

**Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT**

MANAGEMENT OF THE SPRING SNOWMELT RECESSION

An Integrated Analysis of Empirical, Hydrodynamic and Hydropower Modeling Applications

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Prepared by:

Primary Author(s):

Sarah M. Yarnell¹
Ryan A. Peek¹
David Rheinheimer¹
Amy Lind²
Joshua H. Viers¹



¹Center for Watershed Sciences
John Muir Institute of the Environment
One Shields Avenue
University of California, Davis, CA 95616

²USDA Forest Service
Tahoe & Plumas National Forests
631 Coyote Street
Nevada City, CA 95959

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Prepared for:

California Energy Commission

XXXX XXXXXX
Contract Manager

XXXX XXXXXX
Project Manager

XXXX XXXXXX
Office Manager
Name of Office Goes Here

XXXX XXXXXX

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PREFACE

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Management of the Spring Snowmelt Recession: An Integrated Analysis of Empirical, Hydrodynamic, and Hydropower Modeling Applications is the final report for the project entitled “Management of the Spring Snowmelt Recession” (contract number 500-09-033) conducted by the University of California, Davis, Center for Watershed Sciences. The information from this project contributes to PIER’s Energy-Related Environmental Research Program.

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ABSTRACT

Over the past decade, the Natural Flow Regime paradigm has garnered widespread study, discussion and general acceptance in the scientific community as a guide for conservation, restoration and management of rivers. However, one fundamental aspect of the natural flow regime that has received little attention in both scientific study and resource management is the importance of the spring snowmelt recession to ecological stream processes. This study sought to improve understanding of both the ecology, through empirical field studies and hydrodynamic modeling, and water management, through hydropower optimization modeling, of the spring snowmelt flow regime in regulated and unregulated river systems. Substantial differences were observed between regulated and unregulated rivers in flow timing, temperature and spring recession rate of change and duration, particularly in relation to hydropower operation. These hydrologic differences were correlated with observed variation in frog breeding behavior as well as measures of primary and secondary productivity, as evidenced by quantified benthic macroinvertebrate indices. These results support the ecological basis for providing increased instream habitat diversity to promote increased biotic diversity. Using a daily percent decrease in flow methodology to quantify spring snowmelt recession flows, hydrodynamic modeling results showed that flow recessions with down ramping rates similar to those observed in unregulated systems (less than 10% per day) provided the most diverse hydraulic habitat for an appropriate duration in spring to support native species and maximize aquatic biodiversity. Hydropower optimization modeling showed that projected regional climate warming did not necessarily decrease hydropower output in the Upper Yuba River in the near-term, while increased allocations to environmental flows through increased minimum instream flows and limited spring spill down-ramp rates decreased hydropower generation by less than 4% in the near term. The combined results of this study provide resource managers not only with increased knowledge regarding the ecology of the spring snowmelt recession, but also with a series of methods that will help predict the impacts of various spring flow regimes on the diversity of aquatic and riparian species. As such, the results are directly applicable in current and future hydropower relicensing efforts where improved ecological knowledge and various modeling applications can be utilized to guide instream flow determinations.

Keywords: river regulation, spring-snowmelt recession, natural flow regime, two-dimensional (2D) hydrodynamic model, hydropower, hydraulic diversity, flow management,

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EXECUTIVE SUMMARY

The predictable spring snowmelt recession pattern observed in unregulated rivers in the Sierra Nevada is an integral driver of the aquatic ecosystems in these watersheds. Both biotic and abiotic components of these ecosystems have evolved in conjunction with the consistent rate of recession and duration of the spring snowmelt. Disruptions to this important environmental cue via hydropower regulation have significantly altered these ecosystems, biologically and hydrologically, resulting in substantial biophysical differentiation among regulated and unregulated systems. To date, however, quantitative data to support this conclusion have been disparate and sparse, often leading to general inferences about affected ecosystems and thus a lack of understanding of how best to manage springtime flows.

This study sought to improve understanding of both the ecology, through empirical field studies and hydrodynamic modeling, and water management, through hydropower optimization modeling, of the spring snowmelt flow regime in regulated and unregulated river systems. There were two main components of this work: (1) assessing the effects of the spring flow regime on abiotic and biotic stream conditions through analyses of empirical field data and 2-dimensional hydrodynamic modeling results, and (2) applying and enhancing existing systems analysis techniques for multi-reservoir hydropower operations with ecologically meaningful instream flow constraints. The results provide resource managers not only with increased knowledge regarding the ecology of the spring snowmelt recession, but also with a series of methods that will help determine the impacts of various spring flow regimes on the diversity of aquatic and riparian species. As such, these results are directly applicable to current and future hydropower relicensing efforts where instream flow determinations would benefit from improved ecological and operational insight.

