operations from hydropeaking. As the purpose of hydropeaking is to maximize revenue, an optimization method is needed to more accurately simulate operations of hydropeaking facilities. One option is to assume the distribution of energy prices is known during the hydropeaking period, such that the optimal operation policy is to release during every hour that the energy price is above a threshold. A second option worth exploring is to establish relationships between power generation and watershed characteristics other than stream flow. For example, in California energy demand during the summer correlates with air temperature (Franco and Sanstad 2008), since air conditioners, turned on when air temperature is high, are a major energy consumer.

Flood control and rim dams – Though the operations of flood control dams was mostly outside the spatial domain of this model, operation of rim dams can affect upstream operations. For example, the Hetch Hetchy system is operated partially in coordination with flood control operations at New Don Pedro reservoir. Inclusion of rim dams and upstream flood control operations would enable a better understanding of flood risk and control, including the possibility of utilizing higher reservoirs for some flood control.

Water supply demands – Existing water supply demand is limited in two ways. First, included demands are based on historical observations or known supply requirements. Water management projections should also include anticipated changes in other factors that affect future water demand such as future population growth and water use patterns in different sectors. Second, many smaller abstractions within the spatial extent of the model have been excluded for simplification. Including more of the smaller water diversions would help improve overall model accuracy.

Uncertainty and sensitivity – No uncertainty or sensitivity analysis was conducted for this model. Although there are several theoretically robust methods to help map uncertainty in inputs to uncertainty in outputs, the methods require substantial amounts of computational power. An analysis of the most obvious sources of uncertainty, such as inflow hydrology, and an assessment of which parameters the model is most sensitive to would be beneficial.

Conclusions

SIERRA is one of the larger hydropower and montane water resources simulation models. The main contribution of this work is both the model itself, including the methods for simulating hydropower generation, albeit coarse, and the quantitative assessment of hydropower generation impacts of regional climate warming. SIERRA can be used to assess effects of regional climate warming on a wide range of managed water systems and beneficial uses of water in the Sierra Nevada. The model performs well for hydropower facilities in the region for assessments of change at the seasonal and annual time scales.

Though other studies estimate climate change effects on hydropower, they are either very broad or very specific. The work here bridges the gap between generalized, state-wide studies and specific, local studies. We applied SIERRA at the weekly scale using climate warming scenarios of +0, 2, 4, and 6 °C warming. Hydropower generation decreases in all warming scenarios, driven primarily by decreases in the highly productive watersheds in the northern Sierra Nevada. With far-term warming (+6 °C), model results suggest a 9% decrease in mean annual hydropower generation system-wide. This is less than estimates from other studies that consider drier conditions (less precipitation and runoff), but greater than studies that consider warming only (no change in annual runoff). The most substantial decreases in mean annual hydropower generation occur in the northern watersheds, which have large decreases in runoff magnitude. In contrast, the model generally predicts a slight increase in generation with near- and mid-term warming followed by a slight decrease in generation with far-term warming. The model predicts constant declines in hydropower generation in the southern watersheds, though total generation in southern watersheds is small. These results suggest that future struggles over water use will be relatively more pronounced in the northern watersheds.

Two particularly important limitations of the model include the course resolution of the climate change scenarios considered in the rainfall-runoff model and the approximate method used to model hydropower demand and decisions. We recommend considering alternative climate change scenarios and incorporating a hydropower optimization routine, where needed, to more accurately simulate adaptation of regional water management systems to climate warming.

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Appendix 2-A: SIERRA input parameters

This Appendix includes the main physical and operations parameters used in SIERRA, including for reservoirs, run-of-river hydropower, variable head hydropower, water supply demand, instream flow requirements, and diversion conveyances. Some inconsistencies and conventions are worth noting. Source data units are usually in English units. However, WEAP uses SI units. In these tables, English units are mostly used, though some data are given in SI units.

Abbreviations and non-SI units in the tables are:

- mcm = million cubic meters (1.0×10^{6} m^3)
- 1 AF = 1 acre-foot = 1.233×10^{3} m^3
- 1 ft = 1 foot = 3.048×10^{-1} m
- 1 ft^3/s = 2.832×10^{2} m^3/s

Other abbreviations include:

- CDEC = California Data Exchange Center
- USGS = U.S. Geological Survey

Finally, we note again that the watersheds were grouped into mutually independent models (the latter are referred to in the main text), in order from north to south, as follows:

Watershed	**Model abbr.**	**Watershed**	**Model abbr.**
Feather	FEA	Tuolumne	TUO
Yuba	ABY	Merced	MER
Bear		San Joaquin	SJN
American		Kings	KNG
Cosumnes		Kaweah	KAW
Mokelumne	MOK	Tule	TUL
Calaveras	CAL	Kern	KRN
Stanislaus	STN		

Table 2-7. Reservoir parameters.

Watershed	Name	Storage capacity (AF)	Storage capacity (mcm)	Minimum storage (mcm)	Min elevation (m)	Max. elevation (m)	Refill priority	Drawdown priority	CDEC gauge	USGS gauge
American	Caples Lake	21.6	26.6	2.5	0.0	100.0	15	15	CPL	N/A
	Chili Bar Reservoir	3.1	3.9	0	0.0	18.3	55	55	N/A	N/A
	Folsom Lake	977.0	1204.6	0	0.0	100.0	65	65	FOL	N/A
	French Meadows Reservoir	136.4	168.2	61.7	0.0	100.0	15	15	FMD	N/A
	Hell Hole Reservoir	207.3	255.7	38.8 / 86.3	1306.0	1417.3	25	25	HHL	N/A
	Ice House Reservoir	46.0	56.7	17.3 – 53.6	1623.8	1670.3	15	15	ICH	11441100
	Loon Lake	76.5	94.3	0	1928.0	1959.9	15	15	LON	11429350
	Oxbow Reservoir	24.3	30.0	0	0.0	75.0	45	45	N/A	N/A
	Rubicon Reservoir	1.5	1.8	0	1981.2	1996.4	15	15	N/A	N/A
	Silver Lake	8.6	10.7	0.5	0.0	50.0	15	15	SIV	N/A
	Slab Creek Reservoir	16.6	20.5	12.3	512.1	570.0	45	45	SLB	11443450
	Stumpy Meadows Reservoir	20.0	24.7	0	0.0	100.0	45	45	EDN	N/A
	Union Valley Reservoir	277.0	341.5	3.0	1400.0	1484.4	25	25	UNV	11441001
Cosumnes	Jenkinson Lake	41.0	50.6	0	0.0	50.0	65	65	JNK	N/A
Feather	Antelope Lake	24.3	30.0	17	1497.2	1526.2	39	39	ANT	N/A
	Belden Reservoir	2.4	3.0	3.0	0.0	3.9	1	1	N/A	N/A
	Bucks Lake	105.6	130.2	80	1506.9	1571.2	16	16	BCL	11403500
	Butt Valley Reservoir	49.9	61.5	36	1241.8	1259.5	15	15	BTV	11401050
	Frenchman Lake	58.8	72.5	10.6	1669.7	1703.9	98	98	FRD	N/A
	Lake Almanor	1175.0	1448.8	750	1336.5	1370.2	15	15	ALM	11399000
	Lake Davis	85.5	105.5	34.6	1728.2	1760.3	98	98	DAV	N/A
	Little Grass Valley Reservoir	89.8	110.7	55	1475.8	1538.3	15	15	LGV	11395020
	Mountain Meadows Reservoir	24.8	30.6	0	1525.2	1533.1	15	15	MMW	N/A
	Sly Creek Reservoir	64.3	79.3	1.8	1004.3	1076.2	15	15	SLC	11395400
Kern	Lake Isabella	562.4	693.4	0	746.5	794.0	15	15	ISB	11190500
Kings	Courtright Reservoir	123.3	152.0	39	2400.9	2494.5	15	15	CTG	11214550
	Wishon Reservoir	128.6	158.6	20	1917.1	1996.4	16	16	WSN	11214800
Mokelumne	Lower Bear River Reservoir	52.0	64.1	4.1	1706.9	1773.9	16	16	LWB	11315600
	Salt Springs Reservoir	141.9	174.9	6.2	1107.9	1206.4	29	29	SLS	11313500

Table 2-7 (cont'd…). Reservoir parameters.

Watershed	Name	Storage capacity (AF)	Storage capacity (mcm)	Minimum storage (mcm)	Min elevation (m)	Max. elevation (m)	Refill priority	Drawdown priority	CDEC gauge	USGS gauge
San Joaquin	Bass Lake	45.1	55.6	27	986.3	1029.1	17	17	CNV	11243400
	Florence Lake	64.4	79.4	1.25	2188.5	2233.4	15	99	FLR	11229600
	Huntington Lake	89.2	109.9	37	2068.4	2118.4	15	15	HNT	11236000
	Kerckhoff Lake	4.2	5.2	4.3	270.8	299.5	65	65	KRH	11246650
	Lake Thomas A Edison	125.0	154.2	8	2281.0	2329.4	15	16	TAE	11231000
	Mammoth Pool Reservoir	119.9	147.9	5	944.9	1015.0	26	26	MPL	11234700
	Redinger Lake	26.1	32.2	5.28	359.8	427.6	55	55	RDN	11241950
	Shaver Lake	135.6	167.2	0.47	1582.2	1636.8	25	25	SHV	11239500
Stanislaus	Beardsley Reservoir	98.5	121.5	25	953.1	1035.7	25	25	BRD	11292800
	Donnells Reservoir	64.7	79.8	6.2	1411.5	1498.7	15	15	DON	11292600
	Lyons Reservoir	4.9	6.0	1.25	1248.1	1286.3	26	26	LYS	11297700
	New Spicer Meadow Reservoir	184.3	227.2	50	1940.1	2015.9	15	15	SPM	11293770
	Pinecrest Reservoir	18.3	22.6	4	1671.2	1712.2	15	99	SWB	11297700
	Relief Reservoir	12.3	15.2	1.2	2156.6	2232.1	15	15	RLF	11291000
Tuolumne	Cherry Lake	274.3	338.2	0	1353.3	1433.5	17	17	CHY	11277200
	Hetch Hetchy Reservoir	360.4	444.4	123.3	1070.5	1160.1	18	18	HTH	11275500
	Lake Eleanor	26.1	32.2	0	1404.5	1421.3	15	17	ENR	11277500
Yuba-Bear	Bowman Lake	68.5	84.5	0	1648.9	1696.3	15	15	BWN	11415500
	Buck Island Reservoir	1.1	1.3	0	1949.5	1964.7	15	15	N/A	N/A
	Camp Far West Lake	104.5	128.8	0	48.8	96.0	65	65	CFW	N/A
	Englebright Lake	70.0	86.3	74.0	0.0	85.3	35	35	ENG	11417950
	Fordyce Lake	49.9	61.5	0.15	1914.1	1953.8	15	15	N/A	11414090
	Jackson Meadows Reservoir	69.2	85.3	0	1794.2	1841.0	15	15	JCK	11407800
	Lake Combie	5.6	6.8	0	0.0	26.0	55	55	CMB	N/A
	Lake Spaulding	75.1	92.6	0	1472.9	1540.8	15	15	SPG	11414140
	New Bullards Bar Reservoir	966.1	1191.2	288.6	411.5	615.7	25	25	BUL	11413515
	Rock Creek Reservoir	0.4	0.5	0	433.2	440.3	25	25	N/A	N/A
	Rollins Reservoir	66.0	81.4	0	596.0	662.3	45	45	RLL	11421800
	Scotts Flat Reservoir	48.5	59.8	0	0.0	53.3	15	15	SFL	11418250

Table 2-8. Run-of-river hydropower plant parameters.

Watershed	Name	Demand method	Max. flow (ft^3/s)	Fixed head (ft)	Plant efficiency (%)	Hydropower priority	Spill demand priority	Flow gauge	EIA ID
American	Camino	WYI	2000	997	90	39	39	USGS_11441895	430
	El Dorado ID	WYI	150	984	90	15	19	USGS_11439300	238
	French Meadows	WYI	400	656	90	15	19	USGS_11427200	424
	Jaybird	WYI	1378	1476	90	25	29	USGS_11441780	431
	Jones Fork	WYI	281	577	90	15	19	USGS_11440900	534
	Loon Lake	WYI	997	1100	90	15	19	USGS_11429340	432
	Middle Fork	WYI	920	1936	90	25	29	USGS_11428600	425
	Ralston	WYI	924	1312	90	39	39	USGS_11427765	427
	Robbs Peak	WYI	1046	330	90	25	25	USGS_11429300	433
Feather	Belden	Max Capacity	2410	770	90	N/A	25	USGS_11403050	219
	Bucks Creek	WYI	384	2558	90	15	19	USGS_11403700	220
	Butt Valley	Max Capacity	2118	362	90	N/A	29	USGS_11400600	221
	Caribou 1	WYI	1114	1150	90	14	19	USGS_11401110	222
	Caribou 2	WYI	1464	1151	90	14	19	USGS_11401110	223
	Cresta	Max Capacity	3510	290	90	N/A	49	USGS_11404360	231
	Forbestown	Max Capacity	620	795	90	N/A	25	USGS_11396290	417
	Grizzly	Max Capacity	375	705	90	N/A	29	USGS_11404240	7338
	Hamilton Branch	Max Capacity	200	410	90	N/A	21	N/A	242
	Kanaka	Max Capacity	32	542	90	N/A	15	USGS_11396396	54653
	Kelly Ridge	Max Capacity	255	628	90	N/A	35	USGS_11396329	418
	Lime Saddle	Max Capacity	87	462	90	N/A	29	N/A	255
	Poe	Max Capacity	3700	488	90	N/A	59	USGS_11404900	272
	Rock Creek	Max Capacity	2880	535	90	N/A	39	USGS_11403800	275
	Toadtown	Max Capacity	125	131	90	N/A	19	USGS_11389800	714
	Woodleaf	WYI	580	1456	90	14	25	USGS_11396090	419
Kaweah	Kaweah 1	Max Capacity	23	1260	90	N/A	19	USGS_11208720	337
	Kaweah 2	Max Capacity	87	344	90	N/A	29	USGS_11208570	336
	Kaweah 3	Max Capacity	97	750	90	N/A	19	USGS_11207500	338

Table 2-8 (cont'd…). Run-of-river hydropower plant parameters.

Watershed	Name	Demand method	Max. flow (ft^3/s)	Fixed head (ft)	Plant efficiency (%)	Hydropower priority	Spill demand priority	Flow gauge	EIA ID
Kern	Borel	Max Capacity	590	255	90	N/A	14	USGS_11187500	328
	Kern Canyon	Max Capacity	705	264	90	N/A	49	USGS_11192940	7911
	Kern River 1	Max Capacity	412	865	90	N/A	39	USGS_11192000	340
	Kern River 3	Max Capacity	620	850	90	N/A	18	USGS_11185500	339
	Rio Bravo	Max Capacity	1500	121	90	N/A	59	USGS_11193010	50037
Kings	Balch 1 and 2	Max Capacity	843	2379	90	N/A	39	USGS_11216300	217 & 218
	Haas	WYI	825	2444	90	15	29	USGS_11216050	240
	Helms	Max Capacity	2500	1744	90	N/A	19	USGS_11214540	6100
	Kings River	Max Capacity	990	798	90	N/A	49	USGS_11218700	254
Mokelumne	Electra	Max Capacity	1130	1272	90	N/A	49	PG&E_M65	239
	Salt Springs 2	WYI	225	2117	90	15	19	USGS_11313510	N/A
	Tiger Creek	WYI	750	1219	90	25	29	USGS_11316610	287
	West Point	Max Capacity	675	312	90	N/A	39	PG&E_M64	291
San Joaquin	Big Creek 1	WYI	692	1923	90	14	18	USGS_11238100	317
	Big Creek 2	Max Capacity	607	1638	90	N/A	29	USGS_11238380	318
	Big Creek 2A	WYI	625	2200	90	25	19	USGS_11238400	322
	Big Creek 3	Max Capacity	3200	764	90	N/A	49	USGS_11241800	319
	Big Creek 4	WYI	3700	388	90	55	59	USGS_11246530	320
	Big Creek 8	Max Capacity	1332	685	90	N/A	39	USGS_11238550	321
	Eastwood	WYI	2296	1312	90	15	19	USGS_11238250	104
	Kerckhoff 1	WYI	1735	351	90	64	69	USGS_11246950	250
	Kerckhoff 2	WYI	5100	420	90	65	69	USGS_11247050	682
	Mammoth Pool	WYI	2500	1004	90	25	29	USGS_11235100	344
	Portal	Max Capacity	724	190	90	N/A	29	USGS_11235500	354
	San Joaquin 1	Max Capacity	235	1305	90	N/A	49	USGS_11246610	293
	San Joaquin 1A	Max Capacity	167	40	90	N/A	39	USGS_11246590	278
	San Joaquin 2	Max Capacity	150	292	90	N/A	29	USGS_11246570	276
	San Joaquin 3	WYI	150	378	90	15	19	USGS_11244100	277

Table 2-8 (cont'd…). Run-of-river hydropower plant parameters.

Watershed	Name	Demand method	Maximum Turbine Flow (ft^3/s)	Fixed head (ft)	Plant efficiency (%)	Hydropower priority	Spill demand priority	Flow gauge	EIA ID
Stanislaus	Angels	Max Capacity	40	444	90	N/A	39	N/A	215
	Collierville	WYI	1400	2192	90	15	19	USGS_11295250	54555
	Donnells	WYI	700	1151	90	19	19	USGS_11292610	415
	Murphys	Max Capacity	68	684	90	N/A	29	N/A	261
	Phoenix	WYI	25	25	90	25	29	PG&E_S108	264
	Sand Bar	WYI	600	427	90	25	29	USGS_11292860	777
	Spring Gap	WYI	59	59	90	15	39	USGS_11297000	284
	Stanislaus	WYI	830	830	90	25	39	USGS_11295505	285
Tule	Lower Tule R	Max Capacity	35	1140	90	N/A	29	USGS_11202700	365
	Tule River	Max Capacity	70	1544	90	N/A	19	USGS_11201700	289
Tuolumne	Dion R Holm	WYI	1000	2100	90	15	19	SFPUC_HPH	380
	Kirkwood	WYI	1400	1100	90	15	19	SFPUC_KPH	382
	Moccasin	WYI	19	1316	90	16	29	SFPUC_MPH	381
Yuba-Bear	Alta	Max Capacity	56	650	90	N/A	20	USGS_11421725	214
	Chicago Park	WYI	1100	480	90	39	39	USGS_11421780	412
	Colgate	WYI	3700	1125	90	25	29	USGS_11413510	454
	Deer Creek	WYI	66	838	90	14		USGS_11414205	233
	Drum 1	WYI	360	1379	90	15	19	USGS_11414194	235
	Drum 2	WYI	500	1376	90	15	19	USGS_11414195	236
	Dutch Flat 1	WYI	490	581	90	15	29	USGS_11421750	237
	Dutch Flat 2	WYI	600	581	90	15	29	USGS_11421760	413
	Halsey	WYI	294	326	90	48	48	USGS_11425310	241
	Narrows 1	WYI	70	236	90	35	39	USGS_11417970	262
	Narrows 2	WYI	2940	200	90	35	39	USGS_11417980	455
	Newcastle	WYI	392	410	90	59	59	USGS_11425416	632
	Spaulding 1	WYI	550	198	90	19	19	USGS_11414154	281
	Spaulding 2	WYI	200	346	90	18	18	USGS_11414155	282
	Spaulding 3	WYI	330	328	90	17	17	USGS_11416200	283
	White Rock	WYI	3500	780	90	45	49	USGS_11443460	435
	Wise 1 and 2	WYI	473	522	90	59	59	USGS_11425415	292

Table 2-9. Variable head hydropower plant parameters.

Watershed	Name	Owner	Reservoir	Max. flow (ft^3/s)	Efficiency (%)	Tailwater elevation (m)	Flow gauge	EIA ID
American	Chili Bar	Pacific Gas & Electric Co	Chili Bar Reservoir	1659	90	0.0	N/A	225
	Hell Hole	Placer County Water Agency	Hell Hole Reservoir	20	90	1306.0	N/A	763
	Oxbow	Placer County Water Agency	Oxbow Reservoir	1100	90	0.0	USGS_11433212	426
	Slab Creek	Sacramento Municipal Utility Dist.	Slab Creek Reservoir	36	90	515.1	N/A	522
	Union Valley	Sacramento Municipal Utility Dist.	Union Valley Reservoir	1577	90	1400.0	USGS_11441002	6612
Feather	Oak Flat	Pacific Gas & Electric Co	Belden Reservoir	140	90	0.0	N/A	626
	Sly Creek	Northern California Power Agency	Sly Creek Reservoir	700	90	1104.3	USGS_11395400	776
Mokelumne	Salt Springs 1	Pacific Gas & Electric Co	Salt Springs Reservoir	225	90	1107.9	CDEC_SLS	279
San Joaquin	Crane Valley	Pacific Gas & Electric Co	Bass Lake	160	90	986.3	USGS_11243400	230
Stanislaus	Beardsley	Oakdale & South San Joaquin Irr. Dist.	Beardsley Reservoir	620	90	953.1	USGS_11292800	414
	New Spicer Meadow	Northern California Power Agency	New Spicer Meadow Reservoir	200	90	1940.1	USGS_11293760	54554
Yuba-Bear	Bowman	Pacific Gas & Electric Co	Bowman Lake	313	90	1647.7	N/A	848
	Camp Far West	Sacramento Municipal Utility Dist.	Camp Far West Lake	25	90	48.8	N/A	531
	Combie	Nevada Irrigation District	Lake Combie	5	90	0.0	N/A	846 & 847
	Fish Power	Yuba Count Water Agency	New Bullards Bar	5	90	411.5	N/A	4229
	Rollins	Nevada Irrigation District	Rollins Reservoir	840	90	597.0	USGS_11421900	34

Table 2-10. Water supply demand parameters

Watershed	Supply demand name	Weekly demand	Annual demand (million m^3)	Weekly variation	Demand Priority
American	Folsom	N/A	10.7	Variable	65
	Nevada Irrigarion District (NID) 1	Variable	N/A	N/A	23
	Nevada Irrigarion District (NID) 2	Variable	N/A	N/A	23
Feather	California Water Service Company (CalWater) - Oroville	N/A	38.5	Variable	23
	South Feather Water & Power Agency (SFWPA) - Bangor	N/A	11.4	Variable	25
	South Feather Water & Power Agency (SFWPA) - Forbestown	N/A	7.5	Variable	13
Mokelumne	Amador Water Agency (AWA)	N/A	1.7	Constant	33
	Caleveras Public Utilities District (CPUD)	N/A	1.9	Constant	13
Tule	Crabtree-Aiken Ditch Co.	N/A	5.8	Constant	23
	Graham Osborn Ditch Co.	N/A	10.7	Constant	23
	Mt Whitney Ditch Co.	N/A	3.6	Constant	22
	Pleasant Valley Canal Co.	N/A	10.7	Constant	23
	South Tule Ditch Co.	N/A	14.3	Constant	13
Tuolumne	San Francisco Public Utilities Commission (SFPUC)	N/A	(-0.0116*WYI_SJValley + 0.26)*1233	Variable	13
Yuba-Bear	Nevada Irrigation District (NID) 3	Variable	N/A	N/A	53
	Nevada Irrigation District (NID) 4 Cascade	Variable	N/A	N/A	13
	Nevada Irrigation District (NID) 5 Deer Creek	Variable	N/A	N/A	13
	Placer County Water Agency (PCWA) 1	Variable	N/A	N/A	13
	Placer County Water Agency (PCWA) 2	Variable	N/A	N/A	43
	Placer County Water Agency (PCWA) 3	Variable	N/A	N/A	24
	Placer County Water Agency (PCWA) 4	Variable	N/A	N/A	24
	Placer County Water Agency (PCWA) 5	Variable	N/A	N/A	24
	Sly Folsom	N/A	9.3	Variable	65
	South Fork Feather River (SFFR)	N/A	(0.003*WYI_SacValley + 0.0522)*1233	Variable	13
	Yuba County Water Agency (YCWA) Wheatland	Variable	N/A	N/A	47

Table 2-11. Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
American	IFR bl Buck Island	Little Rubicon	Buck Island Reservoir	P-2101 FERC license	12
	IFR bl Buck Loon Tunnel	Rubicon River	Buck Look Diversion	P-2101 FERC license	13
	IFR bl Caples	Caples Cr.	Caples Lake	P-0184 FERC license	11
	IFR bl Chili Bar	S Fk American	Chili Bar Reservoir	P-2155 FERC license	51
	IFR bl Duncan Tunnel	Duncan Cr.	Duncan Tunnel Div. Reservoir	P-2079 FERC license	11
	IFR bl El Dorado ID Canal	S Fk American	El Dorado ID Div. Reservior	P-0184 FERC license	12
	IFR bl French Meadows	M Fork American	French Meadows Reservoir	P-2079 FERC license	12
	IFR bl Hell Hole	Rubicon River	Hell Hole Reservoir	P-2079 FERC license	21
	IFR bl Ice House	S Fk Silver Creek	Ice House Reservoir	P-2101 FERC license	11
	IFR bl Jaybird Tunnel	Silver Cr.	Junction Reservoir	P-2101 FERC license	22
	IFR bl Long Canyon Creek Tunnel	Long Canyon Cr.	Long Canyon Creek Tunnel	P-2079 FERC license	21
	IFR bl Loon	Gerle Cr.	Loon Lake	P-2101 FERC license	14
	IFR bl Ralston Tunnel	M Fork American	Ralston Tunnel	P-2079 FERC license	31
	IFR bl Rubicon	Rubicon River	Rubicon Reservoir	P-2101 FERC license	11
	IFR bl Silver	Silver Fk American	Silver Lake	P-0184 FERC license	11
	IFR bl Slab Creek	S Fk American	Slab Cr. Reservoir	P-2101 FERC license	41
Cosumnes	IFR bl Camp Creek Tunnel	Camp Cr.	Camp Creek Tunnel	Central Valley Project, Sly Park Unit	11

Table 2-11 (cont'd…). Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
Feather	IFR at Pulga Gage	N Fk Feather	Poe Div. Dam	P-2107 FERC license	51
	IFR bl Almanor	N Fk Feather	Canyon Dam	P-2105 FERC license	11
	IFR bl Antelope Lake	Indian Cr.	Antelope Lake Dam	Historical flows	11
	IFR bl Belden Forebay	N Fk Feather	Belden Forebay	Historical flows	21
	IFR bl Cresta Forebay	N Fk Feather	Cresta Forebay	P-2105 FERC license	41
	IFR bl Forbestown Div	S Fk Feather	Forbestown Div. Dam	P-2088 FERC license	11
	IFR bl Frenchman Lake	Last Chance Cr.	Frenchman Lake Dam	Historical flows	11
	IFR bl Grizzly Forebay	Grizzly Cr. of NF Feather	Grizzly Forebay Dam	P-0619 FERC license	11
	IFR bl Hamilton Branch Div	Hamilton Branch	Hamilton Branch Div	PG&E 2000 Hydrodivestiture Draft EIR	11
	IFR bl Kanaka Div	Sucker Run	Kanaka Div. Dam	P-7242 FERC license	11
	IFR bl Lake Davis	Grizzly Cr. of MF Feather	Lake Davis Dam	Historical flows	11
	IFR bl Little Grass Valley Reservoir	S Fk Feather	Little Grass Valley Dam	P-2088 FERC license	11
	IFR bl Lost Creek Div	Lost Cr.	Lost Cr. Div. Dam	P-2088 FERC license	11
	IFR bl Lower Bucks Lake	Bucks Cr.	Lower Bucks Lake	P-0619 FERC license	11
	IFR bl Mountain Meadows	Hamilton Branch	Indian Ole Dam	PG&E 2000 Hydrodivestiture Draft EIR	11
	IFR bl Poe Div	N Fk Feather	Poe Div. Dam	P-2107 FERC license	51
	IFR bl Rock Creek Reservoir	N Fk Feather	Rock Creek Dam	P-2105 FERC license	31
	IFR bl South Fork Div	S Fk Feather	SFk Div. Dam	P-2088 FERC license	11
Kaweah	IFR bl Conduit 1 Div	E Fk Kaweah River	Conduit 1 Div	P-0298 FERC license	11
	IFR bl Conduit 2 Div	M Fk Kaweah	Conduit 2 Div	P-0298 FERC license	21
	IFR bl Conduit 3 Marble Fk Div	Marble Fk Kaweah	Conduit 3 Marble Fk Div	P-0298 FERC license	11
	IFR bl Conduit 3 Middle Fk Div	M Fk Kaweah	Conduit 3 Middle Fk Div	P-0298 FERC license	11

Table 2-11 (cont'd…). Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
Kern	IFR bl Democrat Dam	Kern River	Democrat Dam	P-1930 FERC license	31
	IFR bl Fairview Dam	Kern River	Fairview Dam	P-2290 FERC license	11
	IFR bl FERC 178 Div. Dam	Kern River	FERC 178 Div. Dam	P-0178 FERC license	41
	IFR bl Isabella AUX Dam	Kern River	Isabella AUX Dam	P-0382 FERC license	21
	IFR bl Rio Bravo Div. Dam	Kern River	Rio Bravo Div. Dam	P-4129 FERC license	51
Kings	IFR bl Balch AB Dam	N Fk Kings	Balch AB Dam	P-1988 FERC license	41
	IFR bl Black Rock Dam	N Fk Kings	Black Rock Dam	P-0175 FERC license	31
	IFR bl Courtright Dam	Helms Cr.	Courtright Dam	P-1988 FERC license	11
	IFR bl Kings Penstock	Dinkey Cr.	Kings Penstock	P-1988 FERC license	41
	IFR bl Wishon Dam	N Fk Kings	Wishon Dam	P-1988 FERC license	12
Mokelumne	IFR bl Bear River Div	Cole Cr.	Bear River Div	P-0137 FERC license, 2002 Streamflow Capability Report	11
	IFR bl Cole Creek Div	Cole Cr.	Cole Creek Div	P-0137 FERC license, 2002 Streamflow Capability Report	11
	IFR bl Electra Div	N Fk Mokelumne	Electra Div	P-0137 FERC license, 2002 Streamflow Capability Report	41
	IFR bl Lower Bear River Res	Bear River	Lower Bear River Res	P-0137 FERC license, 2002 Streamflow Capability Report	11
	IFR bl Salt Springs Dam	N Fk Mokelumne	Salt Springs Dam	P-0137 FERC license, 2002 Streamflow Capability Report	29
	IFR bl Tiger Cr. Regulator	Tiger Cr.	Tiger Cr. Regulator	P-0137 FERC license, 2002 Streamflow Capability Report	21
	IFR bl Tiger Res	N Fk Mokelumne	Tiger Res	P-0137 FERC license, 2002 Streamflow Capability Report	31

Table 2-11 (cont'd…). Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
San Joaquin	IFR bl Bear Cr. Div. Dam	Bear Cr.	Bear Cr. Div. Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Big Cr. 5 Dam	Big Cr.	Big Cr. 5 Dam	P-2085 & P-2175 FERC licenses	31
	IFR bl Big Cr. No. 6 Dam	San Joaquin River	Big Cr. No. 6 Dam	P-2085 & P-2175 FERC licenses	41
	IFR bl Bolsillo Cr. Div. Dam	Bolsillo Cr.	Bolsillo Cr. Div. Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Camp 62 Cr. Div. dam	Camp 62 Cr.	Camp 62 Cr. Div. dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Chinquapin Cr. Div. Dam	Chinquapin Cr.	Chinquapin Cr. Div. Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Crane Valley Dam	N Fk Willow Cr.	Crane Valley Dam	P-1354 FERC license	11
	IFR bl Florence Dam	S Fk San Joaquin	Florence Dam	P-2085 & P-2175 FERC licenses	10
	IFR bl Huntington Dam	Big Cr.	Huntington Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Kirckhoff Dam	San Joaquin River	Kirckhoff Dam	P-0096 FERC license	61
	IFR bl Mammoth Pools Dam	San Joaquin River	Mammoth Pools Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Manzanita Dam	N Fk Willow Cr.	Manzanita Dam	P-1354 FERC license	21
	IFR bl Mono Cr. Div. Dam	Mono Cr.	Mono Cr. Div. Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Pitman Cr. Div. Dam	Pitman Cr.	Pitman Cr. Div. Dam	P-2085 & P-2175 FERC licenses	11
	IFR bl Redinger Dam	San Joaquin River	Redinger Dam	P-2017 FERC license	51
	IFR bl SF Willows Cr. Div. Dam	Willow Cr.	SF Willows Cr. Div. Dam	P-1354 FERC license	11
	IFR bl Shaver Dam	Stevenson Cr.	Shaver Dam	P-2085 & P-2175 FERC licenses	21
	IFR bl Tunnel No. 7 to Shaver L.	N Fk Stevenson Cr.	Tunnel No. 7 to Shaver	P-2085 & P-2175 FERC licenses	11
	IFR bl Willow Creek near Rex Ranch	Willow Cr.	Willow Creek near Rex Ranch	P-1354 FERC license	21

Table 2-11 (cont'd…). Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
Stanislaus	IFR bl Angles Div.	Angels Cr.	Angles Div.	P-2699 FERC license	21
	IFR bl Beaver Cr. Div. Dam	Beaver Cr.	Beaver Cr. Div. Dam	P-2409 FERC license	11
	IFR bl Donnells Dam	M Fk Stanislaus	Donnells Dam	P-2005 FERC license	11
	IFR bl Hunters Dam	Mill Cr.	Hunters Dam	P-2019 FERC license	21
	IFR bl Lyons Res Dam	S Fk Stanislaus	Lyons Res Dam	P-1061 FERC license	21
	IFR bl McKays Point Div. Dam	N Fk Stanislaus	McKays Point Div. Dam	P-2409 FERC license	11
	IFR bl New Spicer Dam	Highland Cr.	New Spicer Dam	P-2409 FERC license	11
	IFR bl Philadelphia Div. Dam	S Fk Stanislaus	Philadelphia Div. Dam	P-2130 FERC license	11
	IFR bl Relief Dam	Summit Cr.	Relief Dam	P-2130 FERC license	11
	IFR bl Sand Bar Div. Dam	M Fk Stanislaus	Sand Bar Div. Dam	P-2130 FERC license	31
	IFR bl Utica Dam	N Fk Stanislaus	Utica Dam	P-11563 FERC license	11
Tule	IFR bl Tule R. Div. Dam	M Fk North Fk Tule	Tule R. Div. Dam	P-1333 FERC license	11
Tuolumne	IFR bl Cherry Lake Res	Cherry Cr.	Cherry Lake Reservoir		11
	IFR bl Hetch Hetchy Res	Tuolumne River	Hetch Hetchy Reservoir		18
	IFR bl Lake Eleanor	Eleanor Cr.	Lake Eleanor		11

Table 2-11 (cont'd…). Instream flow requirement (IFR) parameters.