Effects of the Spring Snowmelt Recession on Abiotic and Biotic Stream Conditions

The Mediterranean climate of California has a predictable seasonal pattern of cool, wet winters and warm, dry summers; however, hydroclimatic conditions may vary in any individual year across a spectrum of very wet to very dry. These different water year types are associated with differences in the magnitude and timing of precipitation and associated runoff, as well as correlated shifts in water temperature. The unaltered spring snowmelt recession, however, annually bridges the cold flood flows of winter with the warm low flows of summer and exhibits a markedly predictable pattern. The gradual decrease in discharge and increase in water temperature during the spring recession period provides distinct, reliable cues for reproduction in fishes and amphibians, appropriate habitat conditions for recruitment of riparian vegetation and contributes to diversity in benthic macroinvertebrates (BMI). However, minimal data exist that characterize the differential effects of the spring snowmelt recession in regulated and unregulated rivers on abiotic and biotic conditions. The purpose of this study was to identify and characterize abiotic and biotic patterns across a range of flow regulation types using accessible metrics that can be applied in current and future management efforts.

Intensive field efforts over the course of two consecutive years (2011 - wet and 2012 - dry) collected biological data at six study sites, including surveys of riparian vegetation, algae (biomass), benthic macroinvertebrates, foothill yellow-legged frogs, and fishes. Abiotic data were collected at all sites, including hydraulic habitat, channel morphology, and water quality. Stream temperature and stage were monitored continuously during the project with pressure transducer loggers. Historical gage data were synthesized to quantify differences in flow timing, magnitude, rate of change and duration of the spring recession for each site. Collectively, these data provide one of the most complete syntheses of abiotic and biotic information for a set of rivers in the Sierra Nevada to date, and offer a baseline to compare and contrast the effects of river regulation with unregulated reference sites.

Substantial differences were observed between regulated and unregulated rivers in flow timing, temperature and spring recession rate of change and duration, particularly in relation to hydropower operation type. These differences correlated with observed variation in frog breeding and stream productivity, such as standard benthic macroinvertebrate (BMI) indices. Unregulated sites had the most consistent spring flow patterns and most diverse habitat availability of the study sites, as well as the highest BMI richness and amphibian abundance. Regulated sites were characterized by more inconsistent flow patterns, lower hydraulic diversity through time and lower BMI richness. Algae patterns indicated temporal deviations between sites and significant differences in biomass, largely due to the presence of the invasive diatom, *Didymosphenia geminata*, on regulated reaches. Instream habitat conditions in the regulated bypass reaches were more similar to the unregulated reaches in wet years and more similar to the highly regulated reaches in dry years, with biotic conditions reflecting this intermediary state

All study site rivers have been significantly disturbed in the past through the effects of gold mining, and legacy effects of these disturbances remain, thus other biotic factors reflected a legacy of historical land use conditions and as such varied less across regulation types. Fish surveys showed few differences in species composition across all sites, but presence of several native species associated with spring spawning were observed during the spring snow melt recession period. Riparian vegetation was largely dominated by non-native species, particularly in the Yuba River study sites, and only one site, the Middle Fork American, had more native than non-native plant species. These observations also likely reflect the scale of the study and its study design, which were intended to characterize the ecogeomorphic effects of river regulation in the Sierra Nevada during an important hydrologic period.

The implications of this study are wide-ranging because the results, while limited to only two field seasons, provide not only a comprehensive comparison of key biotic and abiotic factors across rivers with varying degrees of regulation, but also serve as baseline conditions for on-going and future monitoring efforts in the northern Sierra Nevada. The observed relationships between flow variability, hydraulic habitat diversity and biotic diversity, while observational and correlative in nature, are compelling and support findings from previous studies that show increased habitat diversity supports increased biotic diversity. Additionally, the study results support previous findings that native aquatic species utilize various components of the natural flow regime to complete their life cycle, and the spring snow melt recession in particular provides key ecological cues required for successful reproduction. As a result, resource managers can rely on this study not only as a baseline reference, but also for guidance on how managed flows might be improved to increase aquatic habitat diversity and support native biodiversity.

Management of the Spring Snowmelt Recession in Regulated Systems

In unregulated rivers in the Sierra Nevada mountains of California, the spring snowmelt recession links high winter flows to low summer baseflows and is a consistent and predictable portion of the annual hydrograph. Consequently, it is an important resource to both riverine ecosystems and California's water supply. In regulated river systems where the spring snowmelt recession is often captured behind dams or diverted for hydropower, restoration of a more natural spring flow regime can provide distinct ecological benefits, such as breeding and migration cues, increased habitat availability, and greater hydraulic habitat diversity. However, knowledge of how to create and manage an ecologically beneficial spring snowmelt recession in a regulated river system has been lacking.

This study sought to define a methodology by which spring flow regimes can be modeled in regulated systems from the quantifiable characteristics of spring snowmelt recessions in unregulated rivers. Using fundamental flow components such as magnitude, timing and rate of change, the spring snowmelt recession in eight unregulated rivers across the Sierra Nevada

range was quantified to gain a better understanding of the predictability and variability across watersheds (see Appendix A). The analysis found that unregulated Sierran systems behaved similarly with respect to seasonal patterns and flow recession shape (i.e., recession limb curvature), and thus concluded that spring snowmelt recession flows could be modeled in a manner that mimics those predictable characteristics.