Watershed	Name	River	Regulator	Definition source	Priority
Yuba-Bear	IFR bl Bear Meadow	Bear R	Bear Meadow	P-2310 FERC license	11
	IFR bl Bowman	Canyon Cr.	Bowman Lake	P-2266 FERC license	12
	IFR bl Camp Far West	Bear R	Camp Far West Reservoir		61
	IFR bl Combie	Bear R	Lake Combie	P-2266 FERC license	51
	IFR bl Daguerre Point	Yuba River	Daguerre Point Div. Reservoir	State Water Resources Control Board RD-1644	46
	IFR bl Drum Afterbay	Bear River	Drum Afterbay	P-2310 FERC license	14
	IFR bl Dutch Flat Afterbay	Bear River	Dutch Flat Afterbay	P-2266 FERC license	31
	IFR bl Fordyce	Fordyce Cr.	Lake Fordyce	P-2310 FERC license	11
	IFR bl Jackson Meadows	M Fk Yuba	Jackson Meadows Reservoir	P-2266 FERC license	10
	IFR bl Milton	M Fk Yuba	Milton Div. Reservoir	P-2266 FERC license	11
	IFR bl Narrows at Smartville	Yuba River	Englebright Reservoir	State Water Resources Control Board RD-1644	31
	IFR bl New Bullards Bar	N Fk Yuba	New Bullards Bar Reservoir	P-2246 FERC license	23
	IFR bl Oregon Creek Div	Oregon Cr.	Oregon Creek Div.	P-2246 FERC license	22
	IFR bl Our House	M Fk Yuba	Our House Div. Reservoir	P-2246 FERC license	21
	IFR bl Rollins	Bear R	Rollins Reservoir	P-2266 FERC license	41
	IFR bl Scotts Flat	Deer Cr.	Scotts Flat Reservoir		11
	IFR bl South Canal Inflow	Mormon Ravine	South Canal Inflow	P-2310 FERC license	51
	IFR bl Spaulding at Langs Crossing	S Fk Yuba	Lake Spaulding	P-2310 FERC license	12
	IFR bl Spaulding at Spaulding 2 PH	S Fk Yuba R bl Spaulding	Lake Spaulding	P-2310 FERC license	11

Table 2-12. Conveyance parameters.

Watershed	Conveyance	Max. capacity (ft^3/s)	Watershed	Conveyance	Max. capacity (ft^3/s)
American	Buck Loon Tunnel	1260	Kings	Balch Tunnel	843
	Camino Tunnel	2000		Haas Tunnel	825
	Camp CreekTunnel	500		Helms Aqueduct	2500
	Duncan Tunnel	400		Kings Aqueduct Dinkey Cr. Div.	10
	El Dorado ID Canal	165		Kings River Aqueduct	950
	French Meadows Hell Hole Tunnel	400	Mokelumne	Bear River Div.	85
	Hell Hole Middle Fork Tunnel	920		Bear River Div. Tunnel, Fwd	800
	Jaybird Tunnel	1345		Bear River Div. Tunnel, Rev	800
	Jones Fork Tunnel	287		Cole Creek Div.	N/A
	Long Canyon Creek Tunnel	300		Electra Tunnel	875
	Loon Lake Tunnel	997		Lower Tiger Cr. Div. Tunnel	625
	Ophir Tunnel	N/A		Salt Springs 2 Penstock	225
	Ralston Tunnel	836		Tiger Creek Canal	550
	Robbs Peak Tunnel	1250		West Point Diversion	675
	Rockbound Tunnel	1300	San Joaquin	Balsam Diversion Tunnel	2500
	Sly Park Canal	N/A		Bear Diversion Tunnel	450
	White Rock Tunnel	3500		Big Creek 3 Aqueduct	3250
Feather	Belden Tunnel	2410		Big Creek 4 Aqueduct	3700
	Bucks Diversion	330		Big Creek 8 Penstock	1173
	Butt Valley Tunnel	2118		Browns Creek Ditch	80
	Caribou 1 Penstock	1114		Eastwood Tunnel	2500
	Caribou 2 Penstock	1464		Kerckhoff 1 Tunnel	6500
	Cresta Tunnel	3850		Kerckhoff 2 Tunnel	5100
	Forbestown Diversion	660		Mammoth Pool Tunnel	2500
	Grizzly Forebay Tunnel	360		Mono Tunnel	650
	Grizzly Tunnel	400		No. 1 Conduit	210
	Hamilton Branch	210		No. 2 Conduit	160
	Hendricks Canal	125		No. 3 Conduit	160
	Kanaka Div	37		PH 2A Aqueduct	650
	Kelly Ridge Div	350		Portal Aqueduct	650
	Miners Ranch Canal	300		Portal Penstock	1500
	Poe Aquaduct	3700		Tunnel No. 1	700
	Rock Creek Tunnel	2880		Tunnel No. 2	620
	Slate Cr Tunnel	848		Tunnel No. 7	2439
	South Fork Diversion Tunnel	600		Ward Tunnel	1760
	Upper Moicene Canal	65	Stanislaus	Angels Canal	45
	Woodleaf Diversion	620		Donnells Div	750
Kaweah	Conduit No. 3	97		Lower Collierville Tunnel 1	1475
	Conduit No. 3 Marble Fk	50		Lower Collierville Tunnel 2	1475
	Conduit No. 3 Middle Fk	65		Lower Utica Canal	45
	Kaweah 1 Aqueduct	25		Pheonix Canal	33
	Kaweah 2 Aqueduct	85		Philadelphia Aquaduct	60
Kern	Borel Canal	605		Sand Bar Power Tunnel	600
	Kern Canyon Aqueduct	750		Stanislaus Tunnel	530
	Kern River 3 Aqueduct	590		UPA Tunnel Tap	88
	Kern River Flume	412		Upper Collierville Tunnel	200
	Rio Bravo Canal	1800		Upper Utica Canal	88

Table 2-12 (cont'd…). Conveyance parameters.

Watershed	Conveyance	Max. capacity (ft^3/s)
Tule	Lower Tule R Aqueduct	35
	Upper Tule R Conduit	66
Tuolumne	Canyon Power Tunnel	1500
	Dion R. Holm Tunnel	1000
	Hetch Hetchy Aquaduct	900
	Hetch Hetchy Aquaduct to SF	465
	Lake Eleanor Tunnel	720
	Moccasin Aqueduct	900
Yuba-Bear	Bear River Canal	470
	Bowman Spaulding Conduit	325
	Texas Creek Div.	250
	Camptonville Tunnel	1071
	Chicago Park Flume	1100
	Drum 1 Penstock	360
	Drum 2 Penstock	500
	Drum Bear Div.	N/A
	Drum Canal	840
	Dutch Flat 1	490
	Dutch Flat 2	610
	Lohman Ridge Tunnel	1071
	Lower Boardman Canal	N/A
	Lower Wise Canal	473
	Milton Bowman Tunnel	429
	Narrows 1 Penstock	70
	Narrows 2 Penstock	3490
	New Colgate Tunnel	3800
	South Canal	375
	S. Canal to Mormon Ravine	N/A
	South Yuba Canal	125
	Towle Canal	42
	Upper Wise Canal	488

Chapter 3:
Hydropower Costs of Environmental Flows and Climate Warming in the Upper Yuba River Watershed

Abstract

Understanding the trade-offs between water for the environment and water for hydropower in regulated rivers can inform decision-making about hydropower system planning, policy, and operations, especially with anticipated climate warming-induced flow changes. This study uses a multi-reservoir optimization model to assess the hydropower effects of increasing minimum instream flows (MIFs) and imposing weekly-scale down ramp rates (DRRs) in three locations in California's Upper Yuba River (UYR), which is currently used for hydropower generation, yet has high potential for habitat restoration. Trade-offs between DRRs, MIFs, and hydropower are explored with uniform air temperature increases of 0, 2, 4 and 6 °C to approximate anticipated regional warming through 2100. MIF levels explored range from 5 to 35 ft^3/s (0.14 to 0.99 m^3/s) in one location, and from 3 to 10 ft^3/s (0.08 to 0.28 m^3/s) in two other locations. DRRs range from no limit to a maximum allowable DRR of 25%/week. Under base case operations (without additional MIF or DRR), mean annual hydropower generation increases slightly with near-term (+2 °C) warming and decreases slightly with long-term (+6 °C) warming. The univariate and multivariate impacts on hydropower generation and revenue of imposing MIFs and DRRs are explored. With 6 °C warming, the most ecologically beneficial MIF and DRR reduce hydropower generation by 7.9% and revenue by 5.5% compared to base case operations and a historical climate. This has important implications for re-licensing the Federal Energy Regulatory Commission (FERC) license for the project and other hydropower projects, as qualitative results demonstrate the shape of trade-off curves that can be expected for this and other hydropower projects.

Introduction

Hydropower provides relatively cheap and reliable energy, available on very short notice, often within seconds, adding significant flexibility to an energy portfolio (see Chapter 1). It is also politically attractive as a clean, renewable energy source, useful for climate change mitigation (Kosnik 2008; REN21 2011). However, while beneficial for a power supply system, hydropower systems have many effects on local and regional freshwater ecosystems, caused by a range of specific mechanisms. In particular, hydropower systems modify the natural flow regime of rivers (Poff et al. 1997), which are important for native riverine ecosystems (Lytle and Poff 2004; Poff 2009). Streamflow changes directly affect freshwater ecosystems, but also can have cascading effects in the abiotic domain (e.g., modifying the sediment regime), with subsequent effects on local and regional ecological integrity (Bunn and Arthington 2002; Poff et al. 1997; Renöfält et al. 2010), discussed further below. With the ubiquity of hydropower development (Rosenberg et al. 1997), the ecological effects of hydropower have global scale consequences for freshwater biodiversity (Dynesius and Nilsson 1994; Graf 1999; Graf 2006; Poff et al. 2006; Poff and Hart 2002; Rosenberg et al. 1997; Rosenberg et al. 2000).

Because of hydropower system threats to local freshwater ecosystems and the resulting regional- and global-scale consequences, there have been substantial efforts in the past 20 years to better understand 1) how river regulation generally and hydropower systems in particular affect freshwater ecosystems and 2) how new or existing regulation systems can be modified or operated to improve their environmental performance. To re-operate hydropower facilities for better ecosystem management, however, requires an understanding of the potential trade-offs with traditional hydropower uses. This chapter explores this idea by considering the trade-off between hydropower and environmental flows in the context of a warming climate.

Environmental flows

The components of river's flow regime can be broadly characterized by the magnitude, frequency, duration, timing, and rate of change of flow (Poff et al. 1997; Richter et al. 1996) Many components of the natural flow regime—e.g., small floods, large floods, snowmelt, annual low flow, droughts, etc. (Richter et al. 1996)—have a role in ecosystem maintenance by affecting water quality, energy sources, physical habitat, and biotic interactions (Poff et al. 1997). The flow regime, which is naturally dynamic (Poff 2009; Poff et al. 1997), is important for providing physical habitat, cycling nutrients, providing occasional access to floodplains, temperature regulation, maintaining good quality substrate, and providing species' life cycle behavior cues (Baron et al. 2002; Boulton et al. 2000; Bunn and Arthington 2002; Foxton et al. 2000; Lankford 2003; Poff et al. 1997). River flows also provide recreation opportunities such and boating and fishing (Buzinde et al. 2010; Costanza et al. 1997; Daubert and Young 1981; Ligare et al. 2011) and other ecosystem services (Brown and King 2003; Jewitt 2001; Postel and Carpenter 1997). In California's Sierra Nevada, for example, spring snowmelt flows, with characteristic duration, magnitude and rate of change, are particularly important, as they provides stable and predictable flows during the transition from the abiotic stress of large and unpredictable winter flows and biotic stress (competition and high stream temperature) of low summer flows (Yarnell et al. 2010). Restoring the spring snowmelt recession limb is the motivation for this study, as described below. Bunn and Arthington (2002) and Renöfält et al. (2010) review the effects of alterations to various flow regime mechanisms.

While the flow regime has important direct and indirect effects on stream ecosystems, and hydropower systems often harm ecosystems by altering flow regimes, identifying exactly what flow regime a river should be managed for remains challenging and has been an area of active research. Hydropower and other regulating infrastructure can be managed for "environmental flows", defined as "the water that is left in a river ecosystem, or released into it, for the specific purpose of managing the condition of that ecosystem" (King et al. 2003). This is distinguished from "instream flows", which are any flows in the river, regardless of their purpose (Brown and King 2003). Instream flows that are required by law or regulation are called "instream flow requirements" (IFRs).

Several methods have been used to develop environmental flow regimes to inform specify instream flow requirements. These can range from a simple percentage of mean annual flow to multi-year studies using expert scientific panels (Acreman and Dunbar 2004; Arthington and Zalucki 1998; Brown and King 2003; Jowett 1997; King et al. 2003; King et al. 2000; Stalnaker et al. 1995; Tennant 1976; Tharme 2003). Prescribed flow regimes from these studies can range from a fixed minimum flow requirement to flows that vary by season and annual runoff magnitude. Methods can be organized in a variety of ways. Here we consider methods to be "bottom-up," whereby a flow regime is built up from flow regime components to a regime with desired flow characteristics, or "top-down," whereby a flow regime is defined as an acceptable deviation from natural conditions (Arthington and Zalucki 1998; Tharme 2003).

Bottom-up approaches can be classified as lookup tables, functional analyses, and hydraulic habitat modeling (Acreman and Dunbar 2004). Lookup tables are simple— for example, based on a percentage of mean annual flow—and useful when little streamflow or ecological data is available. The most common lookup table method is the Tennant method (Tennant 1976). In a functional analysis, specific, important flow regime features are mapped to ecological functions and quantified using a variety of techniques. The Building Block Methodology described by King et al. (2000) is a functional analysis approach. As described below, the functional analysis approach was used in the present study, where minimum instream flows and down ramp rates are considered important features of the flow regime. In hydraulic habitat analyses, habitat availability, defined by a physical parameter of the river (e.g., wetted perimeter) is mapped to one or more target species, often for different life stages of the species.

Relationships are then established between flow and habitat availability and, subsequently, habitat suitability. The Instream Flow Incremental Methodology (IFIM) (Bovee 1982; Bovee et al. 1998) has been the most widely used habitat rating analysis method in the United States.

The top-down approach begins with the premise that the natural flow regime (Lytle and Poff 2004; Poff et al. 1997) provides the best flows to support native species, as native species have adapted to the particular variability of a particular river. The top-down approach is referred to as a “desktop analysis” by Acreman and Dunbar (2004). The question in the top-down approach is: how much can the river change from its natural condition before an unacceptable level of ecological deterioration is reached (Bunn 1998; Lytle and Poff 2004; Richter et al. 1997)? This approach is implicit in the Range of Variability Approach of Richter et al. (1997), who use specific metrics—Indicators of Hydrologic Alteration (Richter et al. 1996)—to describe the degree of hydrologic alteration from natural as a result of river regulation. More recently, this is explicit in the development of a regional scale approach—the Ecological Limits of Hydrologic Alteration (ELOHA)—that emphasizes both hydrologic alteration assessments and coupling flow alterations with specific ecological consequences (Poff et al. 2010).

There are many legal and regulatory drivers for environmental flows, which result in prescribed “instream flow requirements” (IFRs), from multiple levels of government with input from the private and public sectors. MacDonnell (2009) reviews environmental flows policy in the United States and Canada, while Viers and Rheinheimer (2011) focus on California. In the United States, non-federal hydropower projects are required to obtain a license from the Federal Energy Regulatory Commission (FERC) to operate, as mandated by the Federal Power Act of 1920, as amended. FERC licenses last from 30-50 years and must be renewed to continue operating. A FERC license specifies operating requirements for the license to remain valid, including any IFRs. Re-licensing typically includes negotiations between project stakeholders to determine operating requirements in the project license or, increasingly commonly, in a settlement agreement that, while not legally part of the license, is agreed to by project stakeholders before the license is issued. Because the conditions of the license (and settlement agreement) sets operational requirements for as long as half a century, the re-licensing process is a critical venue for specifying IFRs and for considering anticipated climate warming effects on hydropower operations (Viers 2011).

While usually necessary for ecosystem maintenance, instream flow requirements decrease the ability of a hydropower operator to operate solely based on energy price, thereby potentially decreasing revenue. A better understanding of the trade-offs between IFRs and hydropower production can help resource managers make better decisions about how to operate existing hydropower systems and what IFRs to include in licenses for hydropower operations. Understanding these trade-offs, which can have long-term management implications, is especially important given anticipated long-term effects of climate warming on runoff magnitude and timing.

This study explores effects of imposing more ecologically beneficial instream flow requirements and climate warming on hydropower generation in the Upper Yuba River in the western Sierra Nevada. Specifically, it quantifies anticipated effects of increasing minimum instream flow (MIF) requirements and imposing a maximum down ramp rate (DRR)—the importance of which are described below—in three locations, with both historical and future climate scenarios. To do this, a multi-reservoir water management model using linear programming was developed to find optimal reservoir operations, with instream flow requirements modeled as soft constraints and climate scenarios represented by results from and external climate-sensitive rainfall-runoff model.

Operating hydropower systems for environmental flows

The ecologically harmful effects of river regulation have increased calls to manage river flows based on the natural flow regime paradigm (Poff et al. 1997) and, specifically, to re-operate reservoirs to more closely match natural flows (Loucks et al. 1999; Richter et al. 2003; Richter and Thomas 2007; Watts et al. 2011). As a result, re-licensed projects are increasingly including more ecologically relevant IFRs. However, newer instream flow requirements still typically only include minimum instream flows, maximum hourly- to daily-scale release ramping rates, and, sometimes, occasional pulse flows for small floods (Jager and Smith 2008). This is due to the complexities of quantifying the natural flow regime, the dearth of knowledge about which deviations from the natural flow regime are acceptable or unacceptable and by how much, and the inherent conflicts between the natural flow regime and non-environmental management objectives. The bottom-up approach, whereby important components of the flow regime are emphasized only once they are deemed important, is the only approach used in hydropower operations found in California's Sierra Nevada. A recent example, and the subject of this study, is the ecological benefit of spring snowmelt recession flows (Yarnell et al. 2010).

Reservoirs can be re-operated in several ways to improve downstream flow conditions for ecosystems (Renöfält et al. 2010; Richter et al. 2003; Richter and Thomas 2007). For example, flows can be re-regulated downstream of dams (Olivares 2008; Richter and Thomas 2007). An afterbay or smaller dam downstream of a major dam can attenuate the effect of rapid changes in flow during peaking operations (Olivares 2008). Other options that expand re-operation possibilities include substituting hydropower peaking facilities with other technologies elsewhere in the power system and switching more hydropower to stable base load, optimizing peaking operations among dams across multiple watersheds, relying more on higher-elevation dams for peaking operations, and improved hydrologic forecasting (Richter and Thomas 2007).

Modeling hydropower systems with environmental considerations

Optimization models can help understand the trade-offs between water for direct human use, such as hydropower, and instream flows used to restore river dependent ecosystems and ecosystem services. Many studies have incorporated environmental releases into hydropower optimization models. Jager and Smith (2008) observe that optimization studies incorporating environmental releases generally consider physical habitat (i.e., as a proxy for other environmental considerations), water quality, and fish populations. Of optimization models that incorporate water releases per se for physical habitat, releases are generally incorporated either as minimum flow constraints or as flow deficits to be minimized. In such models, IFRs are typically MIFs resulting from negotiations among hydropower license stakeholders (Jager and Smith 2008). Some exceptions exist. Sale et al. (1982) and Cardwell et al. (1996) both propose optimization methods to maximize beneficial flow for target species based for a single multipurpose reservoir (Sale et al. 1982) and for streams in general, without a reservoir component (Cardwell et al. 1996) with constraints to meet water resources benefits. The former approach is used here; the goal is to maximize revenue subject to environmental constraints, as hydropower production in de-centralized electricity markets is based on maximizing revenues with IFRs considered as legally mandated releases, with a possibility of violation, rather than primary goals.

Fewer hydropower optimization studies incorporate ramping rate constraints (Jager and Smith 2008), which affect hydropeaking operations. Olivares (2008) studied optimization with hourly ramping rates below a reservoir over twenty-four hours and found that afterbay re-regulation can significantly dampen the loss of hydropower revenues from ramping rate and other constraints. Olivares (2008) devised an analytical approach to estimating the economic effects of minimum instream flow requirements below a variable-head hydropeaking plant, but did not develop a similar analytic method to estimate ramping rate constraints. Pérez-Díaz and Wilhelmi (2010) also included ramping rates below a hydropower reservoir. When considering ramping rate constraints on short-term operations, Pérez-Díaz and Wilhelmi (2010) used an explicit optimization method and observed diminishing marginal economic costs of decreased ramping rate restrictions. In each of these studies, hourly ramping rates are considered rather than the longer time step (weekly) down ramp rates considered here.

Harpman (1999) analyzed the economic costs of environmental flow constraints in addition to minimum flows on hydropower releases from Glen Canyon Dam, again at the hourly scale, and observed that a more complex suite of flow constraints is “outside the capability of most existing [hydropower operations] models.” Kotchen et al. (2006) assessed the economic benefits and costs of dam re-operations for enhanced environmental flows from two hydropower dams and concluded that the environmental benefits significantly exceeded the cost. Jager and Smith (2008) list two other examples (Homa et al. 2005; Shiau and Wu 2004) that focus on optimal flow releases below single dams without hydropower.

Several methods could be used to include snowmelt recession flows in an instream flow requirement scheme. MIFs could be designed to provide enough water each month to restore some aspect of the snowmelt recession, but such an approach would not prevent rapid, step-wise reductions in flow. Imposing strict flow magnitudes at a temporal scale fine enough to sufficiently reconstruct the natural recession limb also would reduce the ability of an operator to flexibly respond to natural variability in inflows. In hydropower licenses that include ramp rate constraints, ramp rates are typically defined at the hourly time step in terms of maximum changes in flow rate magnitudes or as maximum stage changes. The former is operationally simple, but may have undesirable ecological consequences, especially at low flows, when a given absolute change may be a large percent change. By contrast, the latter is overly complex in that it requires substantial field work to establish discharge-stage relationships at multiple locations of interest. Less typically, rates of change have been defined as a percent change in release per time step. For example, the Federal Energy Regulatory Commission (FERC) license for the Yuba River Development Project (YRDP) states:

> i. Project releases or bypasses that increase streamflow downstream of Englebright Dam shall not exceed a rate of change of more than 500 cfs per hour.
>
> ii. Project releases or bypasses that reduce streamflow downstream of Englebright Dam shall be gradual and, over the course of any 24-hour period, shall not be reduced below 70 percent of the prior day's average flow release or bypass flow.
>
> iii. Once the daily project release or bypass level is achieved, fluctuations in the streamflow level downstream of Englebright Dam due to changes in project operations shall not vary up or down by more than 15% of the average daily flow.

These requirements dampen the adverse effects of hydropeaking, causing Englebright Reservoir to act as a re-regulating facility. These general concepts can be applied to help restore spring snowmelt recession flows. Just as the YRDP license requires reductions of no greater than 70 percent of the previous day’s average flow, we can specify maximum weekly reductions in flow. This study applies this concept to management of the Upper Yuba River watershed.

Multi-reservoir hydropower optimization

For multi-reservoir system optimization for hydropower, decisions include how much water to release through and around hydropower turbines and how much to store in each reservoir during each time step. The objective can be to minimize unmet demand, as in a combined hydro-thermal system, or to maximize hydropower revenue. Constraints generally include conservation of mass, minimum and maximum storage, minimum and maximum release, and other constraints, which may be linear or non-linear (Grygier and Stedinger 1985; Labadie 2004; Yeh 1985). In practice, this means maximizing the sum of 1) the present benefit of releasing/storing water during each period from now until T periods into the future and 2) the benefit of leaving $\boldsymbol{s}_T$ water in the reservoir at the end of the planning period. Mathematically, the problem can be stated in this high-level form and in discrete time steps, following Grygier and Stedinger (1985) and Labadie (2004), as:

minimize:

$$Z = \sum_{t=1}^{T} B_t\left(\mathbf{s}_{t-1}, \mathbf{r}_t\right) + B_T^{'}\left(\mathbf{s}_T\right) \tag{0.9}$$

subject to:

$$\mathbf{s}_t = \mathbf{s}_{t-1} + \mathbf{q}_t - \mathbf{r}_t - \mathbf{l}_t + \mathbf{C}\mathbf{r}_t \qquad t = 1, \ldots, T \tag{0.10}$$

$$\mathbf{s}_t^{\min} \le \mathbf{s}_t \le \mathbf{s}_t^{\max} \quad t = 1, \ldots, T \tag{0.11}$$

$$\mathbf{r}_t^{\min} \le \mathbf{r}_t \le \mathbf{r}_t^{\max} \quad t = 1, \ldots, T \tag{0.12}$$

where B is the benefit associated with the storage vector **s** (i.e., the storage vector of all reservoirs in the system) at the beginning of each period (t-1) and the release vector **r** during each period t. $B_T^{'}$ is a function measuring the benefit of leaving $\mathbf{s}_T$ amount of water in storage in the reservoirs after the last step. Equation (3.2) is a mass balance constraint for the system; **l** includes any non-beneficial losses (spill, evaporation, seepage) **C** is the connectivity matrix that identifies the upstream/downstream relationships between reservoirs. $\mathbf{s}_t^{min}$ and $\mathbf{s}_t^{max}$ are upper and lower bounds on the storage available for hydropower generation and $\mathbf{r}_t^{min}$ and $\mathbf{r}_t^{max}$ are the minimum and maximum allowable releases, respectively, either through the turbines (for power generation or spinning reserve) or as spill.

To apply this model, one must 1) define the benefit functions **B** and **B**' for each period (the functions will likely differ for each reservoir); 2) define the minimum and maximum releases ($\mathbf{r}^{\min}$ and $\mathbf{r}^{\max}$) for each period; and 3) determine and apply the best method to solve the problem. For hydropower generation with profit maximization as an objective, the benefit function will typically include electricity price times energy generation and possibly a discount factor for long planning horizons (Grygier and Stedinger 1985; Labadie 2004; Yeh 1985). However, energy generation is a non-linear, non-convex function of storage: potential energy available for energy generation increases non-linearly with storage (Creager and Justin 1927), which poses mathematical and computational challenges, even with advances in computing power. Typically, the constraints are fairly straightforward, although complexities may be introduced by additional constraints, such as environmental and recreational releases (Labadie 2004), as done in this study.

Study area: The Upper Yuba River watershed

High-elevation hydropower reservoirs in the Sierra Nevada typically store water for later diversion to fixed, high-head plants some distance from the reservoir, either downstream or in another watershed. The same water is often diverted several times in a series of hydropower facilities. High elevation reservoirs that store and divert water for high-head energy generation typically reduce instantaneous and annual flows directly below the reservoir—a stretch of river called a “bypass reach”—to a legally mandated minimum instream flow (MIF) requirement, which is often less than minimum natural flows.

The Yuba River watershed, approximately 3,000 km^2, is near the northern end of the western Sierra Nevada, with a centroid of Latitude 39.45°, Longitude -120.84°. The water management system of the Yuba River watershed is unique (e.g., Carron 2000; Harpman 1999; Olivares 2008), but it represents other high-elevation systems in the Sierra Nevada of California and elsewhere (e.g., Snowy Hydro Scheme, Australia). The streams of the Yuba River watershed are managed primarily for hydropower with a complex network of reservoirs, diversions, conveyance facilities, and hydropower plants (Figure 3-1). The watershed averages approximately 7% (2,500 GWh/year) of California's in-state hydropower energy production[1] and about 8% (1.7 MAF) of total annual inflow[2] to the Sacramento-San Joaquin Delta, a major hub of California's water system.

The Yuba River watershed has two major hydropower systems: the Yuba-Bear/Drum-Spaulding (YB/DS) system in the upper portion of the South Fork Yuba (SF Yuba) and the Middle Fork Yuba (MF Yuba) Rivers, collectively called the Upper Yuba River (UYR), and the Yuba River Development Project (YRDP), in the lower Yuba watershed (Figure 3-1). The YB/DS system, the focus of this study, historically produced approximately 1,000 GWh/year from 1983-2001[3], about 3% of California's annual hydropower energy production.

Approximately $160\text{x}10^6$ m^3/year ($130\text{x}10^3$ AF/year) of water is diverted from the Middle Fork and South Fork Yuba Rivers into Lake Spaulding, with energy captured along the way, for release to a cascade of hydropower plants in the Bear River watershed. Other major reservoirs in the greater Yuba River watershed include New Bullards Bar reservoir, which stores water for flood control, water supply, and hydropower along the North Fork Yuba River, and Englebright Reservoir, a legacy reservoir originally for trapping mine tailings.

The YB/DS system captures and diverts water from four large reservoirs and several small ones from the MF Yuba, Canyon Creek (a tributary of the SF Yuba), tributaries of Canyon Creek, and the SF Yuba above Canyon Creek (Figure 3-3). Water not released to meet minimum instream flow requirements or spill in the UYR is diverted via Lake Spaulding to South Yuba Canal for municipal water supply deliveries or to Drum Canal for hydropower in the adjacent Bear River watershed and subsequent low elevation water supply. The four main reservoirs in the UYR system—Jackson Meadows Reservoir on the MF Yuba, Bowman Lake on Canyon Creek, Lake Spaulding on the SF Yuba, and Lake Fordyce on Fordyce Creek above Lake Spaulding—have a combined capacity of 262 TAF, 11 times mean annual runoff into the reservoirs. Of this stored water, 900 cfs, or 27 TAF/year, can be diverted to South Yuba Canal and Drum Canal. Of this 900 cfs, 850 cfs can be diverted to the Bear River via Drum Canal while 200 cfs can be sent to the South Yuba Canal.

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[1] Historical energy generation from the U.S. Energy Information Agency (http://www.eia.gov/cneaf/electricity/page/data.html)

[2] Historical inflows from the California Data Exchange Center (http://cdec.water.ca.gov)

[3] See Footnote 1.

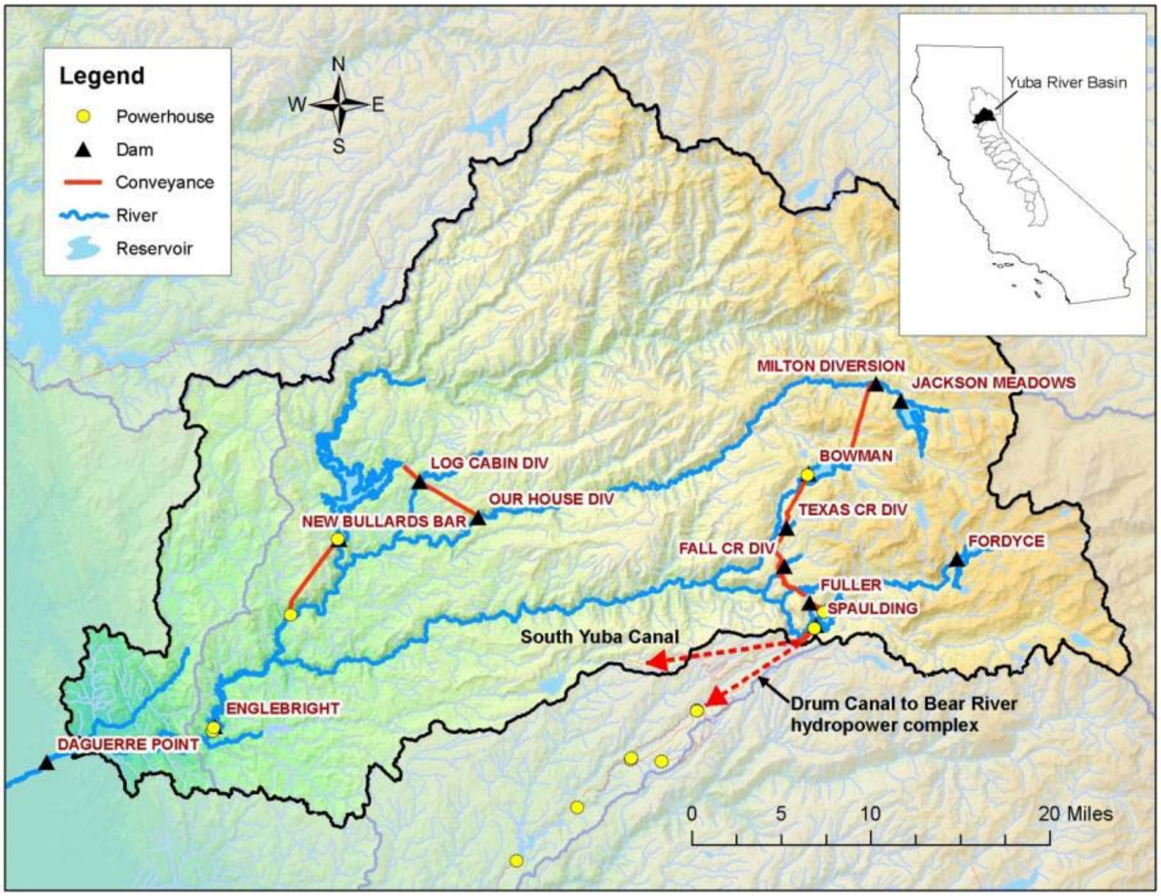

Figure 3-1. Modeled features of the Yuba River basin.

Flow regulation effects in the Yuba River watershed

A particularly important part of the natural flow regime in the upper Sierra Nevada mountains, including the Yuba River watershed, is the spring snowmelt recession limb (Yarnell et al. 2010). Flows during the spring snowmelt period in the Sierra Nevada can be characterized by the rate of decrease in flow rate from one time step to the next. Historical natural mean daily rates of decrease in the western Sierra Nevada typically range from about 10% per day in late-May, roughly the peak of the spring snowmelt period, followed by a steady decrease to about 5% per day or less by late September, the end of the dry season. Weekly rates range from 50% per week during the peak snowmelt period around late-May to about 10% per week toward the end of the dry season. Snowmelt recession flows therefore provide a predictable supply of water between the highly unpredictable, large magnitude winter flood season and the warm, low flow period at the end of summer (Yarnell et al. 2010). In the upper Sierra Nevada, including the Upper Yuba River watershed, spring snowmelt flows are typically eliminated below medium to large reservoirs. Figure 3-2 demonstrates this in the South Fork Yuba River at Langs Crossing below Lake Spaulding. This study focuses on these two effects: decreased flows generally and the elimination of snowmelt recession flows.

River regulation in the Yuba and Bear River watersheds also affect native freshwater ecosystems in other ways. For example, there are substantial flow alterations in the Bear River from hydropeaking. Other general flow effects include inopportune magnitude and timing of flows for recreation (e.g., boating and angling). Downstream, Englebright Dam currently prevents the passage of fall-run Sacramento Valley Chinook salmon (*Oncorhynchus tshawytscha*) into what was once excellent spawning habitat in the upper

Yuba River watershed. Other, smaller barriers prevent further migration into good quality spawning habitat, including Log Cabin and Our House diversion dams (Figure 3-1).

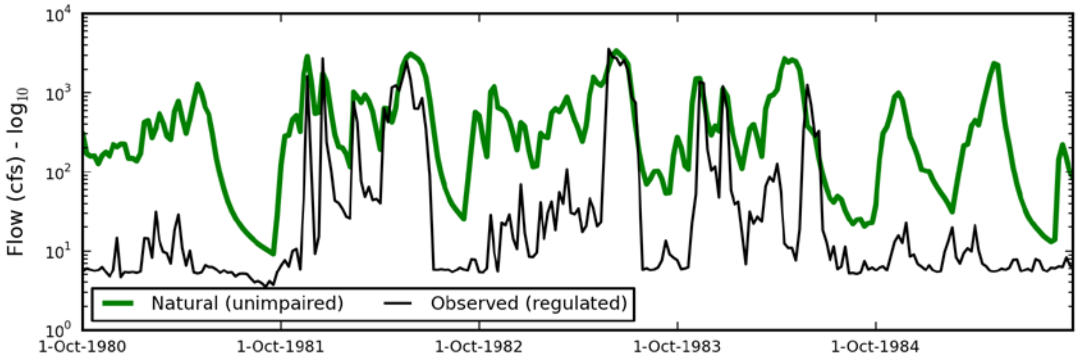

Figure 3-2. Unimpaired and regulated flows in the South Fork Yuba River at Langs Crossing (USGS# 11414250) below Lake Spaulding.

Environmental flow options in the Upper Yuba River

Because of the effects of river regulation, there has recently been considerable effort by a range of non-governmental organizations to modify the system's structure and operations to improve environmental flows. Among many re-operations options to manage the Yuba for freshwater ecosystem services, environmental interest groups have emphasized the importance of improving environmental flow conditions in the Upper Yuba River at three key locations: 1) Middle Fork Yuba River below Milton Diversion Dam, 2) Canyon Creek below Bowman Lake, and 3) South Fork Yuba River below Lake Spaulding (Figure 3-3).

Reservoirs in the Sierra Nevada often have hydropower plants that allow the operator to capture energy from MIF releases. In the UYR, such plants include Bowman powerplant (Bowman Lake) and Spaulding No. 2 powerplant (Lake Spaulding). Spaulding No. 2 powerhouse has a capacity of 200 cfs, substantially larger capacity than the 1 cfs MIF just below Spaulding Dam or the 5 cfs MIF further downstream that was considered in this study. Spaulding No. 2 powerhouse historically generated energy from water supply diversions to the South Yuba Canal. Because diversions via the South Yuba Canal are limited by its capacity of 145 cfs and by actual demand for water supply, there is extra capacity in Spaulding No. 2 powerhouse. The extra capacity can generate energy from water that is not otherwise diverted to the more productive Bear River. Much of the high flow observed in the SF Yuba River below Spaulding (Figure 3-3)—up to 200 cfs—is released from L. Spaulding via Spaulding No. 2 powerhouse. That Spaulding No. 2 has historically unused extra capacity and is above the main IFR location below L. Spaulding has important implications for this study.

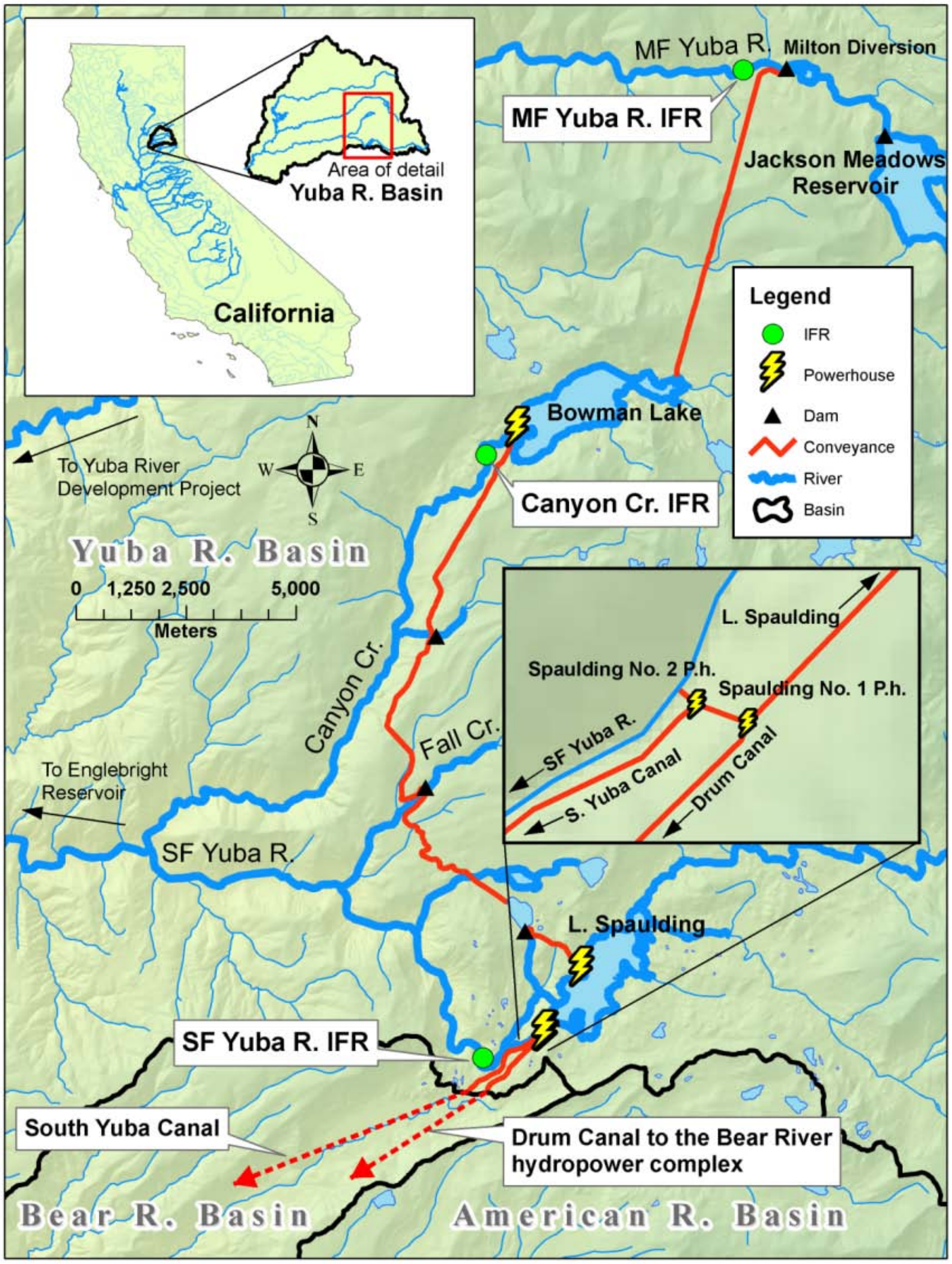

Figure 3-3. Study area with Instream Flow Requirement locations.

Climate warming effects on hydrology and hydropower

California’s climate is expected to warm by 2 to 6 °C over the next 50 to 100 years, reducing snowpack in the Sierra Nevada, with earlier runoff and reduced spring and summer flows (Dettinger et al. 2004; Hayhoe et al. 2004; Zhu et al. 2005). These general climatic and hydrologic changes will cause substantial changes in the timing, magnitude, duration, and frequency of flow conditions in the western Sierra Nevada watersheds (Stewart et al. 2005; Vicuna et al. 2007; Young et al. 2009; Zhu et al. 2005).

Climate warming-induced hydrologic changes also affect long-term hydropower operations planning. Several studies have evaluated the effects of climate warming on California's water resources systems in general and on high-elevation hydropower systems in particular. Tanaka et al. (2006) demonstrated that California's larger water resources systems are generally likely able to adapt to climate changes. Similarly, Vicuna et al. (2010), in a study of the Merced River watershed in the central Sierra Nevada, adaptation strategies, including conjunctive use, can reverse reductions in a watershed's economic benefits that would otherwise occur with warming. Vicuna et al. (2008) studied one watershed in detail (the American River watershed) and concluded that hydropower systems in the Sierra Nevada without enough storage to accommodate changes in run-off will be affected by climate change. How they are affected depends on the new climate. In drier years revenue decreases and in wetter years revenue increases, although generation changes were found to be greater than revenue changes, due to the facilities' abilities to always generate during higher price periods. Madani and Lund (2010) used an energy-based hydropower optimization model (Madani and Lund 2009) of hydropower systems throughout California to similarly show that high-elevation hydropower systems were sensitive to changes in total runoff, but that the systems were flexible enough to minimize revenue losses by storing water for use later in the year when energy was more valuable.

In related work, Mehta et al. (2011) developed a simulation model of the American, Bear and Yuba (ABY) hydropower systems by using historical statistical relationships between weekly hydropower generation and penstock flows by water year type. These historical relationships translated into a significant reduction in annual hydropower generation with climate warming scenarios of +2, 4, and 6 °C (see also Chapter 2).

Though methods have been used to study the potential effects of climate warming on hydropower operations (e.g., Madani and Lund 2010; Vicuna et al. 2009; Vicuna et al. 2008), we found no study that explores the combined effects of instream flow requirements and climate warming on hydropower system performance.

Methods

Most hydropower producers in a market-based energy system seek to maximize revenue. The broad objective of the hydropower optimization model here was therefore to maximize total revenue from energy generation plus additional benefits (e.g., demand) less penalties for unmet IFRs subject to physical and operational constraints. The main decision variables are flows at system locations, which include releases from reservoirs or other diversion points. IFRs include minimum instream flow requirements (MIFs) and maximum down ramp rates (DRRs) at specific locations. This approach fits broadly into the traditional multi-reservoir optimization framework reviewed above and is extended to include rates of change in reservoirs and channels. The method is developed to be solved by linear programming, though other optimization methods could be used.

Assumptions

Assumptions described here directly affect the formulation of the model method. Other relevant assumptions, such climate changes to hydrology, area are described elsewhere as needed.

Hydropower operations – All hydropower plants in the system are assumed to operate in peaking mode, responding to wholesale hourly energy prices. In actual operations, plants used to generate energy from minimum instream flow releases also contribute to base load energy supply; this is represented accurately in optimization models (see, e.g., Olivares 2008). As described below, this requires the use of concave non-linear release-revenue curves to account for diminishing marginal returns for flows at time steps longer than one hour.

Hydropower facility characteristics – Head is assumed constant for each powerhouse. This assumption is generally true for the larger hydropower plants, such as those in the Bear River hydropower complex, most of which are high-head plants. However, power output from smaller reservoirs, such as Bowman powerhouse, is likely more sensitive to head changes in Bowman Lake than assumed here. Generation efficiency and specific weight of water are also assumed constant, although generation efficiency can change under different operating conditions.

Water gains and losses – Water is assumed to enter the system at specified inflow locations and leave at specified outflow locations. Gains from direct precipitation on water bodies and losses from surface water evaporation are small and neglected. Gains and losses from groundwater also are neglected.

Objective function

The objective function is mostly hydropower revenue with penalties for missing water supply delivery targets, unmet instream flow requirements, and spill.

Hydropower revenue – Though broader energy portfolio considerations are important from a strict hydropower operations perspective, impacts of increasingly stringent environmental release requirements and changes in natural runoff patterns are measured by changes in monetary revenue. Therefore, the first goal is to maximize the total revenue π produced over the entire planning horizon of T time steps t and across all N powerhouses ph:

Maximize:

$$z = \sum_{t}^{T} \sum_{ph}^{N} \pi_{t,ph} \tag{0.13}$$

Revenue is a function of energy price times energy generation:

$$\pi_{t,ph} = \overline{p}_t \cdot E_{t,ph} \tag{0.14}$$

where $\overline{p}_t$ is the ‘average’ price per energy unit during time period t and E_t is energy generated during the same time period. Energy is a function of powerplant efficiency (η), head (h), specific weight of water (γ) and flow (Q) through the turbines. If head and the specific weight of water are assumed constant, the power equation is:

$$E_{t,ph} = \eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot Q_{t,ph} \tag{0.15}$$

Here, flow (Q) is in units of total volume per time step t, rather than instantaneous flow. Time periods are typically assumed to be either peaking periods, with high on-peak prices, or non-peaking periods, with low, off-peak prices. In reality, prices vary hourly in much finer gradations. More importantly, price $\overline{p}_t$ depends non-linearly on the percent (θ) released of total plant generating capacity (Q^{max}) during time period t, as discussed by Olivares (2008). Price $\overline{p}_t$ is therefore:

$$\overline{p}_t = \overline{p}_t\left(\theta_t\right) \tag{0.16}$$

where $\theta = Q/Q^{max}$. Equation (3.6) is modified accordingly, with subscripts omitted for brevity, as:

$$\pi = \overline{p}\left(\theta\right) \cdot \eta \cdot h \cdot \gamma \cdot Q \tag{0.17}$$

Since θ is a function of Q and Q^{max}, total per-time step revenue for each powerhouse is generally:

$$\pi = R\left(\eta, h, \gamma, Q, Q^{max}\right) \tag{0.18}$$

where R nonlinear release-revenue curve. Since flow is assumed the only variable, (3.10) is revised to use a normalized release revenue curve:

$$\pi = \eta, h, \gamma \cdot Q^{max} \cdot R\left(\theta = \tfrac{Q}{Q^{max}}\right) \tag{0.19}$$

The normalized revenue curve $R(\theta)$ is developed in a piece-wise linear fashion, as described below, for use in the objective function..

With $Q = Q^{max} \cdot \theta$, the objective function becomes:

$$Z = \sum_{t}\sum_{ph} \eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot R_{t,ph}\left(Q_{t,ph}\right) \tag{0.20}$$

With piece-wise linearization of revenue function R, this becomes:

$$Z = \sum_{t}\sum_{ph}\left(\eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot \sum_{n} m_{t,n} Q_{t,ph,n}\right) \tag{0.21}$$

where m_n is the slope of each release-revenue curve piece or segment (n) and $Q_{ph,n}$ is the flow released over the curve piece.

Objective function additions – Instream flow requirements are typically introduced to multi-reservoir optimization problems as a constraint, where flow in a river channel must exceed a fixed minimum instream flow (Labadie 2004), though have also been included as flow deficits to be minimized (Jager and Smith 2008). As fixed constraints may cause infeasibilities, particularly if inflows are insufficient to meet minimum flow requirements, and to recognize that IFRs are operational (i.e., not physical) constraints, the latter approach is used here. Deviations from desired flow ranges, defined as constraints, are penalized in the objective function.

Though spill generally does not need to be penalized in optimization models, a penalty was needed for spill to the Middle Fork Yuba to prevent the model from spilling from the UYR system to generate hydropower in the downstream Yuba River Development Project. A spill penalty term is therefore included in the objective function, though the penalty incurred is usually zero.

There are additional benefits in the objective function. Water supplied at each demand location (d) has a benefit (B^{supply}). To prevent the reservoir from completely emptying at the end of the time period, it is also necessary to value end-of-period storage (the final condition) with benefit (B^{V_0}).

With additional penalties and benefits included, the objective function becomes:

$$Z = \sum_{t}\sum_{ph}\pi_{t,ph} + \sum_{t}\sum_{d}B_{t,d}^{supply}Q_{t,d} + \sum_{res}B_{res}^{V_f}V_{f,res} + \sum_{t}\sum_{r}\sum_{v}M_{t,r}^{v}Q_{t,r}^{v} \tag{0.22}$$

where M represents a penalty (dollars/unit flow) on flow violation Q^v, which includes unmet instream flow requirements and spill in reach r. Some violations are mutually exclusive (e.g., deficit and excess flows). Penalties have non-zero values only where and when needed.

Physical constraints

Physical constraints consist of general mass balance at each node, inclusive of reservoirs, boundary conditions (inflow hydrology), and infrastructure capacities.

Node mass balance – For a general optimization model with a node-arc configuration (e.g., Labadie 2004), storage (V) in a node at the end of the current time step t is the sum of storage from the last time step $t – 1$ plus flows (Q) into the node less flows out of the node during time step t. Flows into the node include inflows (*in*) from upstream nodes and local gains (*gain*), while flows out of the node include releases (*rel*) to downstream nodes and local losses (*loss*):

$$V_t = V_{t-1} + \sum_{in}\mathbf{C}Q_{t,in} + \sum_{gain}Q_{t,gain} - \sum_{rel}\mathbf{C}Q_{t,rel} - \sum_{loss}Q_{t,loss} \tag{0.23}$$

where **C** is the connectivity matrix specifying the Boolean connectivity between upstream and downstream nodes.

Equation (3.15) generally captures gains from and releases to other nodes via rivers (possible freshwater habitats, or (*hab*), spillways (*sp*), releases (*rel*), and other general channels (*ch*). Here, local gains and losses include boundary inflows (*inflow*), demand (*dem*) and outflow (*out*). Other local gains and losses, such as evaporative losses from reservoirs and groundwater fluxes, are omitted, as they are very small in the study area relative to surface water flows.

Inflow – Inflow Q_{inflow} is explicitly defined with boundary inflow I:

$$Q_{t,inflow} = I_t \tag{0.24}$$

Storage – Storage V in reservoirs is constrained by minimum and maximum storage capacities. Any excess storage is lost as spill.

$$V_{t,res} \le V_{t,res}^{max} \tag{0.25}$$

$$V_{t,res} \ge V_{res}^{min} \tag{0.26}$$

When $t = 1$:

$$V_{t-1,res} = V_{0,res} = V_{res}^{init} \tag{0.27}$$

Channel capacities – Artificial conduits, which include powerhouse turbines (*ph*), open and closed channels (*ch*), and non-hydropower release conduits (*rel*), each have a maximum carrying capacity:

$$Q_{t,ph} \le Q_{ph}^{max} \tag{0.28}$$

$$Q_{t,ch} \le Q_{ch}^{max} \tag{0.29}$$

$$Q_{t,rel} \le Q_{rel}^{max} \tag{0.30}$$

These are segregated here for comprehension, though there is no mathematical differentiation among these conduit types in model implementation.

Operational constraints

Operational constraints are used to model management requirements not constrained by physical system characteristics. Here, operational constraints include environmental flow goals, including bounds on absolute and relative releases, and water supply deliveries.

Two types of constraints for environmental flows are considered, based on ecological considerations discussed above: minimum instream flows and maximum down ramp rates. Collectively, these are instream flow requirements. IFRs are modeled with constraints that have flow deficits, which are penalized in the objective function. The constraint for MIFs is:

$$Q_{t,hab} + Q_{t,hab}^{deficit} \ge Q_{t,hab}^{min} \tag{0.31}$$

where Q^{min} is the MIF requirement and $Q^{deficit}$ is the unmet flow requirement, or the flow deficit. The DRR constraint is:

$$Q_{t,hab} + Q_{t,hab}^{down} \ge \left(1 + \Delta_{t,hab}^{down}\right) Q_{t-1,hab}; \forall t > 1 \tag{0.32}$$

where Δ^{down} is the maximum down ramp rate expressed as a percent change in total weekly flow and Q^{down} is the DRR flow deficit.

The latter two constraints are methodologically the most important for the model and application described here, since they were used to describe and impose any environmental requirements. Additional environmental requirements could include a maximum flow requirement and maximum up ramp rate during each time step.

Reservoirs often have maximum rates of change, often due to recreation or structural requirements that water levels do not change too quickly. To account for this, a maximum rate of decrease (V^{down}) is included:

$$\Delta V_t = V_{t-1} - V_t \le V_t^{down} \tag{0.33}$$

Water supply demand is specified as a maximum constraint:

$$Q_{t,dem} \le D_t \tag{0.34}$$

where D is demand and Q is delivery. Demand is valued in the objective function with a real monetary benefit, thus allowing the model to realistically balance releases for multiple uses. A benefit greater than hydropower, but lower than instream flow deficit penalties, ensures that supply demand is met, but not at the expense of instream flows.

Release-revenue curves

Hydropower plants with peaking operations typically generate energy during hours when energy prices are highest. Since prices within a week vary, total revenue from releasing less than maximum capacity during a multi-hour time period will vary with release due to diminishing marginal value of energy. This is represented by the generic non-linear release-revenue function $R(\theta)$ included in (3.11). Though the value of energy as a function of flow can be calculated analytically (Olivares 2008), linearized release-revenue curves are well suited for use in linear programming.

Release-revenue curves for time steps greater than one hour can be created numerically by optimizing releases with specified release constraints over a week given hourly price data. The objective of the optimization problem is:

$$\text{maximize: } z_T = R_T = \sum_{t=1}^{T} B_t\left(Q_t\right) \tag{0.35}$$

where R_T is the total revenue from time t=1 to T, B is benefit from flow Q_t during hour t. Benefits are summed over T hours (i.e., T = 168 if optimizing for hourly releases over a week). For a high-elevation, fixed head powerhouse, benefit B is:

$$B_t\left(Q_t\right) = \eta \cdot \gamma \cdot h \cdot Q_t \cdot P_t \tag{0.36}$$

where η is generation efficiency, γ is specific weight of water, h_t is head and P_t is price. Generation efficiency, specific weight of water, and head are assumed constant. The objective function to maximize becomes:

$$z = \sum_{t=1}^{T} B_t\left(Q_t\right) = \eta \cdot \gamma \cdot h \cdot \sum_{t}^{T} Q_t P_t \tag{0.37}$$

To make the model independent of a particular powerhouse, η, γ, and h are removed from (3.29) and reintroduced after the release-revenue curves are developed. The optimization problem, with constraints, becomes:
maximize:

$$z = \sum_{t=1}^{T} Q_t P_t \tag{0.38}$$

subject to:

$$Q_t \le C \tag{0.39}$$

$$\sum_{t} Q_t \le V_{total} \tag{0.40}$$

where C is the release capacity and V_{total} is the volumetric release capacity over the entire period (i.e., t = 1 through T).
With C = 1, and V_{total} constant, optimal revenue is easily found. A release-revenue curve can then be developed by optimizing for revenue with varying levels of V_{total}. To use the release-revenue curves for a specific hydropower facility, the curves need to be scaled by the maximum capacity of the facility. The scaled curve would then give revenue generated for any given volumetric release, expressed as a percent of release capacity.

These curves could be generated more simply, either numerically from price distribution data over the time period of interest or analytically as described by Olivares (2008). One advantage of the method used in this study is an option to including ramp rate constraints below hydropower plants in future applications. Ramp rate constraints from a hydropower plant cannot be incorporated into release-revenue curves analytically as Olivares (2008) does for minimum instream flows, as optimal releases with ramp rates depend on the energy price time series, and not simply energy price distribution.

Model application

The method was applied to the Yuba River watershed using linear programming, though other optimization techniques could be used. The Upper Yuba River watershed was the focal study area (Figure 3-3). Though the model includes the downstream Yuba River Development Project, which includes the large, multipurpose New Bullards Bar Reservoir, the YRDP does not affect UYR operations. The Yuba River watershed model uses weekly time steps with historical climate and climate change scenarios spanning 1980-2000 (20 years). The model optimizes with perfect foresight over a one year time period, with initial conditions in each year carried over from year to year. In this Chapter, English units for flow are used (1 $m^3/s = 35.3\ ft^3/s$ (cfs)).

To assess the effects of climate warming with instream flow requirements, model parameters were changed as listed in Table 3-1. Table 3-2 lists the constant parameters required for the model application. The following sections describe each change dimension (climate change, MIF, and DRR) and constant parameters used.

Table 3-1. Variable parameters.

Change dimension	**Variable parameter**	**Symbol**	**Units**	**Eqn.**
Climate warming	Boundary inflow	I_t	L^3T^{-1}	(3.16)
Minimum stream flow	Minimum instream flow	$Q_{t,hab}^{min}$	L^3T^{-1}	(3.23)
Down ramp rate	Maximum down ramp rate	$\Delta_{t,hab}^{down}$	%	(3.24)

Table 3-2. Constant parameters.

Constant parameter	**Symbol**	**Units**	**Equation**
Powerhouse head	h_{ph}	L	(3.13)
Powerhouse efficiency	η	%	(3.13)
Value of turbine flow (energy prices)	$m_{t,n}$	$\$/[L^3T^{-1}]$	(3.13)
Unmet flow requirement penalties	$M_{t,r}^{v} = M_{t,r}^{Q^{deficit}}$	$\$/[L^3T^{-1}]$	(3.14)
Spill penalties	$M_{t,r}^{v} = M_{t,r}^{Q^{spill}}$	$\$/[L^3T^{-1}]$	(3.14)
Water supply demand	D_t	L^3T^{-1}	(3.26)
Water supply benefit	$B_{t,d}^{supply}$	$\$/[L^3T^{-1}]$	(3.14)
Powerhouse turbine flow capacity	Q_{ph}^{max}	L^3T^{-1}	(3.20)
Channel capacity	Q_{ch}^{max}	L^3T^{-1}	(3.21)
Reservoir release capacity	Q_{rel}^{max}	L^3T^{-1}	(3.22)
Maximum reservoir capacity	$V_{t,res}^{max}$	L^3	(3.17)
Minimum reservoir capacity	V_{res}^{min}	L^3	(3.18)
Initial reservoir storage	V_{res}^{init}	L^3	(3.19)
Maximum reservoir rate of change	V_{t}^{down}	L^3	(3.25)
End-of-period storage benefit	$B_{res}^{V_f}$	$\$/[L^3]$	(3.14)

Because the rates of decrease for snowmelt are both predictable and last for several months, the weekly time step is well suited for use in a model that considers the natural snowmelt recession flows. Therefore, this study uses a weekly time step.

Climate warming scenarios: Inflow hydrology

To assess the effects of climate warming, this study focuses on changes to inflows. It is likely, however, that several other management and physical elements will also be affected by climate warming, such as water supply demand, energy demand (as reflected in prices), and evaporation.

This study uses weekly inflow hydrology changes anticipated with uniform air temperature increases of +0, 2, 4, and 6 °C, as considered by Young et al. (2009). Young et al. (2009) developed a weekly time step rainfall-runoff model of the western Sierra Nevada, calibrated to the major basin outlets, using WEAP (Yates et al. 2005). Young et al. (2009) intersected subwatersheds—defined by points of management interest—with 250-m elevation bands to create “catchments” with spatially homogeneous physical characteristics and meteorological conditions. Young et al. (2009) applied the rainfall-runoff model assuming uniform air temperature increments of +0, 2, 4, and 6 °C, consistent with general predicted increases in temperature from downscaled global climate models (GCMs) through 2100 (e.g., Hayhoe et al. 2004). These air temperature change levels are considered to represent, respectively, historical, near-term, mid-term, and long-term warming. Young et al. (2009) did not vary precipitation, as there is no broad consensus among downscaled GCM results about whether regional precipitation will increase or decrease (Dettinger 2005), though there are indications of a drier climate (Dettinger 2005; Hayhoe et al. 2004).

Since the results reported by Young et al. (2009) were calibrated for flows at the watershed outlets, additional calibration was required for subwatersheds above the IFR locations in this study. Shallow and deep soil water capacities were adjusted to calibrate flows in the South Fork Yuba River to match, as closely as possible, reconstructed unimpaired flows developed for use during the FERC relicensing process for UYR hydropower projects (unpublished data from DTA | HDR, 2009). The recalibrated flows from Young et al. (2009), as used in this study, generally matched the shape of the reconstructed unimpaired flows, though slightly overestimate low summer flows. Total mean annual modeled unimpaired inflow to the three main reservoirs in the UYR was 3.5% less than the reconstructed unimpaired flows.

The effect of climate warming on mean weekly total unimpaired inflow to the UYR system is shown in Figure 3-4. With a historical climate, unimpaired runoff is dominated by snowmelt. With warming, however, earlier precipitation-driven events dominate. These trends reflect anticipated changes for the Sierra Nevada generally (Young et al. 2009).

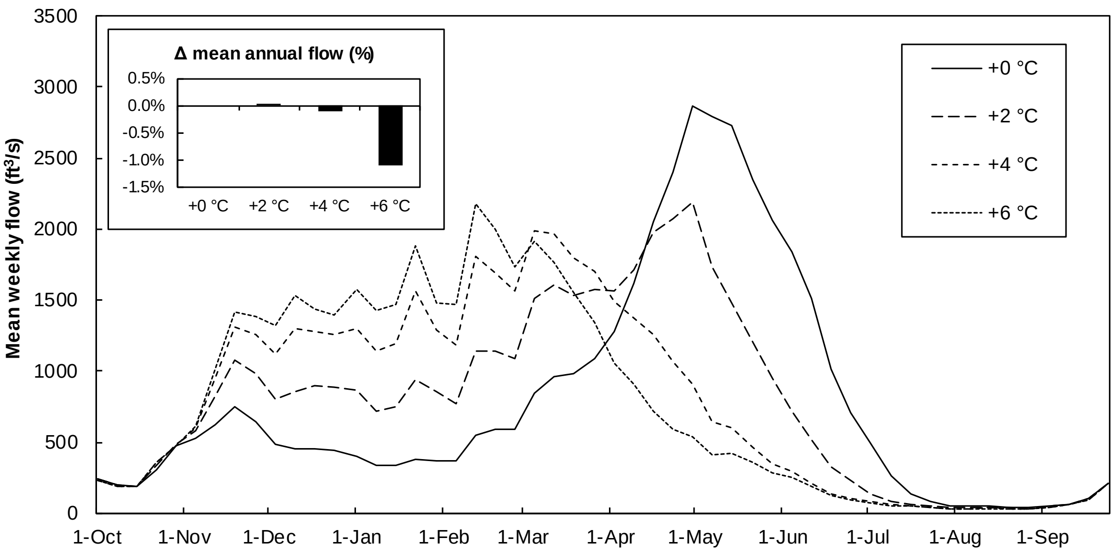

Figure 3-4. Total mean weekly unimpaired flows into the UYR hydropower system.

Management scenarios

Instream flow requirement (IFR) scenarios were developed to assess the hydropower costs of a range of environmental flow conditions for the following three locations (Figure 3-1):

- Middle Fork Yuba River (MF Yuba R.) below Milton Diversion
- Canyon Creek (Canyon Cr.) below Bowman Dam
- South Fork Yuba River and Langs Crossing (SF Yuba R.) below Spaulding Dam

First, a Base Case (BC) scenario was developed to compare the model with historical operations. Second, a range of IFR scenarios were developed to understand the relative effects of imposing a higher minimum instream flow (MIF) and more stringent down ramp rates (DRR) at each location. At each location, scenarios consisting of combinations of MIF and DRR levels were applied, concurrently. A base MIF was developed similar to the Base Case MIF, though with a seasonally uniform MIF. A subsequent range of MIFs represent successive increments of 25% of the additional MIF above the base MIF, up to a maximum MIF. Similarly, DRR levels were set in decrements of 25%/week, from 100%/week (no constraint) to 25%/week. The MIF and DRR levels were combined to create 20 scenarios in addition to the Base Case scenario. The development of BC parameters and MIF and DRR scenarios are described below, with MIF and DRR levels listed Tables 4 and 5, respectively.

Base Case (BC) instream flow requirements

Existing IFRs consist of minimum instream flow requirements at the three locations identified above (Figure 3-1). MIFs range from 2 cfs in the winter in Canyon Creek to 5 cfs year-round in the South Fork Yuba River (Table 3-3).

Table 3-3. Existing minimum instream flow requirements in the Upper Yuba River watershed.

Location	Mean natural flow	Existing MIF requirement	Percent of mean natural flow	Time of year	Source
MF Yuba	149 cfs	3 cfs	2.0%	year-round	P-2266 license
Canyon Creek	128 cfs	3 cfs 2 cfs	2.1%	4/1 to 10/31 11/1 to 3/31	P-2266 license
SF Yuba	502 cfs	5 cfs	1.0%	year-round	P-2310 license

Table 3-3 shows minimum instream flow requirements as a percent of the natural mean annual flow in each river, based on the calibrated runoff used in this study. Thus, 1.0 to 2.1% of mean natural flows at these locations are specifically allocated to the environment. Existing MIFs are fixed requirements; they do not vary seasonally or by water year type. Existing MIFs are thus minimal and do not attempt to mimic any component of the natural flow regime (sensu Poff et al. 1997) other than to meet legal requirements to provide some water for fish (e.g., California Fish & Game Code 5937). There are currently no DRR requirements in the UYR. The MIFs listed in Table 3-3 are used in the Base Case scenario.

Minimum instream flow requirements

Minimum instream flows, which represent one component of the natural flow regime, are assumed to provide essential habitat during the critical summer period, when flows are already naturally low and demand for water for hydropower is greatest. In this study, the MIF levels were set to range between the historical MIF and a new high MIF, set above mean weekly flows during the low flow period based on the inflow dataset for with a historical climate. Mean weekly flows during the low flow period are higher than the mean minimum flows. Thus, MIFs range from ecologically stressful (very low) to ecologically protective (high). The maximum MIFs used were 35 cfs for the SF Yuba and 10 cfs for both the MF Yuba and Canyon Creek. The maximum MIFs represent increases of 600% for the SF Yuba and over 200% for the MF Yuba and Canyon Creek. Though in practice newer MIFs often change by water year type and by month/season, in this study MIFs are assumed constant. MIFs imposed are summarized in Table 3-4.

Table 3-4. Minimum Instream Flow (MIF) scenarios.

MIF scenario (% of additional MIF)	Minimum Instream Flow (cfs)		
	SF Yuba	Canyon	MF Yuba
BC (0%)	5.0	2.0 / 3.0	2.0
0%	5.0	3.0	3.0
25%	12.5	4.75	4.75
50%	20.0	6.5	6.5
75%	27.5	8.25	8.25
100%	35.0	10.0	10.0

Maximum down ramp rate requirements

Epke (2011) noted that flow decreases during the snowmelt period can be quantified as a percent change in flow from the previous time step. This observation was applied in this study by imposing a maximum down ramp rate defined in percentage terms. This approach is both operational simple, as it is easily calculated (Epke 2011), and is ecologically beneficial (Yarnell et al. 2010).

Historical rates of decrease in the study region were used to develop a range of increasingly stringent maximum down ramp rate requirements. In the UYR, mean natural down ramp rates are about 30% at each IFR location from the last week in May through the last week in September, the end of the water year (Figure 3-5) and do not vary substantially by water year type. An ecologically protective 25%/week DRR was used to bind the range of DRR levels. The DRR levels applied therefore ranged from 100%/week allowable DRR to 25%/week allowable maximum DRR, with decrements of 25% (Table 3-5). A DRR of 100% means there is no DRR requirement. Though one could vary the down ramp rate during the snowmelt period to reflect observed variability in natural rates of change, this would likely add little value ecologically, as freshwater ecosystems depend on gradual decreases in spring flows generally rather than specific down ramp rates (S. Yarnell, *pers. comm.*).

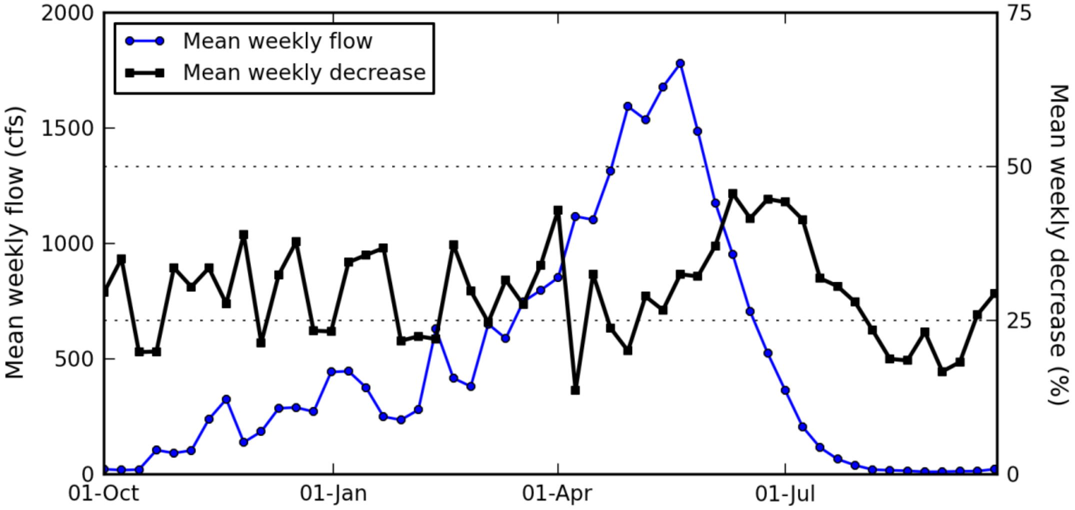

Figure 3-5. Historical mean weekly flow and flow decrease in the South Fork Yuba River at Langs Crossing (1976-2004).

Table 3-5. Maximum Down Ramp Rate (DRR) scenarios.

DRR scenario (%/week)	Down Ramp Rate (% weekly change) SF Yuba	 Canyon	 MF Yuba
BC (100%)	100	100	100
100%	100	100	100
75%	75	75	75
50%	50	50	50
25%	25	25	25

Fixed parameters

Fixed infrastructure parameter values were from publicly available documents, government data, common assumptions, and basic model calibration. Here, the fixed parameters needed in the model application are described.

Powerplant characteristics

Powerplant head and maximum turbine flow capacities were obtained from public Federal Energy Regulatory Commission (FERC) license documents, from US Geological Survey (USGS) flow gage data, and from other third party documents. Constant generating efficiency of 90% and water density of 1000 kg/m^3 were assumed. Powerplant characteristics are included in Table 3-6.

Table 3-6. Upper Yuba River powerhouse characteristics (1 ft = 0.3048 m).

Powerhouse	Fixed head (ft)	Flow capacity (cfs)	Efficiency (%)
Bear River composite	3,140	840	90
Spaulding No. 1	197	550	90
Spaulding No. 2	200	200	90
Spaulding No. 3	330	270	90
Bowman	315	313	90

Bear River hydropower complex

Representation of the Bear River hydropower complex posed a unique challenge, since modeling every hydropower plant in the Bear River watershed was beyond the scope of this work. The Bear River system was modeled as a single composite powerplant with a characteristic head and generating efficiency, supplied with flows via Drum Canal. This was based on the observation that hydropower plants in the Bear River watershed generally operate simultaneously, resulting in a linear relationship between flows diverted to the Bear River via Drum Canal and mean flow through ten powerhouses in the Bear River watershed that use water diverted through Drum Canal.[4]

Using the built-in optimization solver in Microsoft Excel, the composite Bear River powerhouse head was calibrated to achieve a slope of unity for the linear regression between historical energy generation[5] for the real Bear River hydropower complex and generation from the single composite powerhouse using historical Drum Canal flows. The calibration was performed using weekly Drum Canal flows from Jan. 1, 1987 to Sep. 30, 2008, the only period during which flow data was available for most powerhouses. Energy comparisons were at the seasonal scale, as historical energy production was reported monthly. Calibration results are shown in Figure 3-6. Years 1999 and 2000 were excluded from the calibration, as there was no energy reported for two powerhouses (Halsey and Newcastle) during that period. This method resulted in a composite Bear River powerplant head of 957 m (3,140 ft.).

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[4] Powerhouses in the Bear River include: Drum 1, Drum 2, Alta, Dutch Flat 1, Dutch Flat 2, Chicago Park, Rollins, Halsey, Wise, and Newcastle.

[5] Historical generation from the U.S. Energy Information Agency: http://www.eia.gov/cneaf/electricity/page/data.html

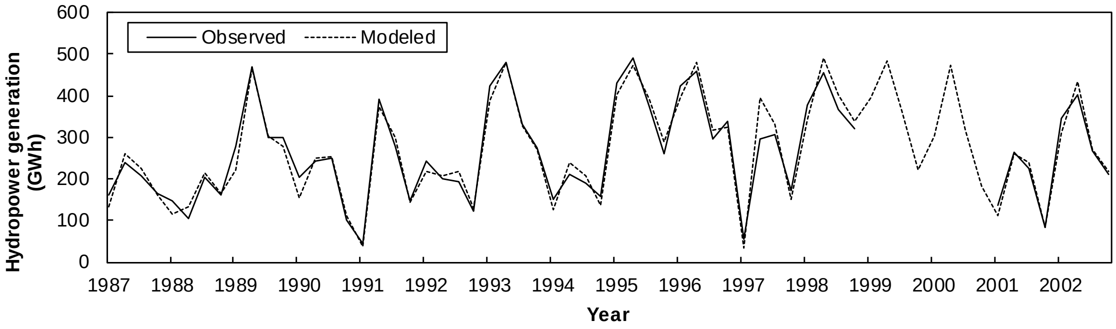


Figure 3-6: Mean seasonal hydropower generation from historical observed energy output from ten real powerhouses (observed) and from historical flows through the composite Bear River powerhouse (modeled).

Energy prices

Hourly energy prices are available from 1998 through 2003 from the University of California Energy Institute (UC Berkeley 2010) and from 2005 through 2008 from the California Independent System Operator (California ISO 2010). Prices from calendar year 2007 were chosen as the most representative year, with no major price anomalies, based on a visual assessment of available energy prices. Energy price data from 2007 was used to develop the non-linear release-revenue curves and linearized curve piece slopes, as described above. Further work is needed to develop a representative long-term time series based on the available record of hourly prices or other means.

Unmet instream flow requirement penalties

Setting costs or penalties for unmet instream flow requirements is important to ensure that IFRs are met. The value of flow through the Bear River hydropower complex is approximately $110/cfs-hour during hours when energy prices are highest ($400/MWh). Therefore, any penalty used to ensure UYR IFRs are met must be above $110/cfs-hour. Penalty magnitudes above this value are arbitrary and meaningful only relative to other unmet IFR penalties, spill penalties, and water supply demand benefit. Penalties of $500/cfs-hour and $250/cfs-hour were assigned for unmet MIFs and DRRs, respectively.

Spill penalties

Spill is excess water released directly into the river below a reservoir, unable to be captured for use. Reservoir optimization models generally avoid spill to maximize benefit from hydropower revenue and other beneficial uses. Releases to meet IFRs are not considered spill. Though the model generally avoids spill, which has an opportunity cost, a penalty was assigned to spill from Milton Dam, the diversion dam for Bowman Spaulding Conduit, which conveys water to Bowman L. and L. Spaulding (Figure 3-1). This penalty was required to prevent the model from releasing water from Milton Reservoir to the downstream Yuba River Development Project's (YRDP) New Bullards Bar Reservoir and Colgate powerhouse via Our House diversion dam on the MF Yuba River. Since the UYR and YRDP systems operate independently, only natural flows or real spill from Milton Reservoir is diverted to YRDP. Though it might be economically optimal to supplement the YRDP with additional releases from Milton Reservoir, the YRDP is already lucrative for its owner, the Yuba County Water Agency; additional water would add little additional value.

Water supply demand and unmet supply penalty

Water supply demands for the towns of Grass Valley and Nevada City via the South Yuba Canal (Figure 3-1) were developed by assuming a linear relationship between the Sacramento Valley Water Year Index (WYI) and weekly demand, the same method used in Chapter 2. The Sacramento Valley WYI is a supraregional index that, when converted to discrete water year types, is used for water supply planning in California and is a proxy measurement for relative annual water availability. Weekly WYI-demand relationships were determined using flow data for historical period of Oct. 1, 1969 to Sep. 30, 2009 (Water Years 1970-2009). This method, termed the Water Year Index method (see Chapter 2), generally worked well on average across all water year types —Wet, Above Normal, Below Normal, Dry, and Critical—when applied using the twenty years of simulated runoff used in the model (Figure 3-7). Year types with greater representation in the historical record (e.g., Critical and Wet years) showed a better relationship between observed mean weekly flow and modeled mean weekly flow than year types with lesser representation (e.g., Above Normal years). No Below Normal years were present during the model period.

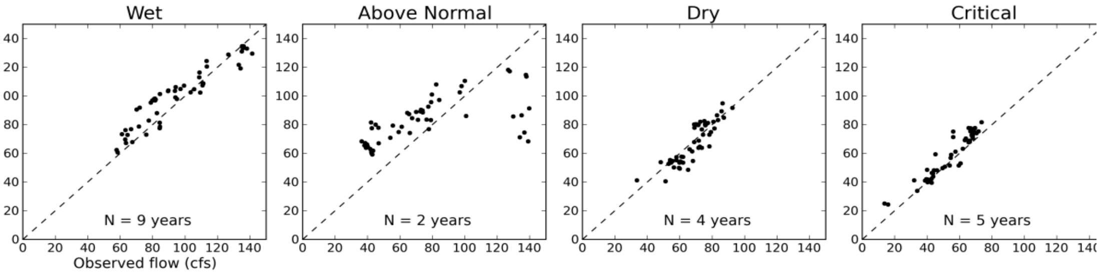


Figure 3-7. Observed and modeled mean weekly supply demand using the Water Year Index method.

As with IFRs, a penalty is used to minimize water shortages. An unmet supply penalty of $150/cfs-hour was used to ensure water supply had a higher value than hydropower, but a lower priority than IFRs.

Reservoir characteristics

Reservoir characteristics include minimum and maximum storage, maximum weekly rates of change in storage, and carryover storage value, summarized in Table 3-7. Maximum storage values were obtained from USGS annual water survey reports for each reservoir included in the model. Though the survey reports often identify minimum storage values, reservoir levels are typically kept above reported values; minimum storage values are based on visual inspection of observed data.

The 5% non-exceedance values of observed absolute weekly decreases for each reservoir during the model period (WY1981-2000) were used as the maximum storage decrease for each respective reservoir. In the smaller Upper Yuba River reservoirs, these values ranged from 3.9 TAF/week (Bowman L.) to 6.2 TAF/week (L. Spaulding) (Table 3-7).

Approximate carryover (end-of-year) storage values were determined during calibration by trial-and-error. Carryover storage in the three main UYR reservoirs is sensitive to both absolute carryover storage values and relative values between the reservoirs. Carryover storage is more valuable in Bowman and Jackson Meadows than in Spaulding, since they can be used to produce hydropower in one additional powerhouse (Spaulding No. 3) in addition to subsequent powerhouses below L. Spaulding. Lund (2000) discusses relative storage priorities analytically for development of operating rules and notes that storage should generally be prioritized for reservoirs with highest potential energy, such as higher reservoirs in a cascade for reservoirs in series, to minimize energy spill.

For reservoirs in the Upper Yuba River, carryover storage values of $150/AF for L. Spaulding, $170/AF for each of Jackson Meadows Reservoir and Bowman L.—no energy is captured between the latter two—resulted in mean carryover storage within 15 TAF of the historical mean for the study period. End-of-year storage is not valued in L. Fordyce, which supplies L. Spaulding without an intermediate powerhouse.

By comparison, New Bullards Bar Reservoir (Figure 3-8) had a storage value of $65/AF. Additional work is needed to identify storage values at different storage volumes and to incorporate this information into the linear programming model.

Table 3-7. Upper Yuba River reservoir characteristics.

Reservoir	Minimum storage (TAF)	Maximum storage (TAF)	Max. rate of storage change (TAF/week)	Carryover storage value ($/TAF)
L. Spaulding	5.0	74.7	6.2	150
Fordyce L.	5.0	49.9	6.0	0
Bowman L.	20.0	68.5	3.9	170
Jackson Meadows Res.	20.0	69.2	4.2	170

Implementation

The optimization model was implemented with linear programming (LP) using the General Algebraic Modeling System (GAMS) and the CONOPT3 LP solver. The water system structure and system parameterization (e.g., conveyance capacities, fixed hydropower head, turbine efficiencies, etc.) were created and organized with HydroPlatform. HydroPlatform is an open-source software package that allows the modeler to segregate water system configuration and data management from modeling and analysis (Harou et al. 2010). System configuration data—node/arc definitions and the connectivity matrix—was exported from HydroPlatform to the GAMS-based model using an intermediary Microsoft Excel workbook. Figure 3-8 shows the schematic representation of the entire Yuba River watershed optimization model in HydroPlatform.

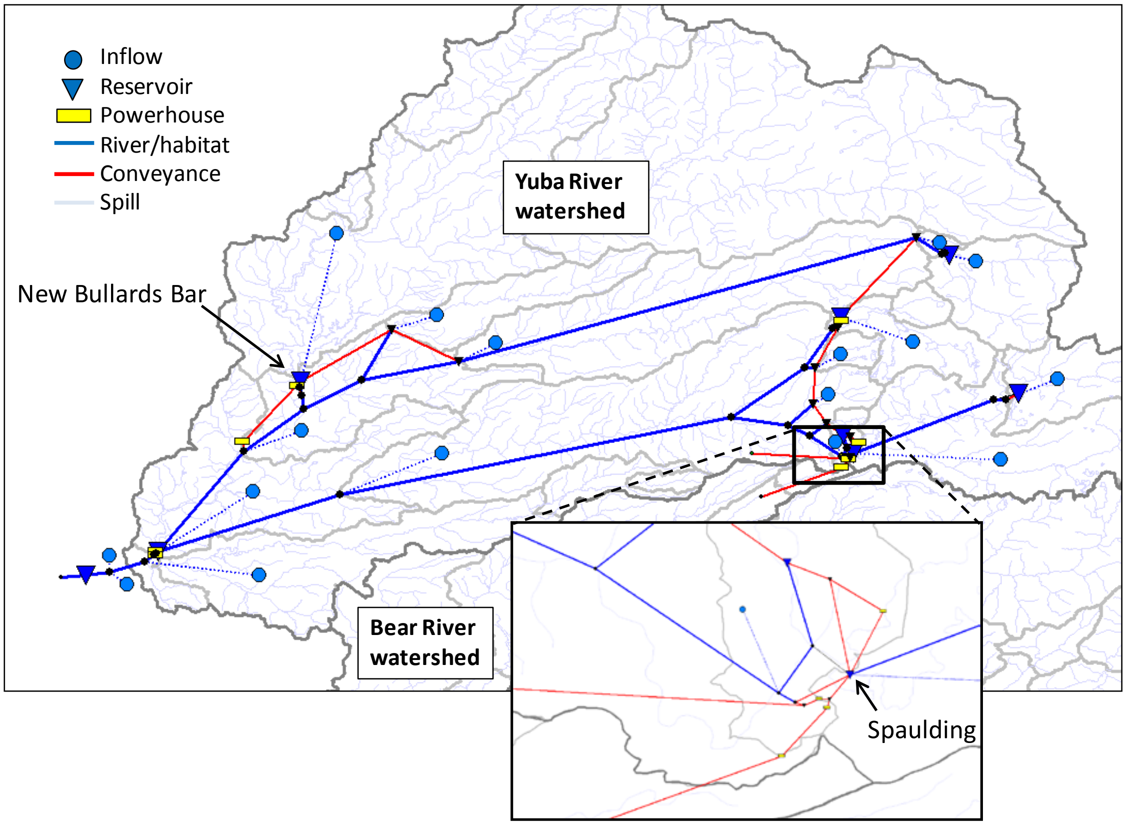


Figure 3-8. Yuba River Watershed optimization model schematic in HydroPlatform.

Results and discussion

Model results for the base case are compared with observations to indicate how well the model corresponds with historical observations. Model corroboration is followed by an analysis of model results with warming, emphasizing specific economic trade-offs among alternative management scenarios with no warming and with warming.

Model corroboration

To ensure the model generally behaved as expected, model results are compared with historical (base case) management and climate scenarios. Comparisons are limited to hydropower flow, hydropower generation, streamflow in the three locations of management interest, and reservoir storage.

Hydropower turbine flow

Optimized mean weekly flows through Drum Canal and, consequently, the composite Bear River Powerhouse, generally match historical observations on average across all years (Figure 3-9). The historical mean for WY1981-2000 was 518 cfs, whereas the modeled mean is 566 cfs, almost 9% higher than historical. Using energy prices from a single, carefully selected year (2007) appears to be sufficient for modeling historical operations. Modeled hydropower generation for plants directly affected by releases from the Upper Yuba River watershed were compared to observed values for water years 1983-2000 and found to be consistent with flow trends of Figure 3-9.

The model also represents observed operations accurately at the weekly scale (Figure 3-10). The model releases at discrete levels due to the piece-wise linearization of the non-linear release-revenue curves. A smooth non-linear release-revenue curve, or a linearized curve with a greater number of discretizations than used in this study, would give a finer gradation in weekly releases. By contrast, completely excluding non-linear, diminishing marginal returns on weekly energy production would result in releases of either 100% (on) or zero percent (off) at the weekly scale. Thus, including piece-wise linearized release-revenue curves, as in this study, is an effective way of representing weekly-scale hydropower production.

Historical reductions in flows at the end of the year (Figure 3-10) are likely due to annual maintenance, as noted above. Though this reduction is not forced in the model, Figure 3-10 shows that in many years it is optimal to reduce flow around the beginning/end of the water year, and thus the best time to take the system offline for maintenance.

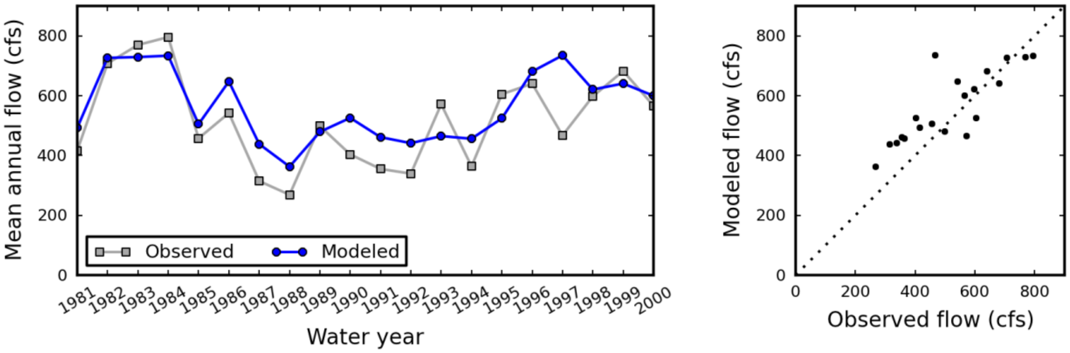


Figure 3-9. Observed and modeled mean annual flows in Drum Canal.

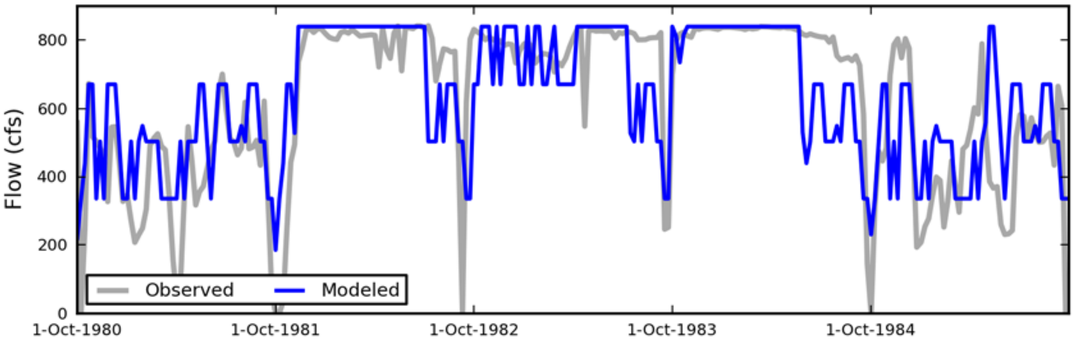


Figure 3-10. Observed and modeled weekly flows in Drum Canal for WY 1981-1985.

Streamflow

The model also captures dominant mean historical streamflow patterns in the Upper Yuba River (Figure 3-11). Modeled mean weekly flow in MF Yuba R. and SF Yuba R. are generally well modeled at the weekly and annual scale, though high flows in the SF Yuba River are not always present in the optimization model. Model discrepancies arise mostly from differences between modeled and observed runoff. The rainfall-runoff model (Young et al. 2009) was calibrated to the basin outlet, not for specific subwatersheds. Discrepancies are also caused by inherent differences between real operations and an optimization model, which has perfect seasonal foresight. For example, the model had perfect foresight of a major flood in 1997, resulting in modeled hydropower generation much higher than what was observed (Figure 3-9) for that year. More importantly, the model produces the major regulated flow regime features of interest here, the rapid curtailment of high spring snowmelt flows, resulting in the complete elimination of the spring snowmelt recession limb, and a substantial reduction in flow magnitudes.

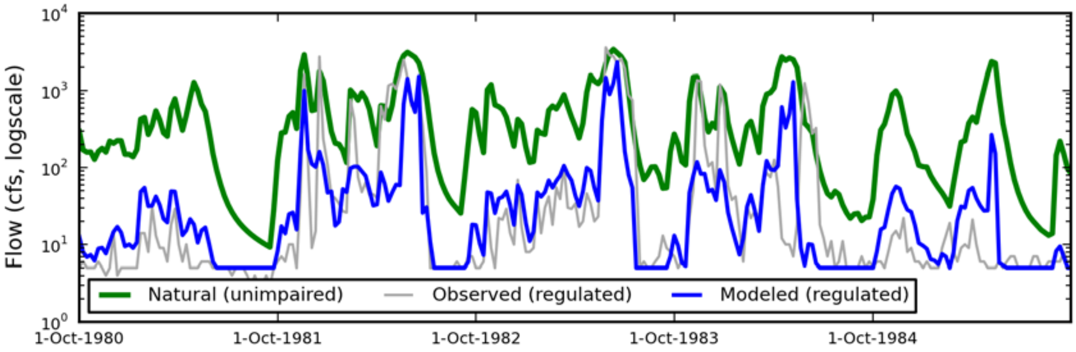


Figure 3-11. Unimpaired and regulated flows in the South Fork Yuba River.

<u>Reservoir storage</u>

The model operates reservoirs in the Upper Yuba River in a similar pattern to historical operations (Figure 3-12); however, on average the model keeps the reservoirs emptier during the spring and early summer than observed storage. This is due to the omission of the requirement to keep reservoir levels constant during some periods for recreation.

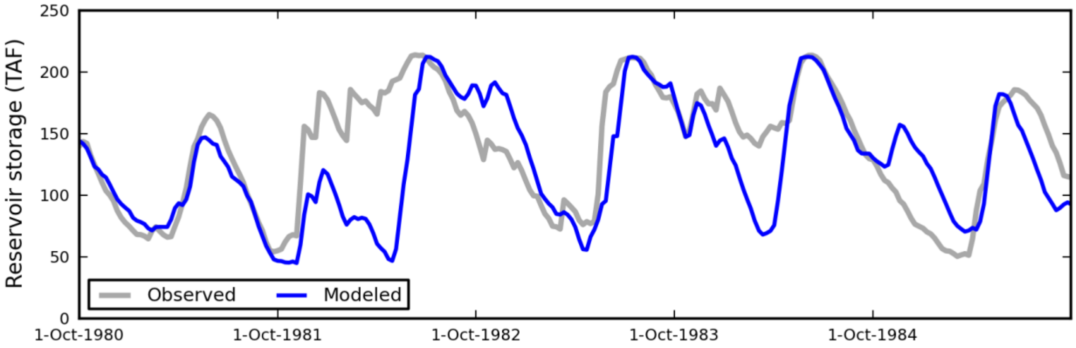


Figure 3-12. Observed and modeled mean weekly reservoir storage in the Upper Yuba River (WY 1981-2000), including L. Spaulding, Bowman L., and Jackson Meadows Reservoir.

Warming and IFR effects on regulated streamflow

In all warming scenarios, the model effectively ensures that instream flow requirements—MIFs and DRRs—are met. This is demonstrated in Figure 3-13 for flows in the South Fork Yuba River for Water Years 1984-85. Results are similar for the Middle Fork Yuba River and Canyon Creek. With no warming, a higher MIF causes releases to be just above unimpaired low flows. With far-term warming (+6 °C) unimpaired flows decrease, yet the MIF requirement ensures that regulated flows do not decrease. The MIF does not, however, ensure that high winter and spring flows are released, which could be ecologically important.

The DRR requirement restores a simplified recession limb that resembles the natural (unimpaired) recession limb in each location. With a warmer climate, which generally reduces snowmelt runoff, the model does not ensure that the timing of the down ramp period remains during the spring. Collectively, the new IFRs as applied result in the maintenance of one feature of the spring snowmelt recession limb—relatively stable, if decreasing, flows—but do not maintain the historically high spring flows.

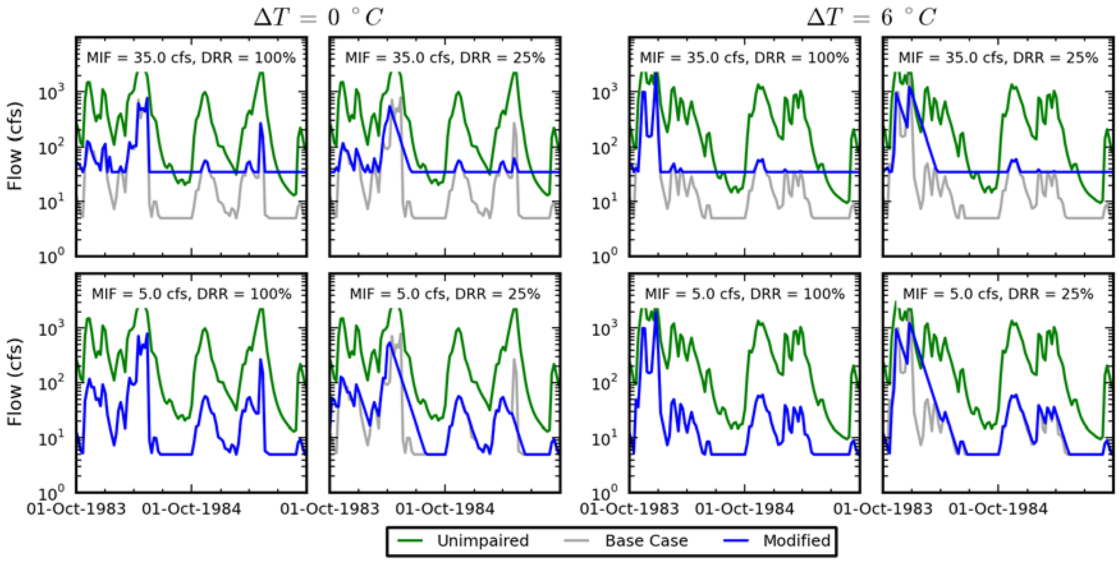


Figure 3-13. Effect of MIF and maximum DRR on regulated flows in the SF Yuba River at Langs Crossing for Water Years 1984-85; DRR units in %/week.

To understand how climate affects hydropower generation and revenue, it is important to understand how spill changes with warming. With no change in IFR, spill decreases with all warming scenarios, with substantially more spill reduction in the near term (Figure 3-14). This change in spill pattern is related directly to the change in unimpaired inflow patterns (Figure 3-4). Figure 3-4 and Figure 3-14 combined show that with no warming, spill generally occurs from high snowmelt flows in late spring, whereas with 6 °C warming, most spill occurs during high, precipitation-driven events during the winter. However, even though winter runoff is greater with 6 °C warming, there is less total runoff than with no warming, resulting in a net reduction in spill. With lesser warming, both snowmelt-driven spill and precipitation-driven spill are less than these two extremes, resulting in an overall reduction in spill. The system-wide changes reflect most changes in each reservoir. However, Lake Spaulding appears to be most sensitive to changes in runoff timing, with a substantial decrease in spill with 2 °C warming, yet a slight increase in spill with 6 °C warming, as shown in Figure 3-15. The similarity in spill changes between Jackson Meadows Reservoir and Bowman L. reflects that they are operated in coordination with each other, almost as one reservoir.

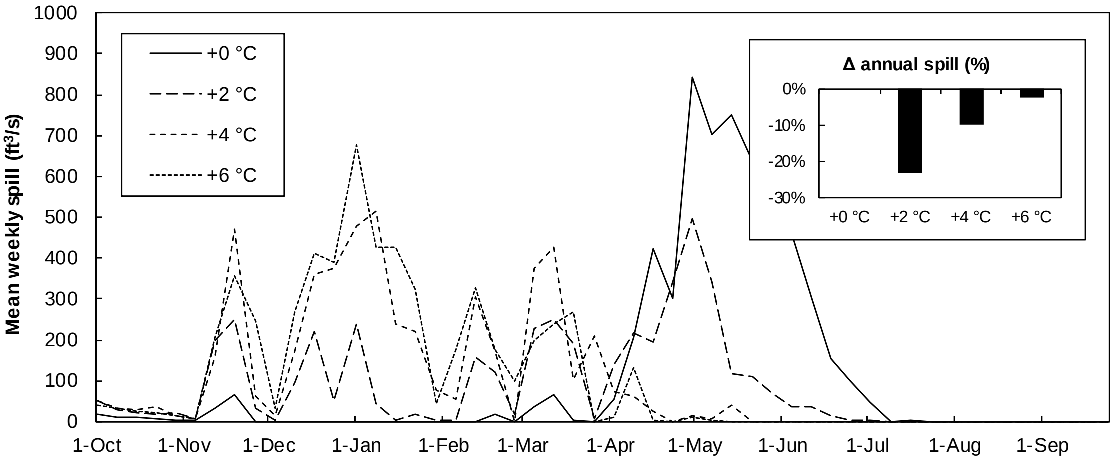


Figure 3-14. Total weekly spill and relative change in spill (inset) from Jackson Meadows Reservoir, Bowman L., and L. Spaulding with Base Case management and climate warming.

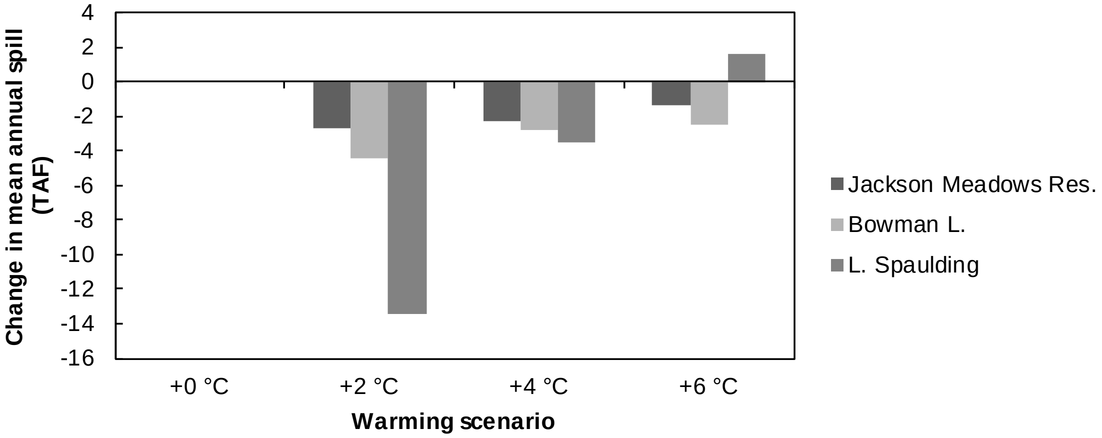


Figure 3-15. Change in mean annual spill from the three main Upper Yuba River reservoirs with warming compared to a historical climate.

Warming and IFR effects on hydropower generation and revenue

The effects warming and instream flow requirements on hydropower generation and revenue can be described in many ways. Here, the relative univariate effects of each of these dimensions are first presented, followed by the combined effects of all dimensions.

Univariate effects

The effects of changing each variable are considered. Warming, MIF, and DRR levels are explored first. Figure 3-16 shows the absolute and relative effects of changes in warming, MIF levels and DRR levels individually on hydropower generation and revenue.

Climate warming effects – Climate warming increases mean hydropower generation and revenue with near term warming. With 2 and 4 °C warming, mean generation and revenue both increase slightly relative to the historical climate. With 2 °C warming, for example, mean hydropower generation and revenue increase, respectively, by 3.3% (48 GWh/year) and 2.2% ($2.0M/year) with base case management, though actual annual changes are higher or lower than zero, with median generation and revenue changes of zero. Only with 6 °C warming do mean generation and revenue decrease, by 1.5% (22 GWh/year) and 1.0% ($0.9M/year), respectively. Relative changes in revenue are consistently less than changes in generation, due to decreasing marginal revenue on flow; any change in weekly hydropower turbine flow affects generation during hours with lowest energy prices.

Though these results are location specific, long-term relative changes are comparable to results reported in other studies. For example, Madani and Lund (2010) estimated a 1.3% decrease in hydropower generation in the western Sierra Nevada assuming warming only, with no change in total annual runoff. In a study of the Upper American River Project, about 50 km (30 miles) southeast of the UYR region, Vicuna et al. (2008) estimated generation changes of between –13%, with a drier end-of-century climate scenario, and +14%, with a wetter scenario.

Increased mean hydropower generation and revenue with 2 and 4 °C warming is caused by two features of the changing flow regime. First, inflows in the Middle Fork Yuba and Canyon Creek increase with near- and mid-term warming, which offsets reductions in inflow in the South Fork Yuba. Second, warming in this and other watersheds (see Chapter 2) creates a more uniform distribution of inflows within the year (Figure 3-4), which reduces spill (Figure 3-14). Though these trends are broadly applicable, specific changes in any given year or year type depend on both the magnitude and timing of changes in inflow, such that some years have much less generation and revenue while other years have substantial increases.

IFR effects – In contrast to the high variability in changes in generation with warming, changes in both MIFs and DRRs consistently decrease hydropower generation and revenue. Both MIFs and DRRs constrain hydropower operations, necessarily causing releases for purposes other than hydropower generation, often at times suboptimal for hydropower generation.

With an increase in additional MIF of 100% (i.e., MIFs at each location are increased to the most ecologically beneficial levels, as identified in Table 3-4), mean annual hydropower generation and revenue decrease by 3.8% (56 GWh/year) and 3.0% ($2.7M/year), respectively. Imposing a maximum DRR to restore the spring snowmelt recession limb affects generation and revenue less than increasing minimum instream flow requirements. With a historical climate, a maximum allowable down ramp rate of 25%/week decreases mean annual generation and revenue by 2.2% (33 GWh/year) and 1.5% ($1.3M/year). As with changes due to warming, revenue decreases less than generation.

More ecologically protective IFRs reduce flow diversions to the Bear River hydropower complex. The existence of Spaulding No. 2 powerhouse, which can generate energy from water released from L. Spaulding to meet downstream water supply and IFR needs, can compensate for some loss in revenue. With maximum MIFs at each location, mean releases to Drum Canal decrease by 23 cfs (4%), while mean releases to SF Yuba via Spaulding No. 2 increase by 15 cfs, resulting in a 17% increase in Spaulding No. 2 flows, with the difference released at the other locations. For these changes in flow, mean annual Bear River generation decreases by about 53 GWh/year (4%), while mean annual Spaulding No. 2 generation increases by a much smaller 2 GWh/year (17%). The disproportionate magnitude loss in the Bear River compared to gains in Spaulding No. 2 is due to the energy capacity differences. Because of these differences, there is a limited ability to capture additional energy from water released into the South Fork Yuba. Additional hydropower capacity at Bowman Dam (Canyon Creek) and Milton Diversion Dam (Middle Fork Yuba) might be able to offset losses in the Bear River, but likely only by a small amount.

Figure 3-16 also shows that the cost of increasing MIFs increases linearly, whereas the cost of imposing a DRR increases nonlinearly, with increasing marginal costs of a DRR. MIFs and DRRs both impose release requirements, but in fundamentally different ways. A MIF simply reduces the total amount of water available for generation in the optimal location and time; the operator still has flexibility to operate for the most valuable peaking. With a higher MIF, the operator will reduce production during hours when energy prices are lowest. A higher MIF is akin to removing water from one part of the system. This is consistent with the results of others who focused solely on climate change impacts (Madani and Lund 2010; Vicuna et al. 2009) and observed that total water availability is the primary variable affecting hydropower generation. However, an ever more stringent DRR changes the flexibility of the operator to operate in peaking mode. In the extreme, a maximum down ramp rate of zero would completely eliminate hydropower system flexibility, resulting in *de facto* base load operations. As the DRR becomes more stringent, the operator has less flexibility to both avoid reduced production when energy prices are low and high production when energy prices are high, resulting in a nonlinear tradeoff between DRR level and generation/revenue.

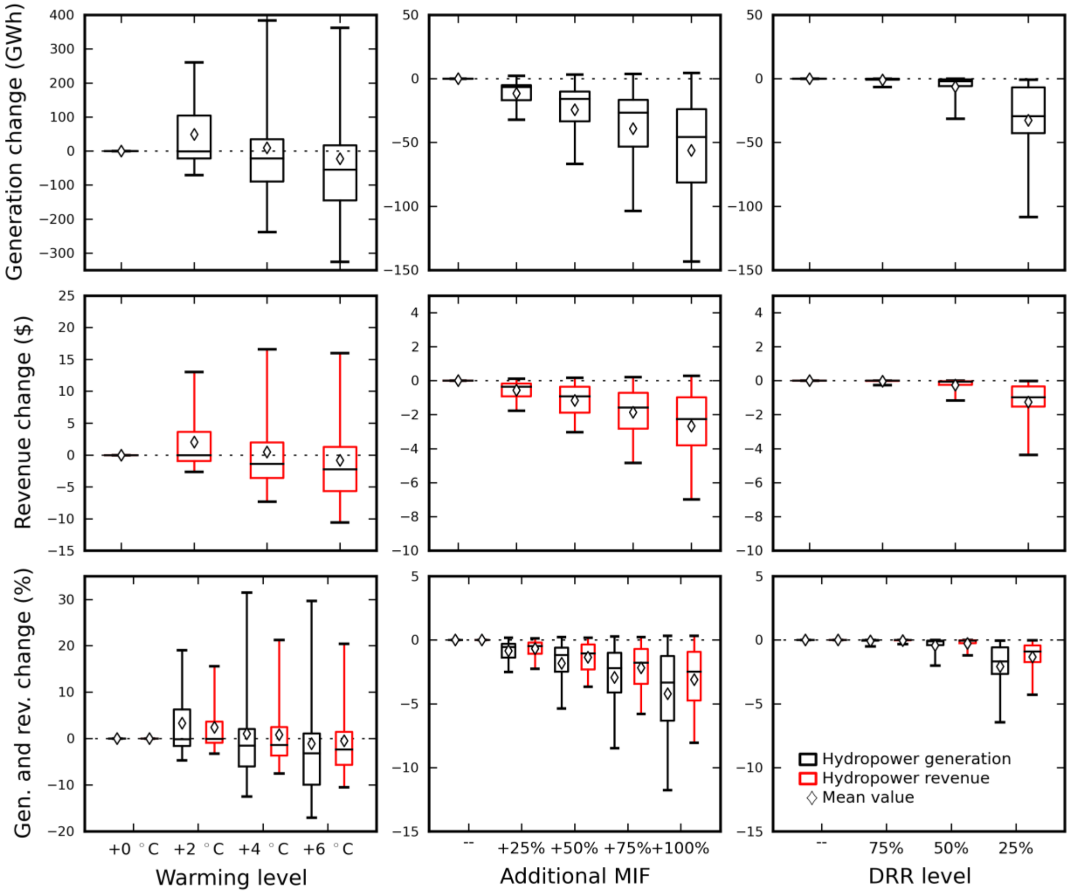
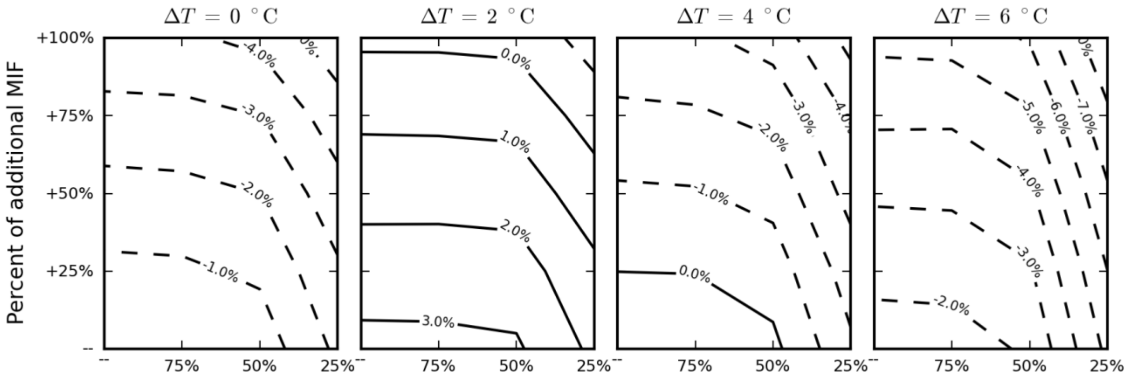


Figure 3-16. Absolute hydropower generation (top) and revenue (middle) and relative changes in generation and revenue from Base Case (bottom) with univariate changes in mean temperature (left), minimum instream flow requirement (center), and maximum down ramp rate requirement (right). Boxplots show annual level quartiles; diamonds show mean annual levels. DRR units are %/week.

Multivariate effects

The combined effects of warming and more stringent IFRs are important and a fundamental driver for this study. Figure 3-17 summarizes modeled changes in mean annual hydropower generation and revenue in the UYR, relative to a historical climate and management, with warming and multiple MIF and DRR levels. The curves in Figure 3-17 show trade-offs for different climates and revenue levels. For example, if the hydropower operator would only accept a 2% decrease in revenue, they should be willing to implement a 25%/week down ramp rate with no increase in MIF, or an MIF of approximately 60% of the additional proposed MIF levels with no DRR, or somewhere in between. As with no additional IFR (Figure 3-16), mean annual generation and revenue generally increase in the near term (+2 °C) under most MIF/DRR combinations.

a) Hydropower Generation change



b) Hydropower Revenue change

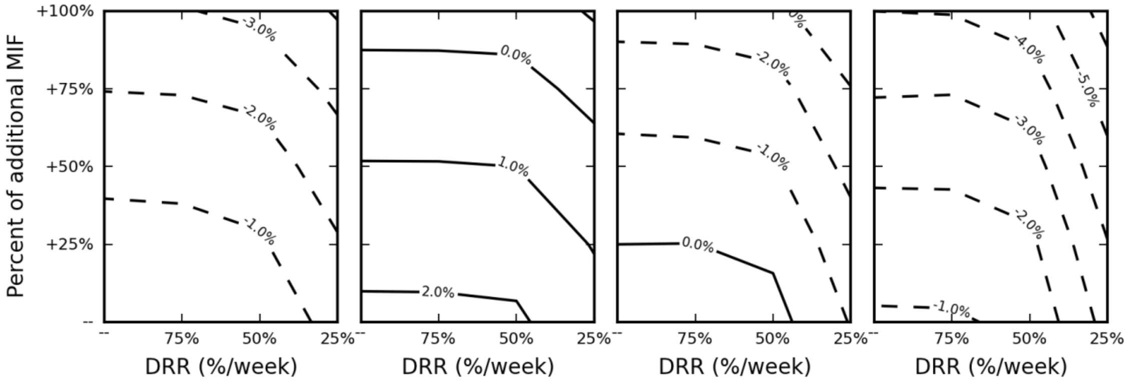


Figure 3-17. Combined effects of warming, MIF, and DRR on mean annual hydropower generation and revenue.

It is useful to explore the extreme points in Figure 3-17, which show changes in generation and revenue with combinations of no or full MIF and DRR levels, with warming. The values of these points are listed in Table 3-8 for generation and revenue and plotted in Figure 3-18 for revenue only. With no warming, a high MIF and more stringent DRR cause a 4.1% reduction in revenue. With 2 °C warming (near-term) the cost of the MIF and DRR is only 1.1%, on average, whereas by 6 °C warming the cost is 6.4%.

Table 3-8. Change in mean annual *hydropower generation and revenue* with warming compared to historical climate and management.

	Generation change (%)				**Revenue change (%)**			
Warming **Scenario**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**

No DRR or MIF	0	3.3	0.7	-1.5	0	2.2	0.5	-0.9
+DRR	-2.2	1.8	-1.8	-5.2	-1.4	1.4	-1.1	-3.3
+MIF	-3.8	-0.2	-2.8	-5.3	-2.9	-0.4	-2.4	-4.0
+DRR, MIF	-5.6	-1.5	-5.3	-8.9	-4.1	-1.1	-4.0	-6.4

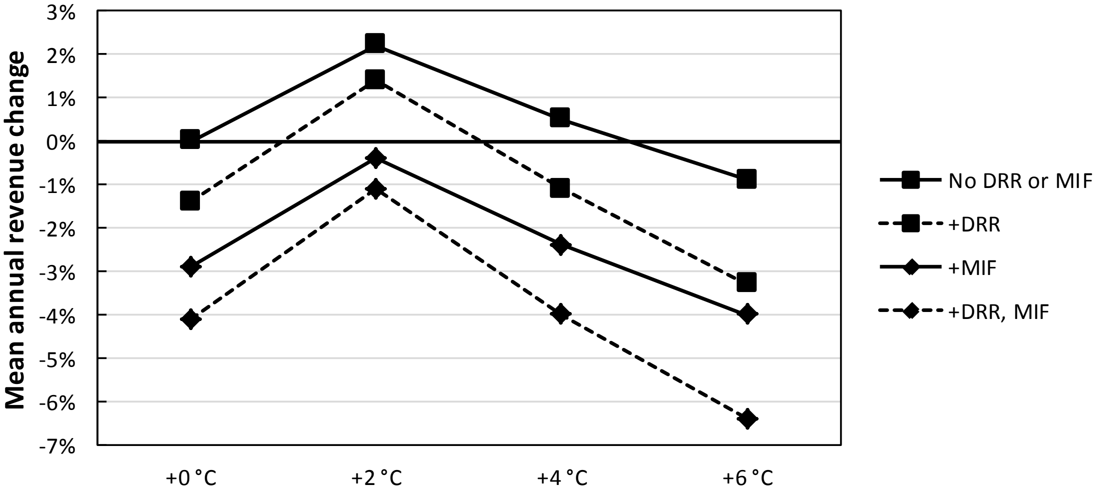


Figure 3-18. Change in hydropower revenue with Base Case (BC) management, a DRR of 25%, additional MIF of +100% and both a DRR and MIFs.

If warming is uncontrollable, from a management perspective, it might also be useful to know how much of the cost—in generation or revenue—can be attributed specifically to the new IFRs. These isolated costs, derived directly from Table 3-8, are listed in Table 3-9 (generation and revenue) and plotted in Figure 3-19 (revenue only). Thus, values plotted in Figure 3-19 are the difference between the lower three lines and the upper line in Figure 3-18. The marginal cost of increasing minimum instream flow requirements is relatively constant compared to the marginal cost of a down ramp rate. This is consistent with the univariate responses to MIF and DRR changes discussed above. The marginal effects of MIFs and DRRs are also apparent in Figure 3-18, where costs appear mostly linear with additional MIF compared to a DRR.

Table 3-9. Change in mean annual *hydropower generation and revenue* with warming compared to historical climate and management due to new IFR.

	Generation change (%)				**Revenue change (%)**			
Warming / **Scenario**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**
+DRR	-2.2	-1.5	-2.5	-3.7	-1.4	-0.8	-1.6	-2.4
+MIF	-3.8	-3.5	-3.5	-3.8	-2.9	-2.6	-2.9	-3.1
+DRR, MIF	-5.6	-4.8	-6.0	-7.4	-4.1	-3.3	-4.5	-5.5

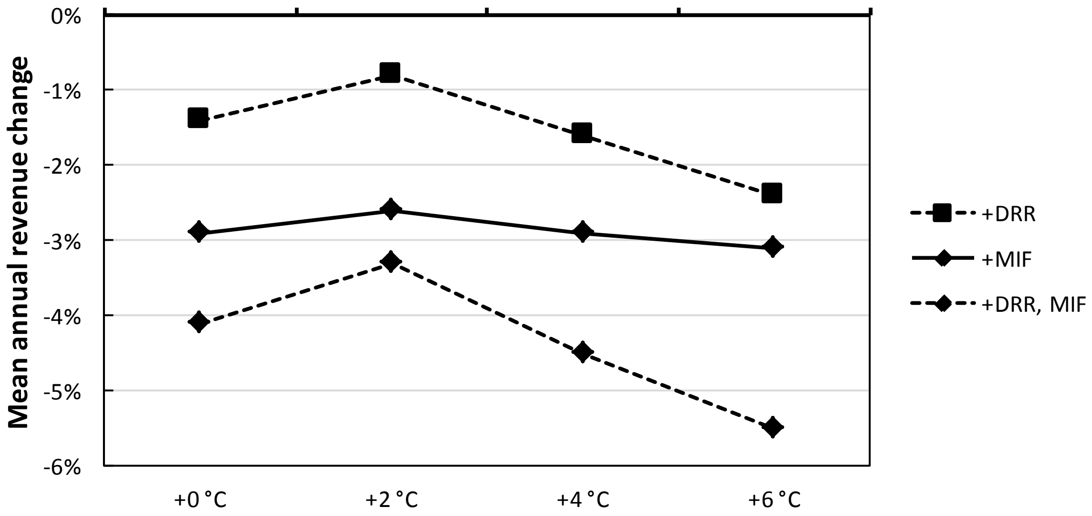


Figure 3-19. Change in mean *annual revenue* with warming relative to Base Case operations with a DRR of 25%/week, additional MIFs of +100% and both a DRR and MIFs.

Finally, we highlight the range of absolute and relative changes in generation and revenue, instead of only changes in mean generation and revenue included in Figures 3-16 to 3-18 and Tables 3-8 to 3-9. Table 3-10 includes the absolute and relative change in mean annual generation for the most ecologically protective scenario (full MIF and DRR) with warming compared to the historical climate and base case management, as well as median, and minimum changes. Table 3-11 shows the same change metrics for hydropower revenue. These values highlight that there is actually high variability among particular years. For example, though mean generation with a high MIF and DRR decreases by 131.8 GWh/year by +6 °C warming compared to with a historical climate and base case management, generation actually increases by as much as 356 GWh in one year and decreases as much as 729 GWh in another year. The changes in Tables 3-8 and 3-9 represent the full range of changes we can expect to with the most ecologically protective scenario considered in this study, given the various model assumptions.

Table 3-10. Change in mean *hydropower generation* with warming and full MIF and DRR compared to historical climate and management.

	Generation change (GWh/year)				**Generation change (%)**			
Warming / **Metric**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**
Change in mean	-82.8	-21.5	-79.0	-131.8	-5.6	-1.5	-5.3	-8.9
Max. change	2.4	225.0	376.5	356.0	0.2	16.4	30.8	29.2
Median change	-57.4	-52.9	-86.0	-114.9	-4.2	-3.4	-6.0	-8.4
Min. change	-204.4	-197.0	-545.0	-729.4	-13.1	-16.9	-28.6	-38.2

Table 3-11. Change in mean *revenue* with warming and full MIF and DRR compared to historical climate and management.

	Revenue change ($M/year)				**Revenue change (%)**			
Warming / **Metric**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**

Change in mean	-3.8	-1.0	-3.7	-5.9	-4.2	-1.1	-3.8	-6.1
Max. change	0.2	11.2	16.2	15.7	0.2	13.4	20.8	20.2
Median change	-2.8	-1.9	-3.9	-5.3	-3.5	-2.3	-4.1	-5.6
Min. change	-10.7	-9.6	-20.7	-29.8	-10.7	-11.8	-20.4	-27.5

Limitations

This research has several key limitations. First, sub-weekly scale environmental objectives, including minimum instream flows and ramping rates, were omitted from release-revenue curves. Olivares (2008) showed that imposing an hourly minimum instream flow below a peaking plant can affect generation. Including MIFs below a peaking facility can be done analytically or numerically, while including DRRs below a peaking facility would need to be done numerically. To include MIFs and DRRs below powerhouses at the hourly scale, one would need to consider that typical high elevation powerhouses in the Sierra Nevada often release into a river or stream. For such powerhouse configurations, the rate of change in powerhouse turbine flow is partially mediated by existing flow in the river, which release-revenue curves would need to account for.

A second important limitation is the perfect hydrologic foresight within a year. Operators in the Sierra Nevada typically benefit from limited foresight, with improved foresight after the winter precipitation period. However, although operators have imperfect foresight, they benefit from experience and manage resources accordingly.

Third, linear programming necessitates either linearization or omission of non-linear system characteristics. Linearization of the release-revenue curves, for example, results in discrete levels of weekly hydropower releases. Additional work is needed to include other non-linearities, such as costs of unmet instream flow requirements and end-of-year reservoir storage value. These could be accounted for with piecewise-linearization or by using alternative optimization methods.

Finally, though the instream flow requirements included in the model are improvements over existing minimum instream flows, they are still fairly simple and do not capture all important environmental flow needs. A more comprehensive study could include spring flow pulses, flushing flows, and requirements that change by season and by water year type, as is typically done in newer licenses. In future modeling efforts, releases could be valued based on their ability to meet quantifiable ecosystem objectives defined by habitat quality metrics or, more broadly, species abundance and diversity metrics.

Conclusions

This study used a linear programming model to understand the univariate and multivariate effects of more ecologically protective instream flow requirements than currently exist in the Upper Yuba River, California, in the context of climate warming. Specifically, increased minimum instream flow requirements and maximum down ramp rates below reservoirs were considered. Important outcomes of this study include the hydropower generation and revenue responses to changes in IFRs with warming.

Regional climate warming does not necessarily decrease hydropower output in the Upper Yuba River. With warming of 2 °C, average annual generation *increases* by 3.3%. With 6 °C warming, generation *decreases* by only 1.5%. The near-term increase is caused by minimal reduction in total annual runoff combined with a more uniform distribution of flows, resulting in reduced spill with little total change in water availability.

With a historical climate, the combination of the most ecologically protective MIFs (35 cfs in the South Fork Yuba River, 10 cfs at other locations) and DRR (25%/week maximum decrease) resulted in mean generation and revenue losses of 5.6% and 4.1%, respectively, compared to BC operations with no warming. With 6 °C warming, the losses with more protective IFRs, beyond what would be lost with base case management, were 7.4% and 5.5%, respectively. These results indicate that even with the most ecologically protective IFR considered in this study, mean annual generation decreases by at most about 7.4%, and only with 6 °C warming; near-term losses (2 °C warming) are lower, and changes would be substantially higher or lower in specific years.

The model could be extended to explore additional questions about potential changes to regional hydropower operations. For example, one could use the model to explore potential effects of using MIFs in the UYR to maintain high spring flows or to create ecological flow pulses. Though it is clear from this and other studies that existing reservoirs can adapt somewhat for hydropower needs, further work is needed to understand if reservoirs also could be used to buffer against potentially ecologically harmful changes in runoff patterns. The model might also be modified to include the effects of upstream operations on lower elevation projects. For example, increased minimum instream flows in the Upper Yuba River would likely alter operations of the downstream New Bullards Bar and Englebright Reservoirs, including potentially increasing their hydropower generation.

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Chapter 4:

Optimizing Selective Withdrawal from Reservoirs to Adapt to Climate Warming

Abstract

Climate change is altering flows and temperatures in California's Sierra Nevada mountains by reducing snowpack, causing earlier runoff and raising stream temperatures. Utilizing the thermal stratification in reservoirs to manage downstream temperatures is a promising adaptation to these changes. This study develops a linear programming model to optimally release water from different thermal layers to minimize deviations from desired downstream temperatures. An explicit objective of the work was to develop a method that can be integrated into a basin-scale multi-reservoir optimization modeling using a network representation of system features. The model objective function is to minimize managed temperature deviations from a target temperature regime. The model is applied with representative thermal dynamics to Lake Spaulding, a multi-purpose reservoir in the western Sierra Nevada that thermally stratifies seasonally and that could be used to manage temperatures for downstream cold water fish. The optimization model for thermal pool management is compared to a single low-level release model. The optimization model hedges the release of cold water to decrease summer stream temperatures, but at a cost of warmer stream temperatures in the winter. The model can be extended to include other nearby reservoirs to optimally manage releases from multiple reservoirs for multiple downstream temperature targets in a larger and more interconnected system.

Introduction

Hydropower facilities can affect their surrounding environment in many ways, including by altering downstream water temperatures. This can potentially harm downstream ecosystems, as water temperature affects all instream species, from primary producers to macroinvertebrates to fish (Cassie 2006; Hynes 1970; Sullivan et al. 2000). Managing downstream temperatures from hydropower facilities is therefore often an important objective in hydropower operations. Because reservoirs in temperate regions thermally stratify seasonally, dams are sometimes outfitted with multiple outlets (Figure 4-1) to allow dam operators to release water from several depths within the reservoir, termed "selective withdrawal". Selective withdrawal is widely used to meet downstream temperature objectives, which can be to release warm water to maintain a warm water fishery, cold water to maintain a cold water fishery, or a pre-determined temperature regime based on pre-dam conditions (Fontane et al. 1981).

Though selective withdrawal has historically been used to mitigate temperature effects of the reservoir itself, selective withdrawal might also be used to adapt to changes in stream temperatures caused by climate warming (Yates et al. 2008). In California's Sierra Nevada mountains, stream temperatures are anticipated to increase substantially with climate warming, harming instream biota (Null et al. 2010). Existing reservoirs could be modified with multiple outlet structures and operated to maintain more suitable downstream temperatures.

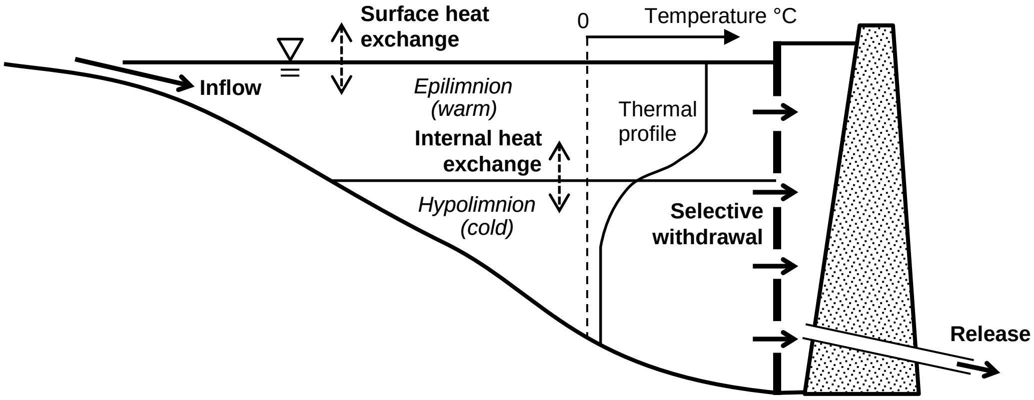


Figure 4-1. Schematic of a thermally stratified reservoir with selective withdrawal from 2 layers. Adapted from Fontane et al. (1981).

This study explores selective withdrawal by developing an optimization model that minimizes the annual sum of deviations from downstream temperature targets using selective withdrawal, in the context of a multi-reservoir system. As is common in temperature management schemes, the objective here, as specified by the optimization problem objective function, is to minimize the deviation of managed temperatures (the decision variable) from target temperatures for habitats, weighted as needed, by releasing water from different thermal pools. Total reservoir releases are assumed already optimized for maximum hydropower revenue with environmental flow constraints (or other management objective) and thermal behavior of the reservoir is assumed. We use hypothetical temperature dynamics and temperature requirements to apply the model to a single reservoir and single habitat that are part of a larger system.

Effects of stream temperature on fish

Stream temperature affects fish physiology and behavior in a variety of ways. Here, we focus on salmonids (family: *salmonidae*), the most populous of the native fish species in California's western Sierra Nevada and considered a good indicator species for overall freshwater ecosystem health. Temperature sets lethal limits, conditions species to different temperature levels, controls development rates, controls metabolic rates needed for short term movements, and guides fish to move to different locations (Brett 1956).

As summarized by (Sullivan et al. 2000), some physiological responses increase continually with increases in temperature (e.g., heart rate) while other responses increase to a maximum then subsequently decrease with further increases in temperature (e.g., swimming speed) (Brett 1971; Elliott 1981). The cumulative effect of the gradation of physiological responses to temperature increases is that total growth, which is a good proxy measure of a variety of physiological responses (e.g., Warren 1971), and survival is determined by both exposure and duration to different temperatures. A second cumulative effect is that salmonids have a temperature range of preference, over which the fish grow, a range of tolerance, over which there is no growth or mortality, a range of resistance, over which mortalities occur in the population in proportion to the duration of exposure, and an upper critical lethal limit, above which mortality rates rapidly increase (Elliott 1981; Jobling 1981; Sullivan et al. 2000). Salmonids in California, which are cold water fish, have a upper lethal limit of about 24 °C (Eaton and Scheller 1996), though many other fish have much higher limits (Magnuson et al. 1979). The threshold range of tolerance threshold—i.e., the threshold above which Chinook salmon (*Oncorhynchus tshawytscha*) become stressed, but do not necessarily die—is approximately 21 °C (McCullough 1999). This is the stress threshold considered by Null et al. (in review) when assessing potential climate warming impacts on stream temperatures in the west slope of the Sierra Nevada.

The maximum efficiencies of the temperature-dependent physiological characteristics of fish occur at different temperatures. However, fish have adapted to be able to account for differences in physiological activity at different temperatures and can therefore survive in an environment with spatial and temporal variability in temperatures. Growth rates are therefore generally stable over a range of temperatures likely to be encountered by a species in its native environment (Hokanson 1977). Sullivan et al. (2000) note that several studies (e.g., Brett 1971; Thomas et al. 1986) have shown that physiological responses of a fish to a range of temperatures are identical to the responses under the time-weighted mean of the temperature range. This has important implications for management, since operations generally require simplicity, such as fixed temperature requirements over a given time period. Thus, if a natural temperature regime is used as a basis for management, some of the natural temperature variability that occurs could be smoothed.

Because of the duration-exposure effect of temperature, and because temperatures, like flows, are naturally dynamic, it is widely recognized temperatures should be regulated by their statistical characteristics, such as limits on days above a specific temperature threshold, rather than by single threshold values (Armour 1991; Olden and Naiman 2010; Sullivan et al. 2000). However, the idea of managing for a natural temperature regime has yet to be fully integrated into environmental flow assessments (Olden and Naiman 2010).

Thermal dynamics in reservoirs and streams

The model assumes thermal behavior in reservoirs, streams, and tributary junctions/diversion points. Though thermal behavior is simplified in the model, it is based on fundamental heat transfer mechanisms in reservoirs and streams, summarized here. The summaries are provided as a general background to inform the optimization study and provide insights for future development, though the concepts are not necessarily used directly.

Temperature is a measure of the amount of heat in a substance per unit mass. Temperature is related to heat by:

$$T = \frac{H}{\rho C_p V} \tag{0.41}$$

where T is temperature (°C), H is heat (J), ρ is water density (kg m^{3}), C_p is specific heat of water (J kg^{-1} °C^{-1}), and V is volume (m^{3}). Water density can be assumed constant, though it does vary with temperature and is fundamental to lake stratification. Heat capacity can also be assumed constant, at 4.18 kJ kg^{-1} C^{-1} for water. Changes in temperature in a water system can thus be tracked with an accounting of heat and water mass through space and time. The number of dimensions considered depends on the problem of interest. Here, only temporal heating is considered, with assumptions made about heat transfers between adjacent well mixed bodies of water.

Heat transfer mechanisms and total heat budgets in reservoirs and rivers is well understood and has been studied extensively (Cassie 2006; Webb et al. 2008). Specific energy/heat transfer mechanisms in reservoirs and rivers include:

- Advection (mass movement of water upstream/downstream/with groundwater)
- Incoming short wave (solar) radiation
- Incoming long wave radiation
- Outgoing long wave radiation
- Conduction and convection at the air/water interface
- Evaporation and condensation

- Bed conduction

Each mechanism affects reservoir and stream heat balances, though how each mechanism acts varies with hydrologic, geomorphologic, and meteorological conditions. Since shortwave radiation originates directly from the sun, much of the heating and cooling of open bodies of water such as lakes and rivers is strongly influenced by daily and seasonal solar cycles.

Heating and stratification in reservoirs

Temperate lakes and reservoirs such as in the Sierra Nevada typically stratify seasonally, during the warmer part of the year, due to meteorological conditions that change with the annual solar cycle (Chapra 1997; Horne and Goldman 1994). Seasonal stratification occurs vertically and affects several physiochemical constituents of a reservoir, including temperature and dissolved oxygen, due to a range of mixing processes. In real operations, several water quality characteristics must be considered. Here, we are focused only on temperature.

At the reservoir surface, heat gains include incoming short wave radiation from the sun, incoming long wave radiation from the atmosphere, and conduction, if the air is warmer than the water surface. Heat losses include outgoing long wave radiation, evaporation, and conduction, if the water surface is warmer than the air. At the surface, atmospheric and back long wave radiation are often in equilibrium. Other mechanisms that can be important influences on heat in reservoirs include advective gains from incoming streams and groundwater and advective losses from outgoing streams, including releases and spill, and groundwater. These processes can be summarized as:

$$H_{lake} = H_0 + H_r - H_e - H_c - H_q \qquad (0.42)$$

where H_{lake} is the heat in the lake, H_0 is the initial heat, H_r is net incoming radiation, H_e is evaporation, H_c is conduction, and H_q is net advective losses (Horne and Goldman 1994). Conduction and advection can also occur at the ground/reservoir interface. Heat exchanges can also be considered by where they occur rather than the actual mechanisms. Thus, (4.2) can be re-written as:

$$H_{lake} = H_0 + H_i - H_o \pm H_a \pm H_g \qquad (0.43)$$

where H_i is heat gain from inflows, H_o is heat loss from outflows, H_a is heat gain via the air/reservoir surface interface and H_g is heat gain from groundwater/reservoir bottom interface. These mechanisms and sources/sinks are depicted in Figure 4-2.

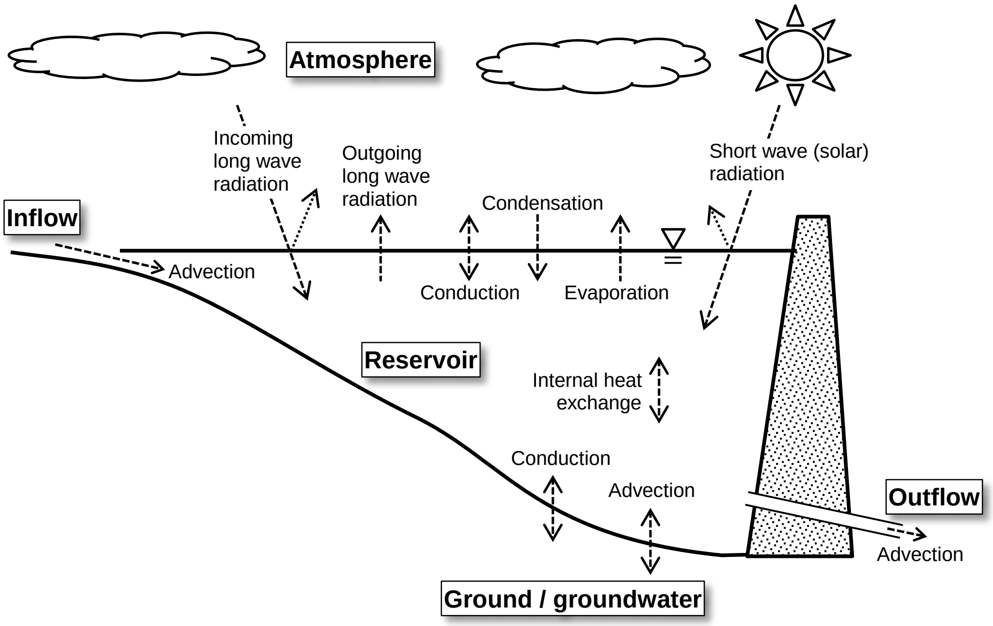


Figure 4-2. Heat fluxes in a typical reservoir.

Each gain or loss in heat can increase or decrease temperature, depending on the temperature of inflows and groundwater, stratification, and outflow location. Inflows and outflows also cause mechanical mixing, affecting thermal dynamics in the reservoir. Generally, advective heating is minimal compared to radiative and convective forces. The specific nature and dominance of the various heating mechanisms varies greatly by reservoir and depends on the unique characteristics of the reservoir, including environmental factors (e.g., wind, air temperature, cloud cover, relative humidity, solar intensity, and so on), the physical configuration of the reservoir (size, shape, and inflow/outflow locations), and operations (outflow magnitudes). In temperate reservoirs typical of the Sierra Nevada, summer stratification is only somewhat influenced by heat gains and losses from inflows and outflows. Fischer et al. (1979) provide a detailed description of external and internal heat flux mechanisms.

Stratification is caused by the differences in density; warmer water is less dense, except below 4°C. During the winter, the reservoir is completely mixed, with a fairly uniform, low temperature. In the spring and summer, the surface of the reservoir gains heat from increasing amounts of incoming solar radiation and conduction from warmer air. Simultaneously, mechanical mixing of surface water by wind causes the warmer surface waters to mix, creating a warm upper layer, called the *epilimnion*. The original deeper, colder water becomes the *hypolimnion*. In reservoir operations, the epilimnion and hypolimnion are also called the ‘warm water pool’ and ‘cold water pool’, respectively. The transition zone, if any, between epilimnion and hypolimnion is called the *metalimnion*, though any sharp temperature gradient within a layer is called a *thermocline*. During the summer, the thermocline in the seasonally stratified reservoir slowly deepens through the summer as more heat enters the reservoir from solar radiation or inflows. Whereas the hypolimnion remains consistently uniform in temperature, there is often a temperature gradient in the epilimnion, with warmer, less dense water at the top and colder, denser water at the bottom. The strength of the gradient depends on the mixing caused by surface winds or other mechanical mixing forces. By fall, the epilimnion still expands, but also becomes cooler, as incoming radiation air temperatures decrease relative to evaporative losses. By winter, the epilimnion has cooled and expanded such that the distinction between the epilimnion and hypolimnion disappears and the reservoir is completely mixed, with a near-uniform temperature.

During the stratification period, the total heat in each of the epilimnion (*e*) and hypolimnion (*h*) after each time step *t* are calculated with a simple heat budget as follows:

$$H_e = H_{e,0} + H_{e,i} - H_{e,o} \pm H_{e,a} \pm H_{e,g} - H_t \tag{0.44}$$

$$H_h = H_{h,0} + H_{h,i} - H_{h,o} \pm H_{h,g} + H_t \tag{0.45}$$

where *H* is heat, subscript 0 is the initial condition, *i* is inflow, *o* is outflow, *a* is exchange with atmosphere, *g* is exchange with the ground, and *t* is transfer from the hypolimnion to the epilimnion. The terms in (4.4) and (4.5) are generic in the sense that heat exchange with the atmosphere can be further defined to include specific heat exchange mechanisms such as evaporative heat losses. Equations (4.4) and (4.5) can be revised using (4.1), per Chapra (1997):

$$V_e \rho C_p \frac{dT_e}{dt} = Q_{in,e} \rho C_p T_{in}(t) - Q_{out,e} \rho C_p T_e \pm J A_s + v_t A_t \rho C_P \left(T_e - T_h\right) \tag{0.46}$$

$$V_h \rho C_p \frac{dT_h}{dt} = Q_{in,h} \rho C_p T_{in,h}(t) - Q_{out,h} \rho C_p T_h - v_t A_t \rho C_P \left(T_e - T_h\right) \tag{0.47}$$

where *V* is volume, *Q* is flow, *J* is per unit area heat flux between the atmosphere and reservoir, A_s is surface area (m^2), v_t is the thermocline heat transfer coefficient (m d^{-1}), and A_t is the thermocline area (m^2). Other subscripts are as defined above. Heat exchange with the earth and with groundwater are assumed negligible. The heat transfer coefficient *v* is a constant, in units of length per unit time, though heat flux from the epilimnion to the hypolimnion varies over time as the thermocline area (A_t), density (ρ), and temperature difference ($T_e - T_h$) change. The stratification cycle is due to changing magnitudes of each component of (4.6) and (4.7) and reservoir mixing characteristics. Equations (4.6) and (4.7) are used to develop constraints in the linear programming model in this study.

Heating in streams

Though the behavior of water temperature in streams is fairly complex (Webb et al. 2008), here we are interested in a basic understanding of stream heating by developing a general heat balance on a parcel of water as it moves downstream. Because the control volume moves with the water, there is no mass flux across the control volume boundary. We are interested in the change in temperature due to the net heat transfer, H_{net}, in the well-mixed parcel of water as it moves downstream. The general advection-dispersion equation governing one-dimensional flow and heat for a column (vertical slice) of water in a river can be simplified to:

$$\frac{dT}{dt} = \frac{H_{net}}{C_p \rho d} \tag{0.48}$$

where *T* is the temperature of the water column and d is the depth (Null et al. in review). Equation (4.8), which is commonly used to represent heating (e.g., Cassie et al. 2005; Edinger et al. 1968; Sinokrot and Stefan 1993), assumes that longitudinal heat changes are advection-dominated, that changes to a parcel of water are much greater in time than in space due to rapid changes in meteorological conditions, and that the wetted perimeter approximately equals the surface width (a wide channel). When (4.8) is discretized for a parcel of water flowing in a particular river reach, it becomes:

$$T_f = T_i + \frac{H_{net} h}{C_p \rho d} \tag{0.49}$$

where T_f is the final (i.e., downstream) temperature, T_i is the initial (upstream) temperature, and h is the travel time of the parcel of water. Equation (4.9) omits changes in volume due to groundwater interaction, evaporative losses, and precipitation. Equation (4.9) is not the general solution to (4.8), but rather a rough approximation for the particular case of relating downstream temperature to upstream temperature; Edinger et al. (1968) discuss the general solution.

The challenge in a stream temperature problem is to define H_{net}, which is a function of hydrology, geomorphology, meteorological and other conditions at multiple spatial scales. Other terms, including depth and travel time, must also be known. Meteorological conditions are as described for reservoirs, above. Groundwater interactions would add even more complexities.

There are two common ways that H_{net} can be estimated. First, it can be explicitly calculated with a thorough accounting of energy gains and losses. This approach is used by Null et al. (in review), who used the following heat budget:

$$H_{net} = H_{sn} + H_{at} - (H_{ws} + H_h + H_{evap}) + H_{bed} \tag{0.50}$$

where subscript *sn* is incoming solar radiation, *at* is incoming long-wave radiation, *ws* is outgoing long-wave radiation, *h* is conduction and convection, *evap* is evaporation, and *bed* is bed conduction. Each term in (4.10) can be calculated or observed directly from meteorological data, or assumed. This approach gives a more detailed understanding of the specific heat change mechanisms, but might be too complex, especially where there is insufficient or large uncertainty in the meteorological data.

Another approach is to use the equilibrium temperature concept stemming from the work of Edinger et al. (1968). Edinger et al. (1968) developed a linear method by noting that the net rate of heat exchange between a body of water and the atmosphere is linearly proportional to the difference between the water temperature and an equilibrium temperature. In any given period of time, the rate of heat exchange, as defined by Edinger et al. (1968), is:

$$H_{net} = K \cdot \left(T_{eq} - T_s\right) \tag{0.51}$$

where K is a heat transfer coefficient, T_{eq} is the equilibrium temperature, and T_s is the surface water temperature, which equals T in a well-mixed body of water such as a stream. The body of water is always moving toward the equilibrium temperature, though the equilibrium temperature changes due to changing meteorological conditions. The equilibrium temperature approach is simpler in formulation than the heat balance approach, though meteorological data are still needed to calculate K and T_{eq} (Mohseni and Stefan 1999). Equation (4.11) is particularly attractive if the K and T_{eq} can be expressed in terms of only air temperature, which is often a more certain product of global climate models (Cassie et al. 2005). Though the equilibrium temperature approach is not used in this study (a simple empirical approach is used), the linear character of the equilibrium temperature approach is well suited for use in a linear programming model.

Heating in stream junctions

Over very short distances the change in temperature of a parcel of water due to heating from radiation and conduction are negligible in fast moving water. Thus, at tributary junctions we consider only convection, with physical mixing of waters of different temperature affecting water temperature below the tributary. A junction is essentially a reservoir with no storage capacity, resulting in no heat storage capacity and no surface area for water-atmosphere heat flux. Heat downstream of a junction or mixing node can therefore be described with a simple heat budget:

$$H_{out} = \sum_{in} H_{in} \qquad (0.52)$$

where H_{out} is the total heat below the junction and H_{in} is the heat from inflows. Written to include temperature, (4.12) becomes:

$$\rho C_p T_{out} \cdot \sum_{out} Q_{out} = \sum_{in} \left(\rho C_p Q_{in} T_{in} \right) \qquad (0.53)$$

If density and heat capacity are assumed invariable through the junction, (4.13) can be simplified to:

$$T_{out} \cdot \sum_{out} Q_{out} = \sum_{in} \left(Q_{in} T_{in} \right) \qquad (0.54)$$

Though in reality mixing occurs in the longitudinal direction below a junction of two streams, the mixing can be assumed instantaneous compared to the overall length of the downstream reach.

Optimizing selective withdrawal for downstream temperature

Fontane et al. (1981) reviews the context in which temperature release decisions are made and the conditions that need to be considered in developing a selective withdrawal optimization model. Release decisions—that is, the combination of releases from each stratification layer—are made with no foresight, or with foresight of temperature needs for the remainder of the season. With no foresight, optimization is not needed and a simulation model can be used, but poorer decisions are likely. This is sufficient when there is enough water in each stratified layer relative to total releases, though there can be complexities related to the annual carryover of reservoir temperature as discussed by Olivares (2008). However, if releases are large relative to total reservoir storage, then there is a high likelihood that one of the thermal pools will be exhausted. If the reservoir is managed for cold water fish, this would result in early exhaustion of the cold water pool followed by a sharp increase in release temperatures. In such cases, anticipation of future conditions is required to hedge the release of cold water such that sufficient cold water is available later in the year to meet temperature objectives. This is particularly relevant for reservoirs that empty and refill annually, which are typical of high-elevation reservoirs in the Sierra Nevada and that are considered here. The use of an optimization model with foresight can suggest optimal releases when the cold water pool might be exhausted.

Release objectives are based on specific temperature targets. However, temperature targets are ideal and likely not always achievable given actual reservoir conditions. A real operational objective—and one used in a an operations model—would therefore be a function of temperature target, typically the minimization of the cumulative deviation, or squared deviation, between release and target temperatures over a fixed time period (e.g., the drawdown period within a year).

Optimal operations of selective withdrawal structures have been studied using several methods, as single- or multi-objective optimization problems. Fontane et al. (1981) developed a model using a combined simulation-dynamic programming (DP) method that minimizes a function of the total squared deviation from a target temperature in a cold water fishery below a single reservoir over a 100 day period during the summer. Fontane et al. (1981) used a single objective, assuming that total reservoir releases are known and that the decision is the how much to release from individual outlets. Olivares (2008) also used DP for a single-objective problem to determine optimal releases from each layer below a reservoir. Rather than assume known releases, however, Olivares integrates temperature objectives into a total release model that maximizes hydropower generation given release and temperature constraints, with temperature constraint consisting of maximum allowable release temperature during each time step. DP is particularly suitable for real-time temperature optimization within a year as it reflects the sequential decision-making that characterizes the selective withdrawal optimization problem. Further, it can readily incorporate non-linearities in the system. However, DP is not ideal for optimization of multi-reservoir systems with many time steps due to the well-known “curse of dimensionality”; the number of possible stage-states increases exponentially with the number of reservoirs, limiting multi-reservoir problems to 3-4 reservoirs.

Carron (2000) used quadratic programming to optimize selective withdrawal for downstream temperature objectives with both steady and unsteady flows. Carron focused on the influence of flow release on temperature and the ability to meet downstream temperature objectives. In this case, instream flow is varied but exogenous for each particular quadratic programming problem, resulting in trade-off curves between instream flow requirement and optimal temperature release, given maximum release temperature targets. Of particular relevance, Carron used an objective function that included minimizing squared deviations from a target temperature at two locations downstream of a reservoir, instead of just one location, which necessitates simulation of longitudinal stream temperature dynamics. Quadratic programming allowed Carron to include a stream temperature simulation model and a non-linear objective function (squared deviations).

Often, temperature or other water quality constraints can be included as an objective in a multi-objective problem. For example, Field (2007) used a genetic algorithm to study the multi-objective problem of maximizing revenue, meeting water supply deliveries, and maintaining water temperatures below a reservoir. Since the study here uses single-objective optimization, a more detailed review of temperature objectives in multi-objective problems is omitted; Field (2007) reviews this topic.

As these and other studies suggest, a range of optimization techniques can be used to estimate optimal releases from a selective withdrawal system, each with advantages and disadvantages. Linear programming is used in this study for its efficiency and ease of application for flow network problem. Piecewise linearization can accommodate many non-linearities encountered in a multi-reservoir system in sufficient detail for planning and policy studies.

The approaches described are applied specifically to releases directly below a reservoir or within come controllable distance below it. Carron (2000) justifies this by recognizing that reservoirs have limited control over the character—both quantity and quality—of a river. Further downstream, reservoirs exert less control over river conditions, which become more influenced by downstream tributaries, groundwater inflows and outflows, and other conditions such as temperature fluxes between the air and groundwater. This is the “serial discontinuity concept”, which posits that stream systems gradually return to more natural characteristics downstream of discontinuities caused by impoundments and other disruptions (Stanford and Ward 2001). Reaches directly below the reservoir are “thermal transition reaches”, controlled almost entirely by reservoir operations and readily predictable atmospheric conditions, but not by tributaries (Carron 2000; Sinokrot and Stefan 1993).

Because the goal in this study was to develop a model that optimizes thermal layer releases in a multi-reservoir system, which spans the landscape to watershed scale, natural influences downstream, such as tributary inflows, are included. With adequate representation of longitudinal stream warming, the serial discontinuity concept will be apparent as the influence of tributaries become more dominant further downstream of managed features such as reservoirs and diversions. At this broader spatiotemporal scale, we can readily apply the model to large, multi-reservoir planning models at the watershed scale, even though the case study described here is limited in spatial scope to a single reservoir and to stream management close to the reservoir.

Methods

The goal of the study was to develop a model to optimally allocate releases from different water levels within a reservoir to manage downstream temperatures within a node-link model framework. A node-link model represents a water system as nodes (reservoir, powerhouse, junction, and diversion nodes) and links (rivers and artificial conveyances), which connect nodes. In this study, stream temperatures are managed by controlling how much water is released from each layer in a thermally stratified reservoir, given assumed thermal dynamics in reservoirs, streams, and nodes.

Assumptions

To simplify the model, we make several assumptions about how temperature behaves in reservoirs and streams, based on the more detailed understanding of temperature dynamics discussed above. Including detailed reservoir and stream temperature dynamics is generally beyond the scope of a reservoir planning model (Olivares 2008). Pragmatically, detailed temperature dynamics are prohibitively complex to incorporate directly into a multi-reservoir optimization model, though a hybrid simulation-optimization scheme could be used. Assumptions about system behavior include the following:

1) Reservoir thermal dynamics are known. Though temperature in each layer is affected by outflows by advection and by the mechanical mixing caused by release hydrodynamics, the assumption is that climate and inflow hydrology are the primary drivers of reservoir thermal dynamics. Johnson et al. (2004) determined that the thermal dynamics of Blue Mesa Reservoir in Colorado, USA was much more affected by climate than by operations. Specifically, the temperature in each thermal layer and the rate at which the epilimnion grows and the hypolimnion shrinks are assumed known. These rates are specified as a deterministic percentage of the reservoir storage capacity. By extension, reservoir inflows and outflows are assumed not to affect reservoir temperatures.

2) Inflows affect reservoir layer size. How inflow partitions to the epilimnion and the hypolimnion is assumed as follows. If inflow temperature (T_{in}) equals or exceeds the epilimnion temperature (T_w), it flows to the epilimnion. If inflow temperature is equal to or lower than the hypolimnion temperature (T_c), it flows to the hypolimnion. If inflow temperature is between the epilimnion and hypolimnion temperatures, a fraction (α_w) flows to the epilimnion and a fraction (α_c) flows to the hypolimnion, depending linearly on how close the inflow temperature is to the temperature of each respective layer. Thus, the partition fractions are defined as:

$$\alpha_w = 1 - \frac{T_w - T_{in}}{T_w - T_c} \tag{0.55}$$

$$\alpha_c = 1 - \alpha_w \tag{0.56}$$

Partition fractions are each between zero and one, inclusive, and sum to unity. They are determined before the optimization model is run.

3) The rate at which streams warm longitudinally is known. As discussed above, streams nonlinearly establish thermal equilibrium with the air and ground longitudinally. Here, the relative change in longitudinal warming is assumed known for each stream segment during each week. This assumption does not account for warming rate dependence on flow and upstream boundary temperatures, as explored by Carron (2000).

4) Temperature is a conservative substance at flow junctions and diversions; any change in total thermal mass through a junction or diversion is assumed to be insignificant.

Objective function

The continuous objective function *f* is expressed generally by Carron (2000) as a function *G* relating the target temperature vector **T** to the control vector **U**:

$$f\left(\mathbf{U}\right)=\int_0^{\tau}\int_0^{L} G\left(\mathbf{U},\mathbf{T}\right) dL\, d\tau \tag{0.57}$$

where τ is time and *L* is space. The control vector **U** includes the suite of decision variables in the optimization problem, which in this case includes flow release from each thermal layer and the temperature release from the reservoir as a whole.

The main objective of the temperature optimization problem considered here is to minimize the location and time weighted non-linear cost of deviation of the managed and target stream temperatures for the downstream end of each stream habitat *h* and time step *t*. This can be represented in a discrete form of (4.17) as:

$$\min z=\sum_t \sum_h c_{h,t}\cdot\left|T_{h,t}-T_{h,t}^{target}\right| \tag{0.58}$$

where *T* is the managed temperature and the main decision variable, T^{target} is the target stream temperature, and *c* is the cost (penalty) of deviating from the temperature target. The cost can be either a single value that varies only by time and space or a function of the level of deviation from the target temperature. This is the approach used in the case study described here, with the non-linear cost linearized in implementation using piecewise linearization.

Though stream temperature is the main decision variable from a general management perspective, in real operations the decision variable is release from each reservoir layer during each time step. Releases from each layer are excluded from the objective function since they are not valued or penalized *per se*. Instead, they are valued indirectly via the constraint set by their effect on downstream temperatures.

The absolute value of deviation is considered, since we assume T^{target} is an ideal temperature regime where high and low deviations are both undesired, though one could modify this to consider T^{target} as only a maximum or a minimum. Since the objective function cannot explicitly include the absolute function, the penalized function is partitioned into a temperature excess (T^{up}) and temperature deficit (T^{down}):

$$\min z=\sum_t \sum_h c_{h,t}\cdot\left(T_{h,t}^{up}+T_{h,t}^{down}\right) \tag{0.59}$$

where T^{up} and T^{down} are non-negative and defined in the constraint set such that:

$$T_{h,t}^{d/s}=T_{h,t}^{target}+T_{h,t}^{up}-T_{h,t}^{down} \tag{0.60}$$

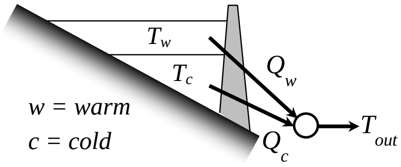
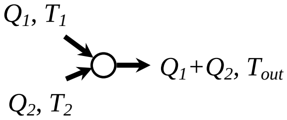
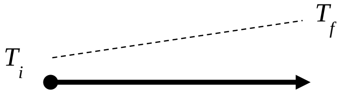
T^{up} and T^{down} are mutually exclusive; if one is non-zero, the other is necessarily zero.

One modification to Equation (4.20) is needed to prevent the hypolimnion-to-epilimnion water transfer from causing infeasibility and to allow the epilimnion to be redefined as the hypolimnion during when the reservoir is completely mixed; this modification is introduced and described below.

Constraints

Constraints include either the explicit decision variable stream temperature T or the implicit decision variables warm layer release Q_w and cold layer release Q_c or both. Constraints used in the model are described, with the three main constraints that govern temperature changes and mixing listed in Table 4-1.

Table 4-1. Thermal mixing and warming in parts of a network flow multi-reservoir optimization model.

Component	Schematic	Constraint
Reservoir (mixing)		$\left(Q_w + Q_c\right)\cdot T_{out} = Q_w T_w + Q_c T_c$
Junction (mixing)		$\left(Q_1 + Q_2\right)\cdot T_{out} = Q_1 T_1 + Q_2 T_2$
Link (warming)		$T_f = T_i + \Delta T$

<u>Reservoirs</u>

Each thermal layer has a mass balance constraint. A mass balance model for other nodes in the network is not needed, since total flows through the network are assumed known. During each time step, each layer receives a fraction α of total reservoir inflows Q_{in} and loses water released downstream Q_r. The warm (w) epilimnion gains volume V_{cw} from the cold (c) hypolimnion[6]. To redefine the epilimnion as the hypolimnion during the completely mixed period in the winter, when there is no distinction between the

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[6] Note the distinction between the cost parameter c and the identifying subscript c.

layers, a similar warm-to-cold layer transfer volume V_{wc} is used and set equal to unity during one week in the fully mixed period. Finally, the epilimnion loses water to evaporation E, though evaporation is assumed zero in the case study discussed here. The epilimnion mass balance is:

$$V_{w,t} = V_{w,t-1} + \alpha_{w,t} \cdot \sum_{in} Q_{in,t} - \sum_{r} Q_{r,w,t} + V_{cw,t} - V_{wc,t} - E_t \tag{0.61}$$

where $V_{w,t}$ is the volume at the end of the current time step and $V_{w,t-1}$ is the volume at the end of the previous time step; other terms are as defined above. Initial conditions $V_{w,0}$ are assumed. Similarly, the hypolimnion mass balance is:

$$V_{c,t} = V_{c,t-1} + \alpha_{c,t} \cdot \sum_{in} Q_{in,t} - \sum_{r} Q_{r,c,t} - V_{cw,t} + V_{wc,t} \tag{0.62}$$

where terms are as defined above.

To account for infeasibilities in some time steps if the transfer volumes (V_{cw} and V_{wc}) were parameters, the transfer volumes are added to the objective function as decision variables and valued, with a constraint that limits their value based on an assumed rate. V_{wc}, for instance, is limited to zero during all weeks except one week during the completely mixed period, when it is limited to unity.

After the addition the transfer volume variables, the modified objective function is:

$$\min z = \sum_{t} \sum_{h} c_{h,t} \left(T_{h,t}^{up} + T_{h,t}^{down} - T_{h,t}^{targ} \right) - b \cdot \sum_{t} \sum_{r} \sum_{l1,l2} V_{l1,l2,res,t}^{transfer} \tag{0.63}$$

where $l1$ and $l2$ represent any two generic thermal layers. The transfer volume variable constraint is:

$$V_{l1,l2,t} \leq V_{l1,l2,t}^{transfer} \tag{0.64}$$

where $V_{l1,l2,t}^{transfer}$ is the transfer volume parameter.

Reservoir releases

One additional mass balance constraint ensures that the sum of the releases from each layer equals total reservoir release. For each outlet during each time step:

$$Q_{r,w} + Q_{r,c} = Q_r \tag{0.65}$$

This release mass balance constraint is sufficient to ensure that the sum of the layers similarly equals the total volume during each time step.

Streams

Equation (4.9) is used to create a general equation to relate the downstream temperature, though it is re-written to be more general as:

$$T_f = T_i + \Delta T \tag{0.66}$$

where ΔT is the change in longitudinal stream temperature along a reach. Equation (4.26) can be used as is, with ΔT assumed known, the approach used in this study, or modified to include known meteorological conditions. In particular, the equilibrium temperature concept of (4.11) could be used with (4.9) to represent warming in a linear programming model.

Mixing at junctions (nodes)

Whereas reservoirs and streams change with location due to meteorological influences, nodes are influenced only by thermal mass transfer from inflows and outflows. We treat heat as a conservative substance and employ (4.14):

$$T_{out,t} \cdot \sum Q_{in,t} = \sum Q_{in,t} T_{in,t} \tag{0.67}$$

Boundary conditions

Finally, we include an equality constraint to specify the temperature of boundary inflows:

$$T_{inflow,us} = T_{inflow}^{in} \tag{0.68}$$

where T^{in} is the temperature of water coming into boundary inflow stream *inflow*.

Case Study: Lake Spaulding, California

Lake Spaulding is a 92.6x10^6 m^3 (75,100 AF) reservoir on the South Fork Yuba River in the western Sierra Nevada mountains, California (see Figure 3-3). As elsewhere in the western Sierra Nevada, climate warming is expected to cause a shift in runoff in the South Fork Yuba River from spring snowmelt-dominated runoff to winter precipitation-dominated runoff. Climate warming is also expected to increase stream temperatures, threatening the long-term viability of aquatic species that cannot survive in water above a critical temperature threshold (Null et al. in review). Lake Spaulding currently has two releases: a low-level release and a high-level release. Without the strategic management of temperature releases, the cold water pool in a reservoir such as Lake Spaulding could be depleted to soon, resulting in subsequent harmful releases of warm water.

The South Fork (SF) Yuba River at Langs Crossing is chosen for this case study (Figure 3-3 and Figure 4-3). Langs Crossing, below Lake Spaulding, is important in the SF Yuba River as there is little additional regulation until much further downstream; conditions at Langs Crossing thus have a substantial ecological effect downstream. Because of this, the Federal Energy Regulatory Commission (FERC) license regulating regional hydropower management includes flow conditions at Langs Crossing. The SF Yuba at Langs Crossing receives water from several sources: water released via a powerhouse to meet instream flow requirements, controlled and uncontrolled spill from Lake Spaulding (though in this study all spill is assumed controlled), and natural runoff from Jordan Creek, a tributary to the SF Yuba R. located just upstream of Langs Crossing. Spill from Lake Spaulding is released into Jordan Creek before arriving at Langs Crossing. This network of release paths and non-managed influences (natural inflows from Jordan Creek) necessitates the use of a node-link type flow optimization model. Figure 4-3 shows the flow schematic of the region around Lake Spaulding and the South Fork Yuba River at Langs Crossing.

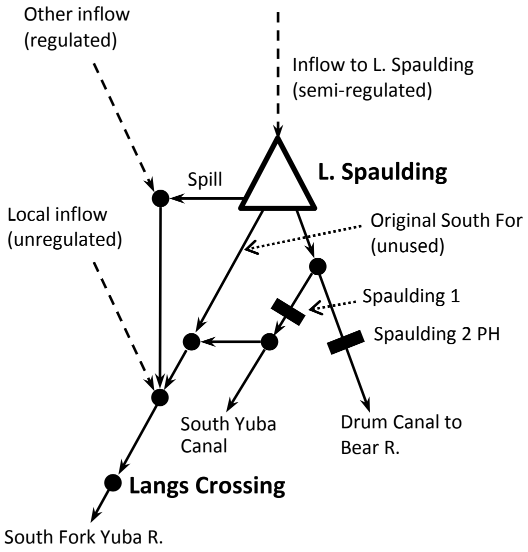


Figure 4-3. Schematic of flows around Lake Spaulding.

The method described is applied to Lake Spaulding with temperature targets in the SF Yuba River at Langs Crossing using simplified thermal stratification based on observed thermal profiles. The method was applied using the General Algebraic Modeling System (GAMS; www.gams.com) with the CONOPT optimization solver. Relevant model inputs are described.

Reservoir thermal regime

Data from observed temperature records from Lake Spaulding from 2008 and 2009 (Figure 4-4) were used to guide development of reservoir temperatures. The hypolimnion stays relatively constant at approximately 7° C during the observed data period. The epilimnion, however, varies in temperature over time. One interesting feature of the development of summer stratification is that stratification does not begin with a clearly defined thermocline between the epilimnion and the hypolimnion. Rather, the epilimnion forms as a poorly mixed layer that gradually decreases in temperature with depth. Over time, the epilimnion becomes more mixed. The result is the epilimnion is initially quite deep, though poorly defined, instead of shallow and well defined. This is evident on 7/16/2008 in Figure 4-4. For simplicity, we assume the thermocline is a sharp gradient, with complete mixing in each layer. The layer interface deepens somewhat over the summer as the epilimnion becomes warmer then cooler, with a maximum temperature of about 17 °C.

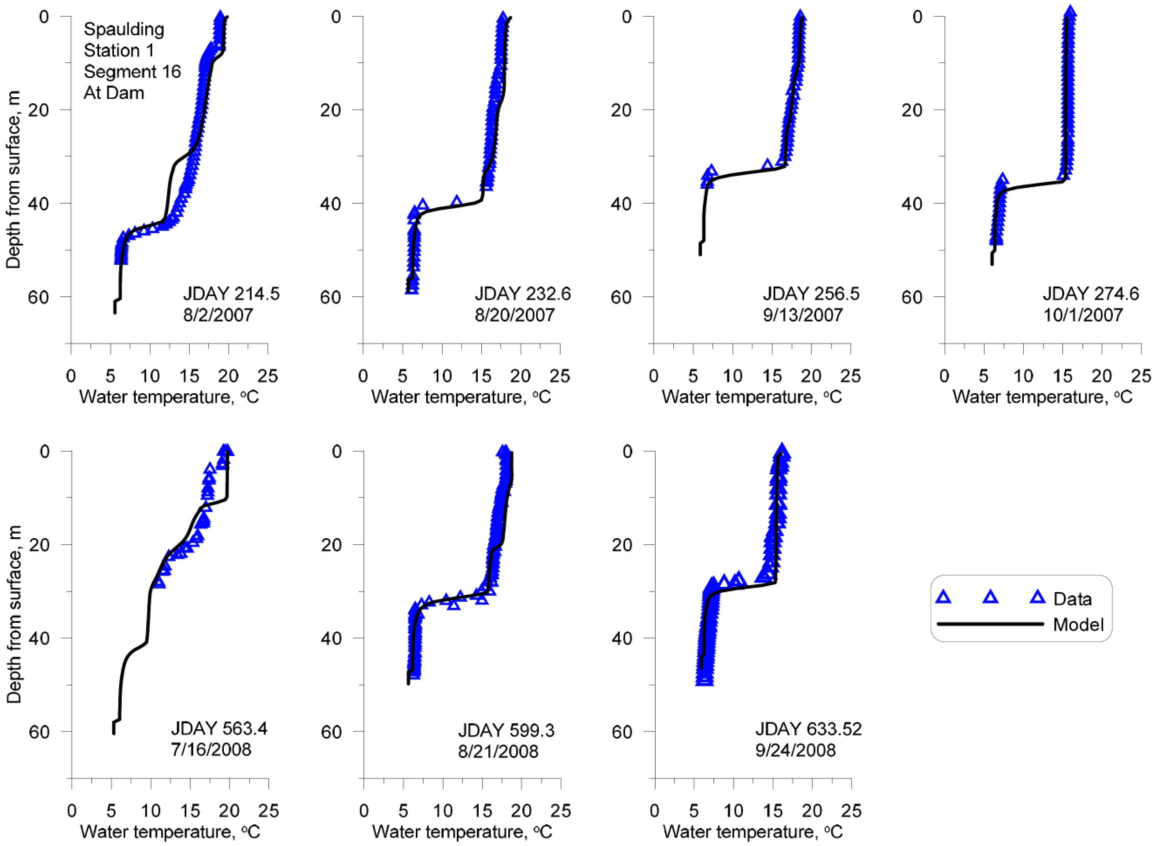
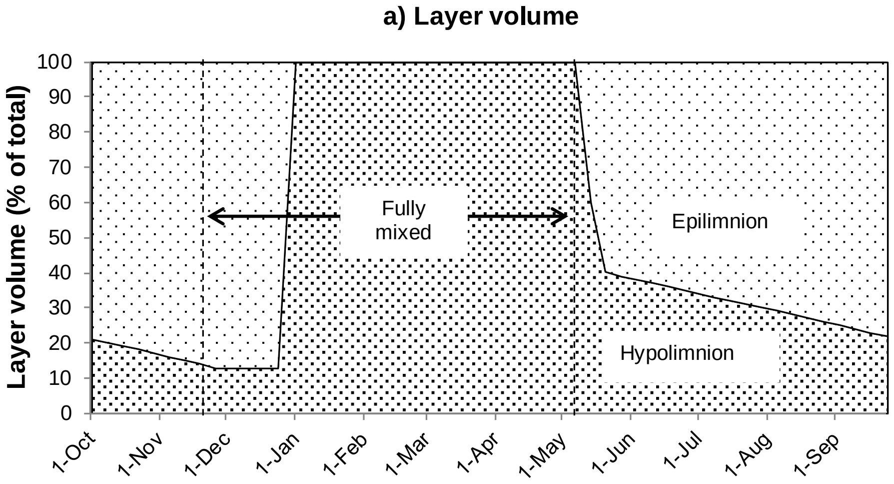


Figure 4-4. Observed and simulated water temperatures profiles in Lake Spaulding near dam. From [PG&E/NID] Nevada Irrigation District and Pacific Gas and Electric Company (2010).

Weekly temperatures and layer volumes are developed from Figure 4-4, the above observations, and assumptions about when stratification begins and ends, based on other work (e.g., Chapra 1997). Temperatures and layer volumes are plotted in Figure 4-5 and listed in Table 4-2. . The maximum reservoir temperature is set conservatively to 18 °C, slightly higher than the observed maximum temperature of 17 °C. The deepening of the thermocline between layers is represented as an assumed rate of increase in the epilimnion volume and a corresponding decrease in hypolimnion size. Though there are no layers during the fully mixed period (late November through early May in Figure 4-5), the layer name designations are retained for intra-annual continuity; the epilimnion becomes the hypolimnion arbitrarily on January 1.



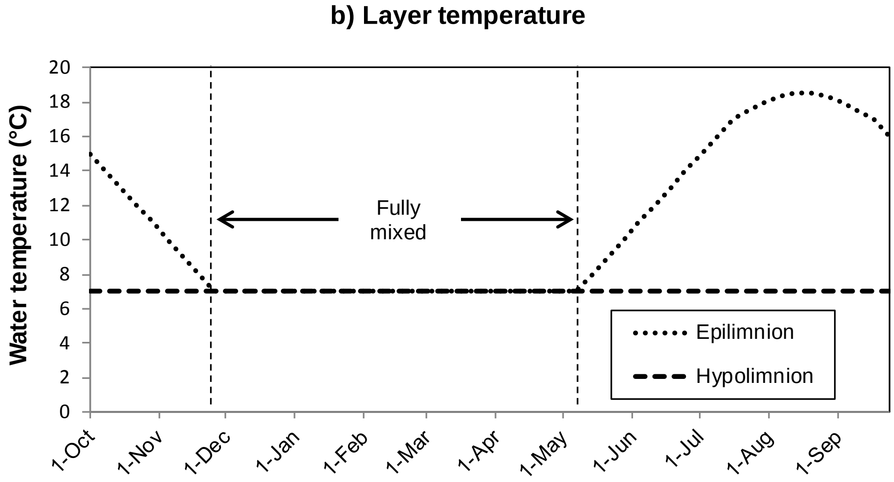
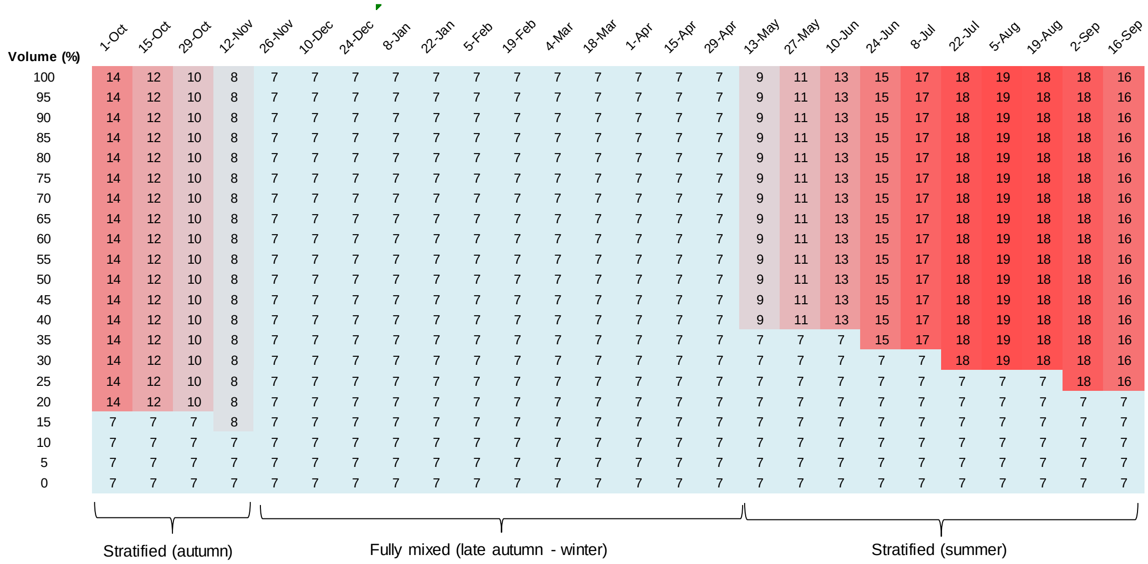


Figure 4-5. Volume and temperatures of layers in a hypothetical thermally stratified reservoir.

Warming is anticipated to increase reservoir temperatures, lengthen the stratification period, and deepen the thermocline (Komatsu et al. 2007). Though no studies have estimated changes in Sierra Nevada reservoir temperatures from global climate warming, Komatsu et al. (2007) estimated an increase in hypolimnion and surface water temperatures of 3.8 °C and 2.8 °C, respectively, with a 3.1 °C in air temperature in a temperate reservoir in western Japan. The epilimnion warms more than the hypolimnion, resulting in stronger summer stratification. Here, for every 2 °C increase in air temperature, the hypolimnion and epilimnion are assumed to increase by 1 °C and 2 °C, generally consistent with the observations of Komatsu et al. (2007). A longer stratification season and deeper thermocline are not represented. In a more developed application, reservoir thermal characteristics, including reservoir thermal layer temperature and the rate of change of the respective layers, would be estimated from a reservoir simulation model.



Volume (%)	1-Oct	15-Oct	29-Oct	12-Nov	26-Nov	10-Dec	24-Dec	8-Jan	22-Jan	5-Feb	19-Feb	4-Mar	18-Mar	1-Apr	15-Apr	29-Apr	13-May	27-May	10-Jun	24-Jun	8-Jul	22-Jul	5-Aug	19-Aug	2-Sep	16-Sep
100	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
95	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
90	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
85	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
80	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
75	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
70	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
65	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
60	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
55	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
50	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
45	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
40	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	9	11	13	15	17	18	19	18	18	16
35	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	15	17	18	19	18	18	16
30	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	18	19	18	18	16
25	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	18	16
20	14	12	10	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
15	7	7	7	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
10	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
0	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7

Stratified (autumn) Fully mixed (late autumn - winter) Stratified (summer)

Table 4-2. Hypothetical mean weekly reservoir temperatures for one water year (Oct. 1 – Sep. 30).

Inflow runoff and stream temperatures

Weekly inflow in this study are from the unimpaired hydrology model developed by Young et al. (2009), calibrated specifically for 15 major watersheds in the western Sierra Nevada, with historical precipitation and with uniform air temperature warming of +0, 2, 4 and 6 °C (see Chapter 2).

Inflow stream temperatures were obtained from Null et al. (in review), who applied the Regional Equilibrium Temperature model (RTEMP; Deas et al. in prep.) to the western Sierra Nevada using runoff from the unimpaired hydrology model developed by Young et al. (2009). RTEMP uses equation (4.9) to estimate stream temperatures in reaches given meteorological conditions, flow conditions, and other physical stream characteristics. Figure 4-6 shows three years of unregulated temperatures from RTEMP in the S. Fork Yuba River at Lake Spaulding. Though the temperatures in Figure 4-6 are altered somewhat with regulation by mixing with releases from Lake Fordyce, on an upstream tributary to the S. Fork Yuba River, it is assumed that these temperatures accurately represent real inflow temperatures to Lake Spaulding.

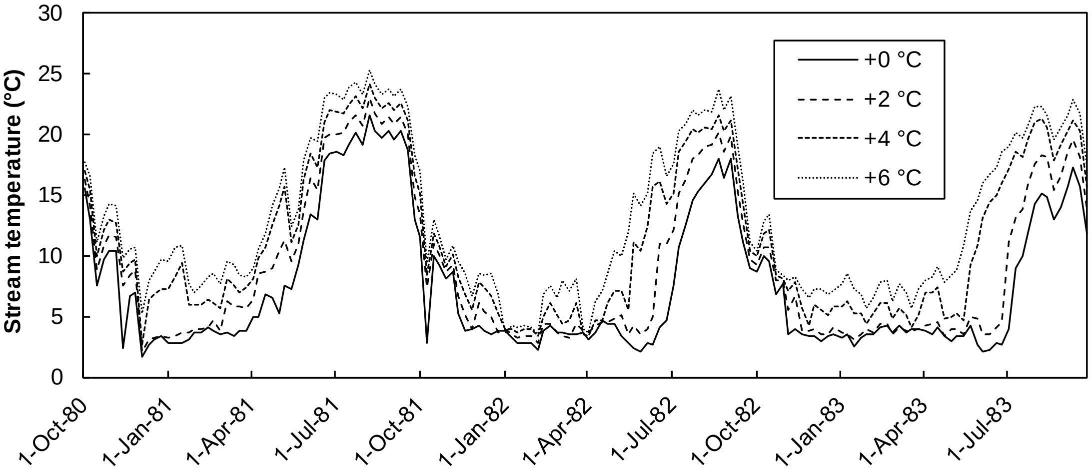


Figure 4-6. Unregulated Lake Spaulding inflow temperature from RTEMP.

Partition fraction

Lake Spaulding inflow temperatures (e.g., Figure 4-6) are used to develop the partition fraction (α) for the contribution of inflow to each reservoir layer. Mean α_{warm} values with warming are shown in Figure 4-7. The partition fraction, which is a function of inflow temperature and layer temperature, increases fractional flow to the epilimnion and reduces fractional flow to the hypolimnion.

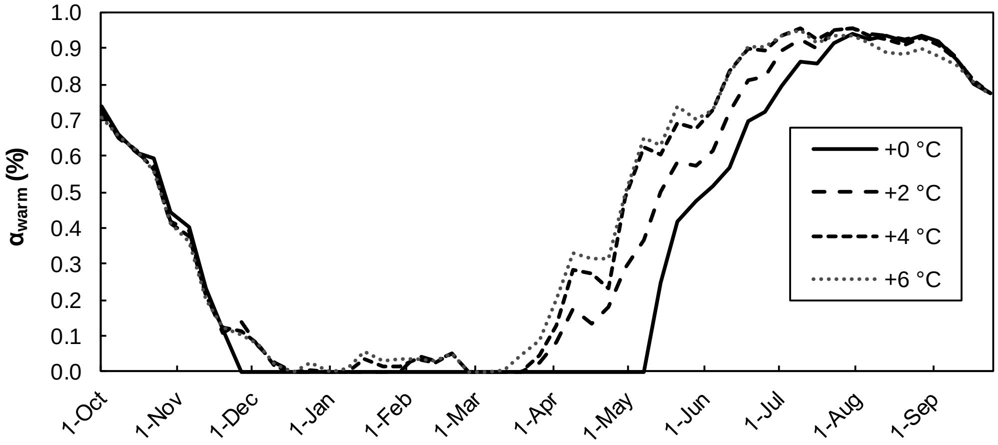


Figure 4-7. Mean warm layer inflow partition fraction (α_{warm}) with warming.

Though partition fractions change with warming, the timing of partition fractions changes little relative to changes in the timing and magnitude of inflows. As the flow regime shifts to a winter precipitation-driven flow regime, we expect greater winter inflow to the cold water pool. Even if the temperature of winter runoff increases, more flow contributes to the reservoir's cold water pool, possibly for use later in the year. This phenomenon underpins the central premise of this case study: as warming increases and the water storage role of snowpack decreases, but reservoirs might be able to not only store more and *colder* water. Though total annual inflow decreases and all stream temperatures increase with 6 °C warming, total cold water inflow increases due to the shift in timing of flows. The specific response of reservoir thermal dynamics to changing inflow temperatures will likely be quantitatively different than the assumptions considered here; a temperature simulation model is needed to refine model parameters.

Longitudinal heating in streams

The Sierra Nevada stream temperature model described by Null et al. (in review) was used to empirically estimate the change in longitudinal temperature needed for (4.26) using (4.9). To account for the dependency of heat changes on stream flow, (4.9) is re-written to include stream flow (*Q*) explicitly. We first note that depth (*d*) and resident time (*h*) are both functions of flow. Resident time is:

$$h = \frac{SL}{v} \tag{0.69}$$

where SL is stream length and v is velocity. Null et al. (in review) approximated depth and velocity as functions of stream flow using the following power equations:

$$d = aQ^b \tag{0.70}$$

and

$$v = kQ^m \tag{0.71}$$

where a, b, k, and m are empirically determined constants set to 1.0, 0.43, 1.0, and 0.45, respectively, from Leopold et al. (1995). Equation (4.9) can now be written to explicitly account for flow:

$$T_f = T_i + \frac{H_{net}SL}{C_p\rho} \cdot \frac{1}{aQ^b \cdot kQ^m} \tag{0.72}$$

Though H_{net} also depends on flow volume (e.g., outgoing long wave radiation) and initial temperature (e.g., heat conduction and evaporation), we assume their effect on temperature change is small compared to other heat transfer mechanisms such as incoming solar radiation and that their dominant influences are included in (4.9). The term $\left(H_{net}SL\right)/\left(C_p\rho\right)$ was calculated from the temperature results of Null et al. (in review) for the 250 m elevation range below the South Fork Yuba at Langs Crossing.

Stream temperature target

Though there is much literature on responses of fish and other aquatic species to temperature and some literature and guidance on managing reservoirs for temperatures, the concept of a *natural temperature regime* akin to the *natural flow regime* (Poff et al. 1997) for inclusion in environmental flow assessments for planning and operating infrastructure has received less attention in the freshwater conservation community (Olden and Naiman 2010). In this study, a natural temperature regime (Cassie 2006; Olden and Naiman 2010) is assumed to be the ideal stream temperature for the downstream ecosystem.

Weekly stream temperatures in the unimpaired SF Yuba River at Langs Crossing, as estimated by Null et al. (in review) are used to develop the target temperature regime, with mean weekly historical temperatures, with no inter-annual variation, used to represent the natural temperature regime. Figure 4-8 shows the target temperature and simulated stream temperatures for unimpaired flows at Langs Crossing. Not all aspects of the natural temperature regime are represented by the mean weekly temperature. For example, the weekly variability seen in the natural runoff temperatures is not represented in the target temperature regime. However, as noted above, physiological responses to a given mean temperature are similar to responses to a range of temperatures around the mean. Additionally, the stream will be naturally variable at smaller scales due to diurnal fluctuations in incoming solar radiation and heterogeneity in mixing in the river.

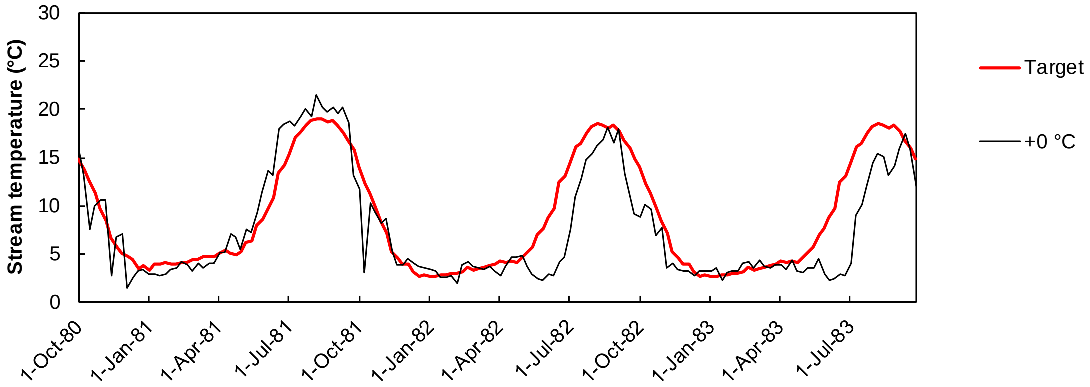


Figure 4-8. Simulated unimpaired and target stream temperatures, South Fork Yuba at Langs Crossing.

The cost of deviating from target temperatures is linearized with three pieces, with deviation ranges and costs as listed in Table 4-3. Deviations above and below the target temperature are weighted equally, since we assume the natural temperature regime is as important as simply keeping the stream temperature below a maximum temperature. Only relative costs are important; the use of dollars as a cost unit is arbitrary.

Table 4-3. Piece-wise linear costs of deviation from target stream temperatures.

Deviation range (°C)	Cost ($/°C)
$0 \leq D \leq 1$	5
$1 < D \leq 3$	10
$3 < D$	20

Case study results

One objective of this work was to understand if and how reservoirs might help ameliorate problems from warming of streams. We assess the results of applying the method to Lake Spaulding with climate warming scenarios, first assuming the more ecologically protective instream flow requirements are in place. This is followed by an investigation of the influence of instream flow requirements on system response.

Regulating temperatures with and without selective withdrawal

We first note the weekly time series of temperature in the South Fork Yuba River at Langs Crossing. Figure 4-9 shows target and achieved stream temperatures at Langs Crossing for the first three years (water years 1981-1983). Assuming the reservoir is operated for new environmental flows, with a minimum instream flow requirement of 35 ft^3/s (1.0 m^3/s) and a maximum down ramp rate of 25%/week (see Chapter 3), regulated stream temperatures deviate from the target temperatures in all years, but generally deviate more in the winter, when the reservoir releases much warmer water than the target mean weekly temperature. Although some naturally colder water comes into the river from Jordan Creek below L. Spaulding (identified as “local inflow” in Figure 4-3), stream temperature is controlled mostly by conditions in L. Spaulding. During the winter, the coldest water in the reservoir, the hypolimnion, is warmer than naturally cold winter flows. However, with a historical climate, the system is generally able to meet warmer temperature targets during the summer, when the reservoir can effectively control release temperatures from each layer. With warming, however, the model is often unable to meet temperature targets during the summer, resulting in more frequent and greater magnitude deviations from the temperature target than with the historical climate during the summer. These trends are also evident from mean weekly temperature across all years (Figure 4-10). Winter managed temperatures are consistently greater, on average, than what would occur without the reservoir. Summer managed temperatures, however, are consistently much closer to the summer target temperature, based on unimpaired natural historical temperatures.

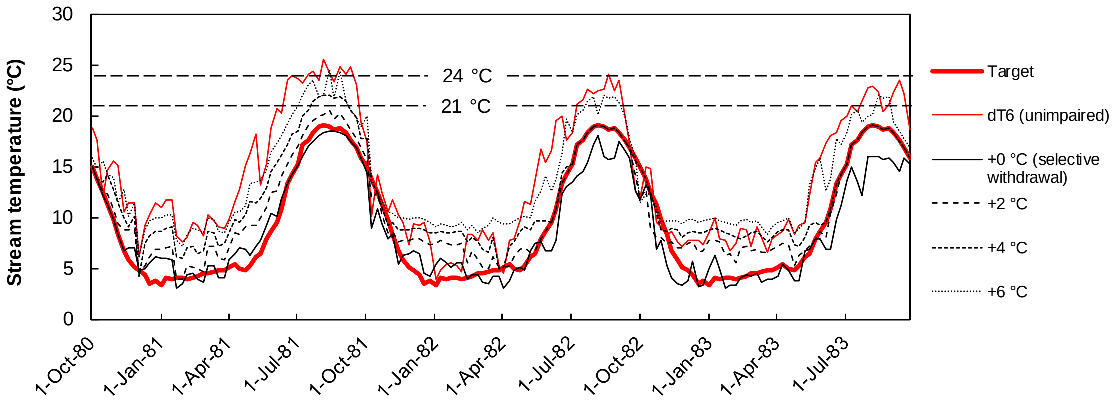


Figure 4-9. Weekly target and achieved stream temperature with selective withdrawal for enhanced instream flow requirements for Water Years 1981-1983.

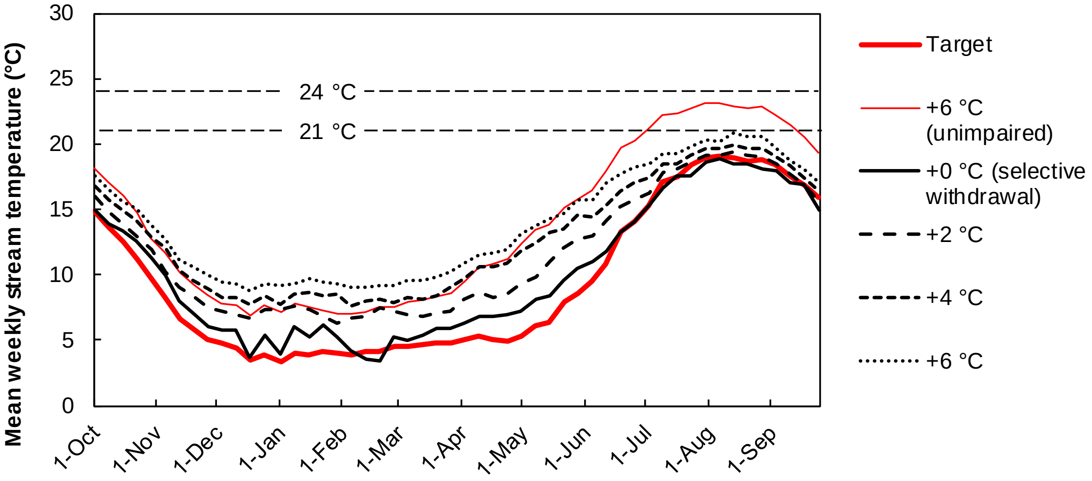


Figure 4-10. Mean weekly target and achieved stream temperature with selective withdrawal for enhanced environmental flows.

The response of the system without the use of selective withdrawal provides insight into how an ideal selective withdrawal system manages temperature to meet downstream targets more effectively. Without temperature control such as selective withdrawal, we assume the reservoir releases water via a low-level outlet at the base of the reservoir and by spill. The low-level outlet therefore always releases first from the cold water pool, then from the warm water pool if there is insufficient cold water. Conversely, spill is always first from the top, taking first from the warm water pool. Because there is no release decision, a simple spreadsheet-based simulation model was developed to determine releases and downstream temperatures using the same parameters and assumptions as in the optimization model. Figure 4-11 shows the stream temperature results of the simulation model for the first three years of the case study period. Because the low level release model is incapable of adhering to a prescribed temperature regime, it results in undesirable high stream temperatures (e.g., late summer flows) and rapid fluctuations in spill. The differences between the low level release model and the optimized selective withdrawal model are discussed below.

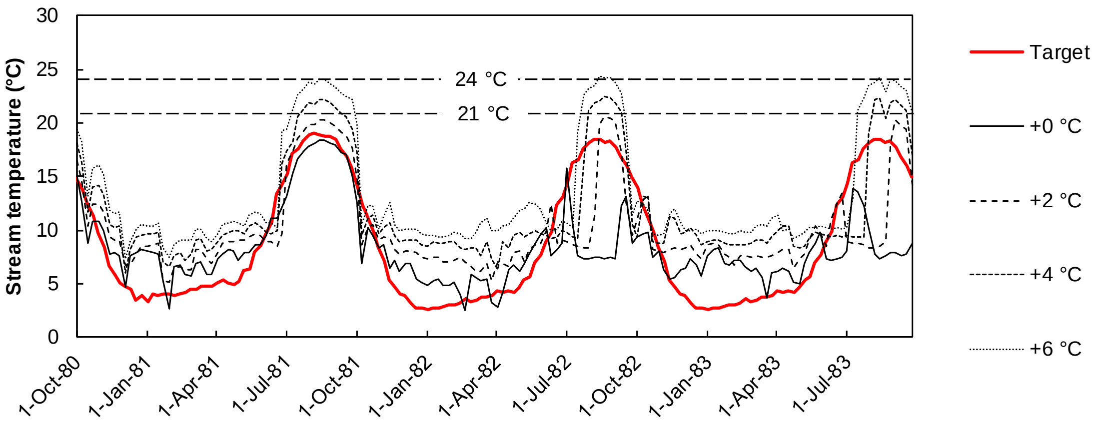


Figure 4-11. Simulated stream temperatures in the South Fork Yuba River at Langs Crossing with a low level release only (no selective withdrawal) at Lake Spaulding.

From an ecological perspective, absolute deviation from the temperature target in any given week is less important than avoiding drastic temperature changes and remaining below the critical thresholds of 21 °C and 24 °C. Figure 4-12 shows the distributions of unimpaired and regulated temperatures during the period of analysis (WY 1981-2000) for the climate warming scenarios are shown in. Similarly, Figure 4-13 shows the distribution of temperatures with and without selective withdrawal, with 2 and 4 °C warming scenarios omitted for clarity. The average number of weeks per year greater than the critical biological thresholds of 21 and 24 °C for each warming scenario and management scheme (unimpaired, low level outlet only, and full selective withdrawal) are summarized in Table 4-4 and plotted in Figure 4-14. An unimpaired flow regime results in stream temperatures equaling or exceeding 21 and 24 °C for about 26.1% and 3.8% of the weeks, respectively, with 6 °C warming. A low level outlet reduces the number of weeks above these thresholds to 21.2% and 4.7% of the time. The use of selective withdrawal reduces threshold exceedances even further to 12.4% and 1.3% of the time. With just 2 °C warming, the low level release and selective withdrawal completely prevent all temperature threshold exceedances.

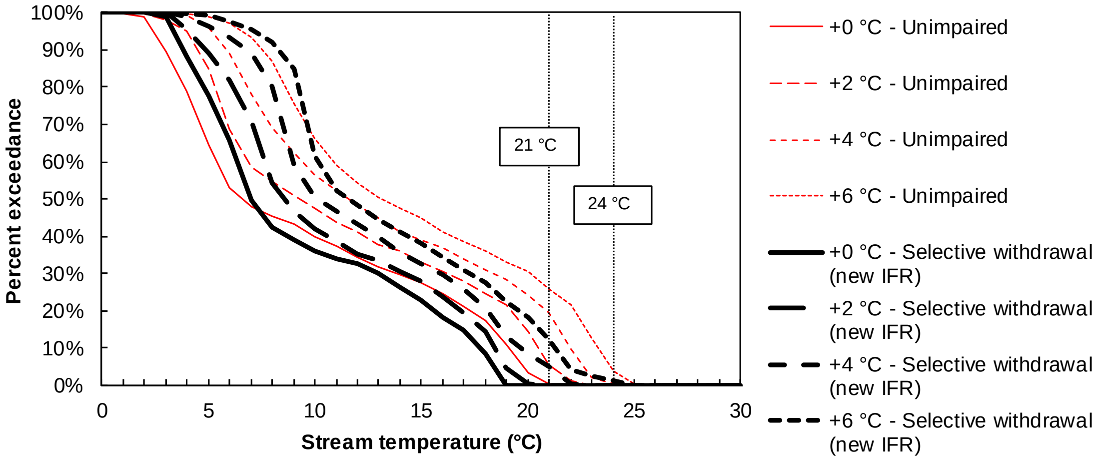


Figure 4-12. Stream temperature distribution for unimpaired flows and regulated flows with new instream flow requirements.

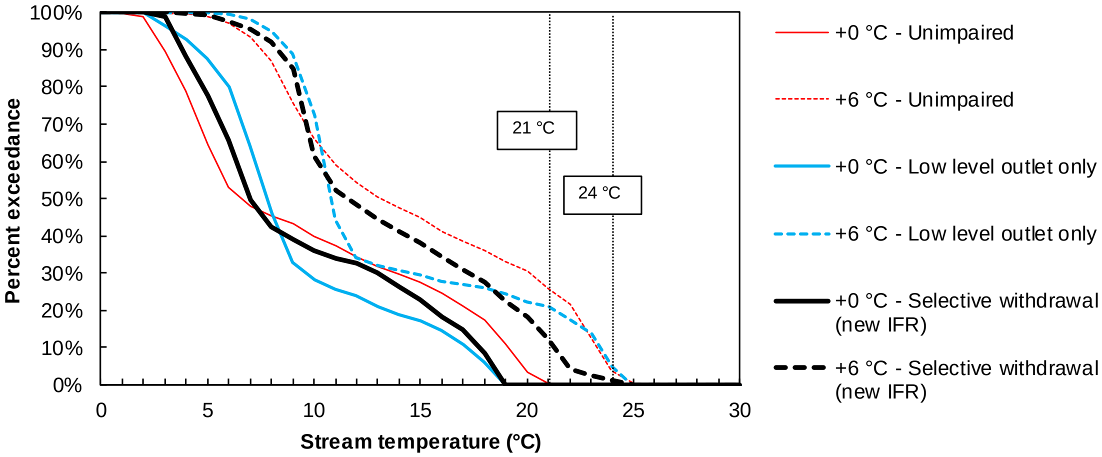


Figure 4-13. Stream temperature distributions for unimpaired flows, low level outlet only (no selective withdrawal) and regulated with selective withdrawal.

Table 4-4. Average weeks per year exceeding (inclusive) 21 and 24 °C for different management schemes.

	Weeks ≥ 21 °C				Weeks ≥ 24 °C			
Management	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**	**+0 °C**	**+2 °C**	**+4 °C**	**+6 °C**
Unimpaired	0.3 (0.6%)	3 (5.7%)	10.1 (19.3%)	13.6 (26.1%)	0 (0%)	0 (0%)	0.2 (0.3%)	2 (3.8%)
Low level outlet only	0 (0%)	0 (0%)	7.4 (14.1%)	11 (21.2%)	0 (0%)	0 (0%)	0 (0%)	2.5 (4.7%)
Selective withdrawal	0 (0%)	0 (0%)	2.8 (5.3%)	6.5 (12.4%)	0 (0%)	0 (0%)	0 (0%)	0.7 (1.3%)

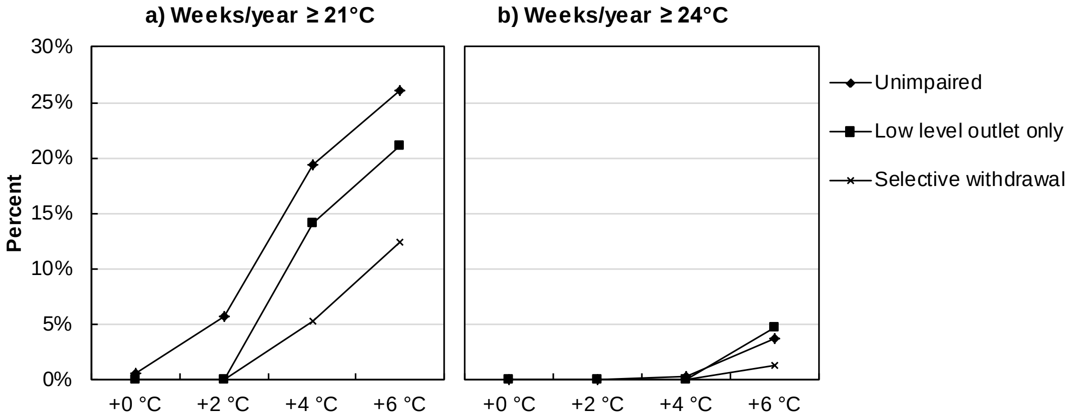


Figure 4-14. Average weeks per year exceeding 21 and 24 °C (inclusive) for different management schemes and climate warming scenarios.

Reservoirs store cold water whether or not there is a selective withdrawal system. Many reservoirs release water that is too cold for downstream fisheries, such that selective withdrawal is used to increase water temperatures that would otherwise be too cold. Here, however, because selective withdrawal is used for cold water fish, it is important that the selective withdrawal scheme completely prevents downstream temperatures from exceeding 24 °C. However, the prevention of lethal stream temperatures in the summer necessarily increases stream temperatures in the winter in all warming scenarios. This demonstrates the tendency of the selective withdrawal optimization model to hedge the use of cold water. In contrast, the low level outlet cannot hedge for temperatures. These differences are demonstrated in Figure 4-15, which compares stream temperatures managed with a low level release only and selective withdrawal in the South Fork Yuba River for the year 1981, with a historical climate. From about May through July, hedging causes the temporal redistribution of temperatures; stream temperatures are almost identical during other times of the year.

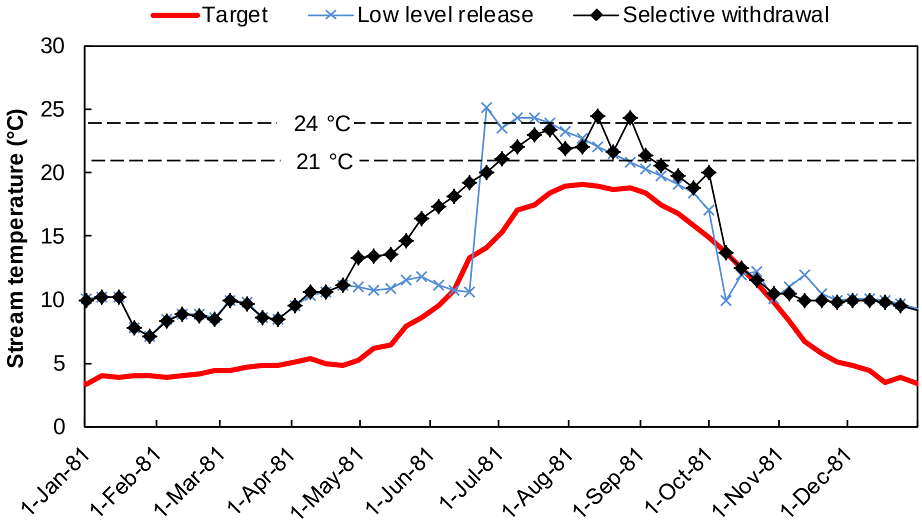


Figure 4-15. Target temperature and managed stream temperature with low level release and selective withdrawal with a historical climate.

Importantly, the selective withdrawal optimization model lowers temperatures during the summer by penalizing deviations from the target temperature regime, rather than by explicitly prohibiting temperatures above the critical thresholds. This characteristic of the selective withdrawal optimization model is particularly important with climate warming, since deviations are penalized equally throughout the year, resulting in a fairly uniform rise in managed stream temperatures during the warm period. Though the case study resulted in no managed stream temperatures above 24 °C, an additional constraint or penalty on an absolute maximum stream temperature might be required.

Though the reduction of absolute average number of weeks above the critical thresholds of 21 and 24 °C are important, the selective withdrawal system has other advantages over just a low level outlet. In Figure 4-11 we see that a low level outlet causes rapid changes in stream temperatures from warm to cold or cold to warm. The selective withdrawal system effectively prevents these temperature shocks. Though this is not explicitly required in the model, the non-linear penalty curve for temperature deviations causes the model to distribute deviations throughout the year rather than in specific time periods, resulting in adhering to the relatively smooth target temperature regime as closely as possible.

The selective withdrawal optimization model also reduces the duration of high stream temperature events anticipated to occur with warming. Figure 4-16 shows the distribution of durations of temperature events above 21 °C. Without regulation (unimpaired flows), the duration of stream temperatures above 21 °C reaches 19 weeks with 6 °C warming. With 6 °C warming generally, most years have high unimpaired stream temperatures lasting between 15 and 20 weeks, much greater than the maximum of 2 weeks or less with a historical climate. Flows equal to or exceeding 24 °C are 4 weeks or less with warming and there are no flows above 24 °C with a historical climate. The low level outlet reduces high temperature durations of 21 °C and 24 °C events to 13 and 4 weeks or less, respectively, with 6 °C warming. With selective withdrawal, the maximum 21 °C and 24 °C temperature event durations are 13 and 6 weeks, respectively, with 6 °C warming. That the maximum duration above 24 °C (in water year 1986) is higher with selective withdrawal than with only a low level release is a result of the selective withdrawal optimization model adhering to the temperature regime. Where the low level release model allows short duration spikes in temperature, the selective withdrawal model values gradual increases and decreases in temperature, resulting in a potentially longer duration high temperature events.

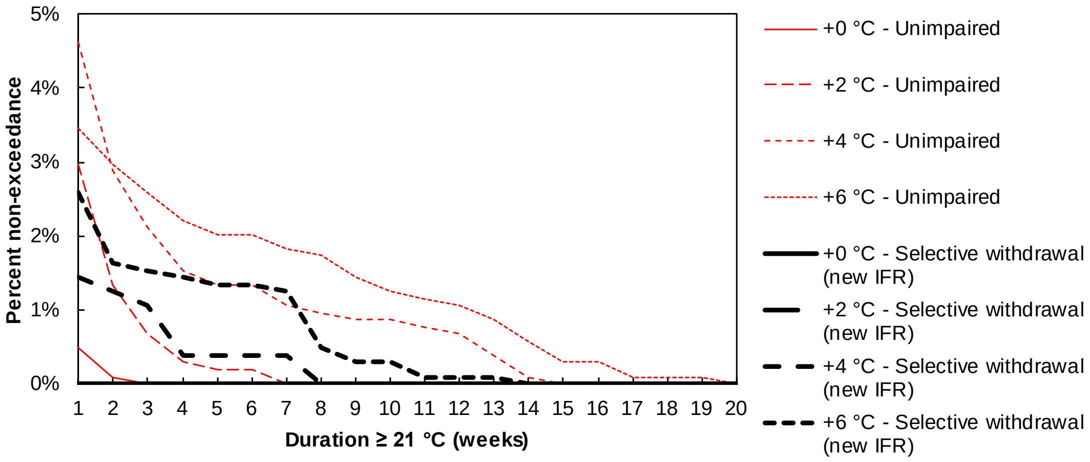


Figure 4-16. Stream temperature event durations above 21 °C with selective withdrawal.

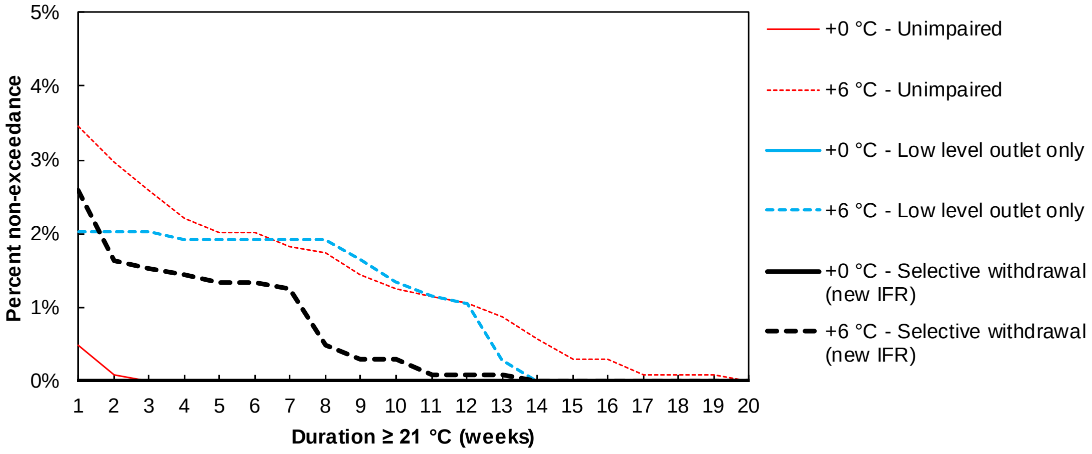


Figure 4-17. Stream temperature event durations above 21 °C with a low level outlet only and selective withdrawal.

Selective withdrawal with historical instream flow requirements

Though the main interest here is with releases managed for enhanced instream flow requirements—a more likely future for the South Fork Yuba River at Langs Crossing than historical requirements—we also note the response of the optimized system to historical operations, with minimal instream flow requirements and without releases for the spring snowmelt recession limb. With historical operations (Figure 4-18), the model has a greater ability to meet the temperature target than with higher minimum instream flows (see Figure 4-10). This is also reflected in the long term distribution of stream temperatures (Figure 4-19). The difference in model results with different releases is influenced by several factors, only one of which is integrated into the model. First, a greater instream flow requirement depletes the cold water pool sooner. This management concern is well-represented in the model. Greater releases also reduce the rate of longitudinal cooling in the stream (Carron 2000). The dependency of longitudinal warming on flow rate is not currently represented in the model, which reduces the value of a more comprehensive assessment of the effect of minimum instream flows on release temperatures in this study. Longitudinal warming also depends on boundary temperature conditions, such as the upstream temperature in any reach below a release point. This effect is not included in the model, but could be with linearization of a curve representing *f* as a function of upstream temperature.

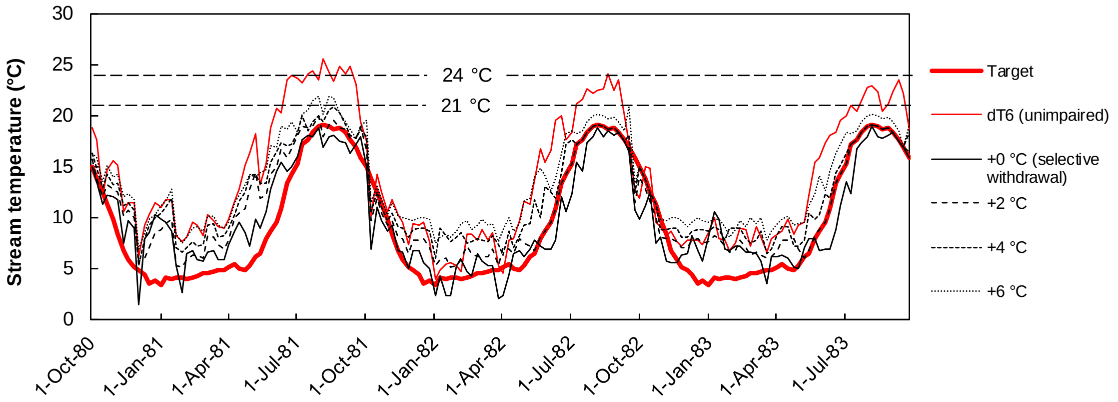


Figure 4-18. Weekly target and achieved stream temperature with selective withdrawal for historical instream flow requirements for Water Years 1981-1983.

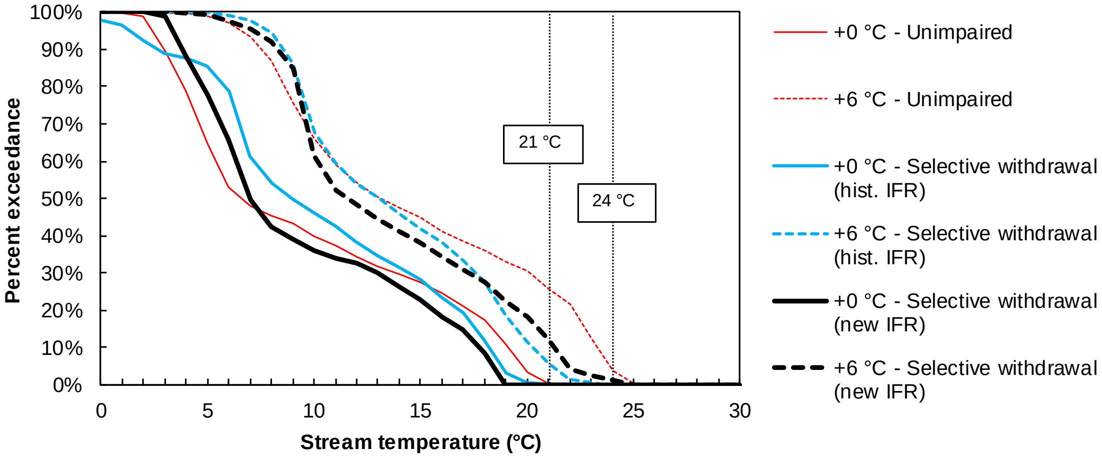


Figure 4-19. Stream temperature distributions for unimpaired flows and selective withdrawal with historical and new instream flow requirements (IFR).

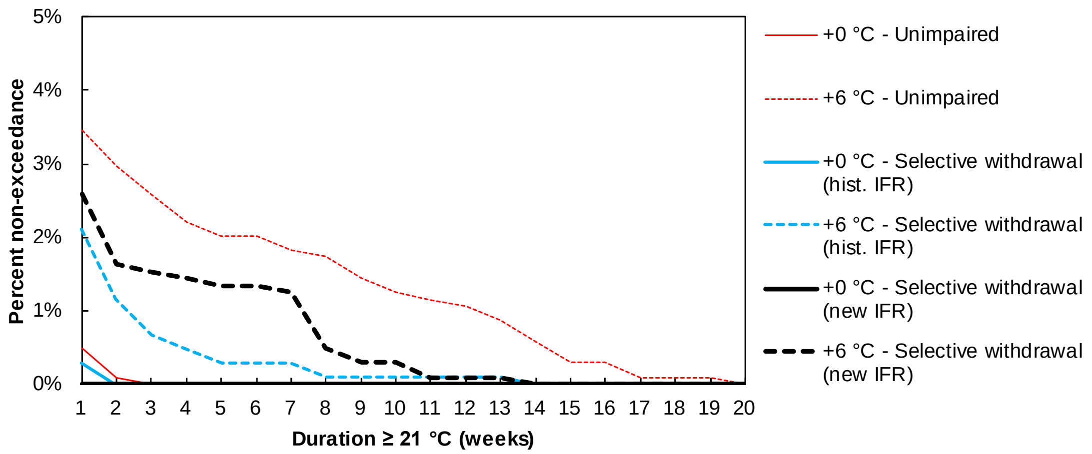


Figure 4-20. Stream temperature event durations above 21 °C with historical and new instream flow requirement (IFR) and selective withdrawal.

Reservoir behavior

To understand the behavior of the model, we explore the behavior of reservoir pool operations, only considering optimized operations with selective withdrawal and new instream flow requirements. First, reservoir pool storage volumes with a historical climate are shown for the first five years of the study period (Oct. 1, 1980 – Sep. 30, 1985) in Figure 4-21. Though the thermal behavior is simplified, the trends reflect what is expected, based on model input: warmer temperatures in the summer cause the formation of a warm upper layer, which grows and, later in the year, cools until it becomes indistinguishable from the cold layer in the winter. Figure 4-21 reflects the ability of the reservoir to store colder water, represented by the mean reservoir temperature. In wetter years (1982-1983), more cold water is stored, keeping mean reservoir temperatures lower than in years with less reservoir storage.

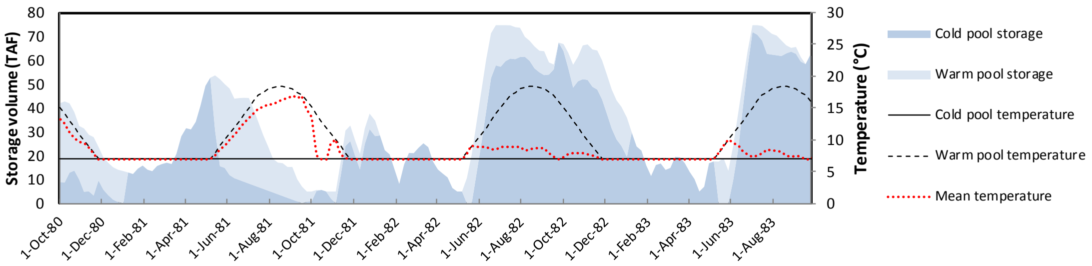


Figure 4-21. Reservoir storage and temperature time series with a historical climate.

We seek to understand how the reservoir behaves with warming, given known reservoir thermal dynamics. To do this, we first look at the mean weekly storage in each thermal pool and cold, warm, and mean pool temperatures for each warming scenario, as shown in Figure 4-22. The magnitude and timing of both mean total storage and storage in each pool changes. As peak reservoir storage shifts to earlier in the year, storage at the end of the water year decreases. Figure 4-22 also shows how mean reservoir temperature increases with warming. In particular, maximum mean reservoir temperature increases from approximately 13 °C in July to about 21 °C in late September with 6 °C warming.

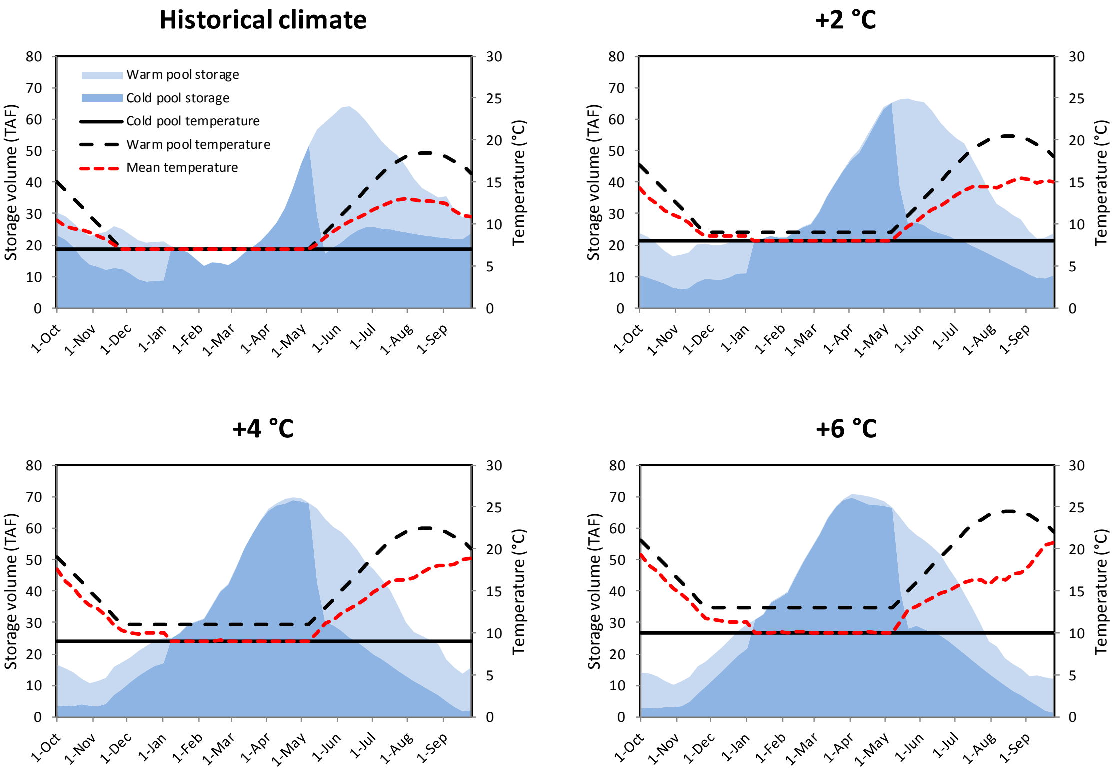


Figure 4-22. Mean reservoir storage and temperature with warming.

Mean storage in each layer is also shown in Figure 4-23, in which the change in mean weekly timing and magnitude with warming is more apparent. Water in the cold pool (hypolimnion) shifts to earlier in the year, such that with 6 °C warming the cold pool is completely exhausted by the end of the year. However, though the end-of-year cold pool decreases, the total cold water pool increases. In contrast, total warm pool volume decreases, while the amount of end-of-year warm water storage increases with warming. These results show that the model depends increasingly on the ability to release cold water later in the year to meet stream temperature targets. The model tries to release as little warm water as possible during the summer.

Though the model can effectively manage the available cold water to minimize deviations from the temperature targets in the summer, these results show that the model would likely be unable to prevent more frequent occurrences of lethal releases with further warming. With 4 and 6 °C warming the cold reservoir pool is almost completely exhausted by the end of the year, on average, leaving little additional adaptive capacity with far term warming.

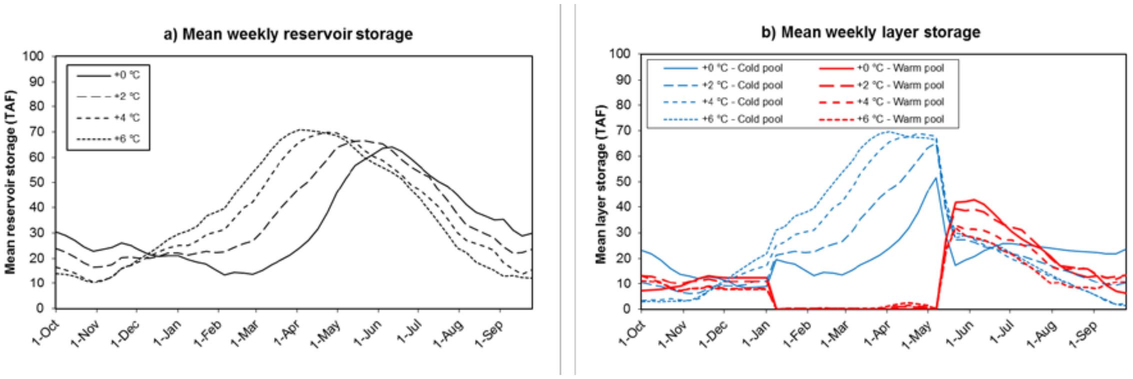


Figure 4-23. Mean weekly (a) total reservoir storage (b) and layer storage with warming.

Limitations and future work

The primary limitation of this method is the need to simplify the thermal dynamics in reservoirs. For example, reservoir inflows and outflows are assumed to have negligible effects on reservoir thermal dynamics. While this is reasonable for a planning model or short-term operations, in reality inflows would have an effect. Additionally, reservoir inflow temperatures are assumed known, as needed to determine the fractional partitioning of inflow to each layer, which removes the dependency of downstream reservoir operations on upstream reservoir operations. Reservoir temperature simulation studies could be used to determine how much this would likely affect optimization results.

A second major limitation is the assumption of linear warming rates in stream reaches. This assumption is generally reasonable for short reaches, though less so for longer reaches, as stream temperatures increase longitudinally at decreasing rates as they approach their equilibrium temperatures. This could be accounted for in two ways. First, each segment could be divided into smaller segments (sub-reaches), with decreasing warming rates in successive downstream sub-reaches. However, this would require considerations of computational speed, since increasing the complexity of the model with piecewise linearization would necessarily reduce speed. Second, the warming rate could be set conservatively high, such that modeled downstream temperatures in a given reach are higher than they would likely be with real operations. This would further ensure that modeled temperatures represent the worst-case scenario for fish harmed by extreme high temperatures.

A second limitation in representation of stream thermal dynamics is the lack of dependency on upstream boundary conditions. As with longitudinal warming, this limitation can be addressed in the model itself or with appropriately adjusted warming factors. Multiple linearized warming curves could be used to account for the dependency of stream warming on upstream conditions. Alternatively, the warming factor can be based on assumptions about the stream temperatures that are likely to be released, for example by assuming released temperatures will be close to the target stream temperature at point of release.

Suggestions for future work

The work presented here is focused on assessing a very specific set of conditions, specified by model inputs. However, it may be of interest to generalize the results to provide broader insights about reservoir operations for downstream temperature management. Specifically, it could be useful to quickly identify when selective withdrawal would likely provide the best option to maintain downstream temperatures below a specified target. If a variable, natural temperature regime is important, as in this work, then it is clear from Figure 4-15 that selective withdrawal (or a temperature control device generally) is the only option. However, if only a maximum temperature limit is required, a low level outlet without selective withdrawal might be sufficient. On the other hand, conditions might be such that even selective withdrawal is incapable of maintaining downstream temperatures below a high temperature limit (e.g., Figure 4-14).

To determine whether a low level outlet is sufficient, selective withdrawal is needed, or that neither will suffice, one could compare warm season releases with cold season inflow, both mediated by reservoir storage capacity. Thus, one can compare the ratio of storage capacity to warm water release with the ratio of cold water inflow to storage capacity. If warm season release is sufficiently low, cold season inflow is sufficiently high, and storage capacity is high, a low level outlet would suffice to maintain a downstream cold water fishery. Conversely, if the warm season release is high, cold season inflow is low, and reservoir capacity is low, even a well-managed selective withdrawal scheme would likely be insufficient to keep downstream temperatures low if surface reservoir temperatures are high. This is conceptualized below in Figure 4-24, where S_{max} is reservoir storage capacity, R_{warm} is warm season release, and I_{cold} is cold season inflow. A detailed investigation of the regions in Figure 4-24 would reveal the actual shape of the region boundary curves, but they are likely convex.

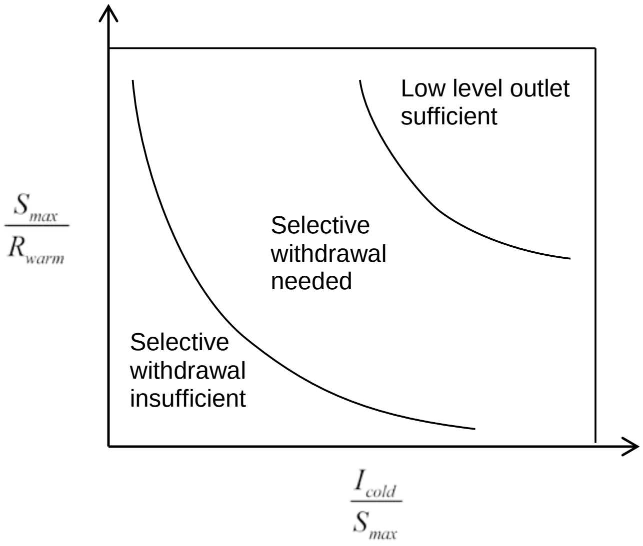


Figure 4-24. Conceptual range of suitability for selective withdrawal.

Additional future work includes refinements of the model itself, as suggested above. In particular, a reservoir temperature simulation model is needed both for the case study used here (L. Spaulding in the Upper Yuba River watershed) and for any reservoir(s) for which this method is applied. Further theoretical work which might yield insights into reservoir management includes a more detailed assessment of heat and heat management instead of temperature management described here. Though fish respond physiologically to stream temperatures, the concept of a "natural heat regime" could better inform reservoir planning and management for stream temperatures.

Conclusions

The value of the work described here is twofold. First, the study demonstrates an effective method of including an instream temperature optimization model using selective withdrawal in a flow network using linear programming. Second, it highlights how a temperate reservoir might be used to help adapt to climate warming by managing downstream temperatures. In particular, results from the case study indicate that Lake Spaulding, a seasonally stratified reservoir in the Sierra Nevada, could be used to reduce the number of weeks per year above critical temperature thresholds if outfitted with a good selective withdrawal system and managed properly. As expected, an ideal and optimally managed selective withdrawal system manages downstream temperatures better than a single low level outlet.

Since the selective withdrawal optimization model described uses results from a simulation model as input, it does not need to be run just once, but instead could be run iteratively with any one of a number of one-, two-, or three-dimensional reservoir water quality simulation models that exist. Similarly, the model could be run iteratively with a reservoir release model in a broader evolutionary algorithm that considers combinations of water quantity and quality in a multi-objective optimization problem.

Though the case study demonstrated how reservoirs can help reduce downstream temperatures that follow a specified stream temperature regime, partly by providing cold water storage and partly by managing releases, the study also demonstrates that a reservoir cannot completely maintain historical stream temperatures. Climate warming will increase not only rates of warming in streams, but also reservoir temperatures and seasonal stratification dynamics. The reservoir can compensate for some loss in snowpack by re-regulating temperatures (and flows), but cannot replace snowpack entirely. To even partially compensate for lost snowpack requires that the system be managed optimally, as informed by operations planning studies. Optimal management requires an ability to adapt system operations to changing management conditions, including environmental conditions and, likely, management targets.

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Chapter 5:
Conclusions and Future Work

The general goal of this work was to develop and evaluate multi-reservoir management models and modeling techniques to better understand the implications of climate change for restoring environmental flows and temperatures. The specific studies explore both the regional scale effects of climate warming on hydropower generation—including the entire upper west slope of the Sierra Nevada mountains—and more assessments of the possibility of including better environmental flows and temperatures in specific locations. Several broad conclusions can be drawn from this work:

1. Regional-scale simulation models that include multiple water sectors to assess regional vulnerabilities to hydrologic changes associated with anticipated warming are both necessary and possible. While the Sierra Nevada-wide water resources simulation model described in Chapter 2 is best used at coarse temporal (monthly to seasonal) and spatial (watershed) resolutions, it is an ambitious and successful first step toward higher resolution accuracy for more detailed impacts assessments.
2. Substantial hydropower losses are likely to occur in the northern and southern part of the upper west slope of the Sierra Nevada with end-of-century (+6 °C) warming. Central watersheds, however, could very well see very little reduction in generation, due to a combination of a more uniform distribution of runoff and existing reservoir capacity to accommodate hydrologic changes. Hydropower losses could be much greater if reductions in annual flows are greater than those considered here.
3. Re-operating reservoirs in the upper Yuba River watershed to more slowly ramp down releases at the end of the traditional spill period to restore ecologically beneficial spring snowmelt recession flows is not likely to affect hydropower generation or revenue substantially. This is because the hydropower operator can shift hydropower production to different parts of the year to accommodate down ramp restrictions. These results are likely to hold true for any hydropower system where a down ramp rate is imposed, as a down ramp rate changes the timing of hydropower generation, not the total water available for hydropower production.
4. Including selective withdrawal for downstream temperature management in a water management model is possible using a node-link type optimization framework with linear programming. This method, with careful model parameterization, is a promising option for understanding the efficacy of using selective withdrawal in a multi-reservoir system.
5. Selective withdrawal can likely ameliorate harmful increases in stream temperature from climate warming. In particular, optimally designed and managed selective withdrawal can likely help keep downstream stream temperatures within a range suitable for a cold water fish where lack of a reservoir—or a reservoir without selective withdrawal—would release water with temperatures that frequently exceed biologically harmful temperatures.

Although the outcomes of these studies contribute to our understanding of reservoir management and hydropower at the intersection of water management, ecosystems, and climate warming, there are many opportunities to improve this work practically and conceptually. Promising options for improving and building on the collective utility of these studies are described below.

Integrating models

The studies described here can inform further studies in pursuit of the broader motivations of this work, as described in Chapter 1: to better understand the potential for re-operating existing hydropower and other water resources systems for better water resources management, in particular for better management of water for freshwater ecosystems. Computer models such as those described here can create both an inventory of regional effects of existing operations, possibly with different exogenous conditions such as climate warming, and to help quantify effects of new operations. In the Sierra Nevada, regional-scale models are needed due to the tightly connected nature of water and electricity resources within California. In this context, the most useful long-term modeling goal from the studies here is an integration of the methods and models presented. This could be done in two ways: by combining the models and methods as they currently exist, with some conceptual improvements as needed, or by establishing by developing completely different approaches to better integrate multiple management objectives and to include non-linearities. The former is the best approach, as it leverages existing models, is easy to understand to non-specialists, and is computationally efficient.

The simulation model in Chapter 2 creates the basic framework for a large-scale, small time step (weekly) operations model that includes all water use sectors. Chapter 3 demonstrated the ability of the linear programming optimization model to accurately represent historical operations and to include at least one more advanced instream flow requirement in addition to a standard minimum instream flow requirement. Since the optimization model is driven by economics, which reflects the real management of water as a scarce resource, understood in economic terms, the use of the optimization model in the larger, WEAP-based simulation framework is a straightforward improvement. This would allow a more detailed representation of hydropower (and other) operations at a temporal scale that is not currently captured by the simulation model. The temperature optimization model described in Chapter 4 could then be readily applied to the entire upper west slope Sierra Nevada after applying the Sierra Nevada-wide optimization model to determine optimal releases. This approach would require additional effort to actually implement, though the studies described here provide most of the building blocks to do this, conceptually and otherwise.

An alternative conceptual approach to integrating the existing models is to manage for quantity and quality simultaneously (Loucks et al. 1981). The approach used here (Chapters 3 and 4) was to optimize first for quantity (flows) then for quality (temperature), such that quantity and quality are considered independently. Though this approach is commonly used, quantity and quality are both valued in real water systems, such that the optimal management decisions should consider both quality and quantity in a unified optimization scheme, though not necessarily as one multi-objective optimization problem. This topic and options for integration are discussed by Chaves et al. (2003). One of the challenges of integrating quality and quantity in an optimization scheme is the complexity of quality characteristics in real systems, resulting in the need for a simulation-only iterative approach, a combined optimization (quantity) and simulation (quality) approach, or an optimization-only approach that greatly simplifies quality dynamics. Metaheuristic techniques, which include evolutionary algorithms such as genetic algorithm, can be used in a simulation-only approach, whereby both quantity and quality are simulated many times with successively better decisions based on analyzing the results of previous simulations. Though metaheuristic approaches can easily accommodate simultaneous multiple objectives and non-linearities, they require many simulations and are therefore too computationally expensive for application to the many complex systems typical of the Sierra Nevada. In a combined optimization-simulation approach, such as used by Chaves et al. (2003), water quantity is optimized and the resulting quality characterized with simulation.

In the optimization-only approach, both quantity and quality are considered in the objective function of an optimization model. For example, this approach was used by Mehrez et al. (1992) to manage salinity levels in water deliveries in a large, multi-source water supply system using non-linear programming (GAMS/MINOS), by Hayes et al. (1998) to manage dissolved oxygen and temperature in a multi-reservoir hydropower system using optimal control theory, and by Olivares (2008) to study the management of temperatures downstream from a single reservoir with selective withdrawal using dynamic programming. To explore selective withdrawal management in a multi-reservoir system, Paredes and Lund (2006) used a linear programming model based on analytic operating rules to optimally manage releases from multiple layers in reservoirs in parallel. Of these, only Hayes et al. (1998) include water quality changes within the system model, noting that "efficient solution of this problem is challenging because of the problem nonlinearity, high dimensionality of the state space, existence of state-space constraints, and the requirement for dynamic solutions over an extended time horizon."

Either of these approaches—water quantity optimization followed by quality optimization or a combined quantity-quality optimization scheme—would work in the Sierra Nevada. However, it is likely that the best near-term option is the further refinement of the water quantity model, with the integration of a flow optimization routine into the Sierra Nevada system-wide model, followed by development of a water quality simulation model. Once baseline water quality conditions, particularly temperature, due to operations can be established, an integrated water quantity-quality optimization model can be developed to inform new operational possibilities.

Using models to inform long-term planning for ecosystems

Finally, information gleaned from improved regional-scale water management models can be used to better plan freshwater ecosystem management with a changing climate (Lester et al. 2011). Quantitative assessments of vulnerability of all water sectors to climate warming are needed. While the impacts assessments used in Chapter 2 are a good start, assessments should be expanded to consider the combined effects of climate exposure, exposure uncertainty, system response, and adaptive capacity (Füssel and Klein 2006; IPCC 2007) to characterize the vulnerability of regulated environmental flows to climate warming. Ultimately, the effects of multiple management domains across a range of environmental domains (Bratrich et al. 2004) need to be assessed within this vulnerability assessment framework for specific reaches across a region to most effectively inform regional freshwater ecosystem management priorities. The models presented here, with the improvements described, could be used for some management and environmental domains, yet no single model would be able to adequately represent all environmental impacts.

To help assess the vulnerability of environmental water, for example, comprehensive, everything-included water resources management models can be used to quantitatively assess hydrologic alterations due to infrastructure operations. The Indicators of Hydrologic Alteration (IHA) method (Richter et al. 1996) is a good starting point for such assessments, though would need to be tailored to the local natural flow regime (Poff et al. 1997). IHA-type analyses are needed with both historical and anticipated future climate conditions to provide a basic understanding of current and projected effects of current, baseline operations on instream flows. Such analyses should also be expanded to include effects on other important river characteristics, such as temperature and sediment. These analyses require improved operations representation as coarse-scale models, such as those described and used in Chapter 2, inadequately address in-river conditions with enough specificity to inform detailed IHA-type analyses.

The utility of IHA-type analyses to ecosystem assessments is limited since they do not place relative importance or value to the many hydrographic components that are quantified. Others have shown that specific features have disproportionate ecological benefits. Thus, any IHA-type method should be combined with an importance weighting scheme to be most ecologically relevant. Though identifying the ecological importance of specific flow (and temperature) regime features remains an active area of research, sufficient progress is being made (e.g., Yarnell et al. 2010) such that we can begin to incorporate quantitative alteration assessments into ecologically meaningful local and regional water management studies (Poff et al. 2010).

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