Using a methodology that quantifies spring snowmelt recession flows in terms of a daily percent decrease in flow, a series of flow recession scenarios were created for application in an existing study site on the regulated Rubicon River. Four scenarios, ranging from a slow natural recession to a short fast recession typically observed in regulated rivers following cessation of high flow spills, were evaluated within a two-dimensional hydrodynamic model at an existing study site. The effects of the flows on suitable habitat for Foothill yellow-legged frogs (*Rana boylei*), a California species of special concern, were evaluated, and the distribution and diversity of hydraulic habitat through time was assessed. Using a spatial niche approach, the hydraulic habitat conditions were considered with regard to native aquatic species guilds, and the effects of each flow scenario on aquatic biodiversity were determined. The modeling results show that flow recessions with slow ramping rates similar to those observed in unregulated systems (less than 10% per day) were protective of Foothill yellow-legged frog egg masses, while flows that receded at rates greater than 10% per day resulted in desiccation of egg masses and potential stranding of newly hatched tadpoles. Furthermore, recession rates of less than 10% per day provided the most diverse hydraulic habitat for an appropriate duration in spring to support all native species guilds and maximize aquatic biodiversity.

The methodology described in this study can be easily applied to regulated systems throughout the Sierra Nevada, as well as to other snowmelt regions with knowledge of regional unregulated flow characteristics. The 'flow calculator' created for use in this study has recently been utilized within the Federal Energy Regulatory Commission (FERC) hydropower relicensing process on the Yuba-Bear Drum-Spaulding project (FERC #2266) to create flow recessions that more naturally transition from high spill flows to minimum instream flows.

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

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 aspect of the study explored effects of incorporating more ecologically beneficial instream flow releases, coupled with climate warming impacts on hydropower generation in the Upper Yuba River in the western Sierra Nevada. The study used a multi-reservoir optimization model to assess the potential hydropower costs of increasing minimum instream flows (MIFs) and imposing weekly-scale down ramp rates (DRRs), separately and in combination, in three hydropower facilities in California's Upper Yuba River (UYR). Trade-offs between DRRs, MIFs, and hydropower generation and revenue were explored with uniform air temperature increases of 0, 2, 4 and 6 °C to observed hydroclimatic conditions to approximate anticipated regional warming through 2100.

Specifically, the model quantified anticipated effects of increasing MIF requirements and imposing maximum down ramp rate DRRs—which have ecological importance—in three locations, with both historical and future climate scenarios. 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 an external climate-sensitive rainfall-runoff model.

MIF levels explored ranged from 5 to 35 ft³/s (0.14 to 0.99 m³/s) in one location, and from 3 to 10 ft³/s (0.08 to 0.28 m³/s) in two other locations. DRRs ranged from no limit to a maximum allowable DRR of 25%/week. Under base case operations (without additional MIF or DRR), mean annual hydropower generation increased slightly with near-term (+2 °C) warming and

decreased slightly with long-term (+6 °C) warming. Regional climate warming did not necessarily decrease hydropower output in the Upper Yuba River. With warming of 2 °C, average annual generation *increased* by 3.3%. With 6 °C warming, generation *decreased* by only 1.5%. The near-term increase was 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 6 °C warming, the most ecologically beneficial MIF and DRR reduced hydropower generation by 7.9% and revenue by 5.5% compared to base case operations and a historical climate. This has important implications for hydropower relicensing 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.



North Fork Yuba River, Spring 2012.

Photo Credit: R. Peek

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CHAPTER 1: Effects of the Spring Snowmelt Recession on Abiotic and Biotic Stream Conditions

1.1 Introduction

Over the past decade, the Natural Flow Regime paradigm (Poff et al. 1997) has garnered widespread study, discussion and general acceptance in the scientific community as a guide for conservation, restoration and management of rivers (e.g., see Marchetti and Moyle 2001, Richter et al. 2006). However, one fundamental aspect of the natural flow regime that has received little attention in both scientific study and resource management is the importance of the spring snowmelt recession to both geomorphic and ecological stream processes. Yarnell et al. (2010) presented a conceptual model for the ecology of the spring snowmelt recession, with an emphasis on Mediterranean-montane systems. In the conceptual model, they delineated those components of the natural flow regime most relevant to the recession hydrograph and their relation to physical and biological stream processes, and discussed these components with regard to the success of native riverine species. While they found many studies in the existing literature that supported various aspects of their conceptual model, they had found no studies that directly addressed the relationship between the spring recession and stream ecology. In managed river systems, increased understanding of these fundamental relationships between the spring snowmelt flow regime, abiotic and biotic stream conditions will aid water resource managers when complex decisions are required to balance multiple water resource needs.

The goal of the study presented here was to quantify the variability in the spring flow regime across a series of regulated and unregulated rivers using techniques discussed in Yarnell et al. (2010) and assess the relationship between the associated instream habitat heterogeneity and species diversity. Specifically, the study compared the flow variability within each study river to variability in abiotic stream conditions, such as the diversity of hydraulic habitat, and variability in biotic conditions, such as benthic macroinvertebrate diversity. Relationships between the abiotic and biotic characteristics were evaluated with the goal of elucidating the degree to which spring flow conditions contribute to the success and diversity of native aquatic species.

The study built on previous academic and FERC commissioned studies conducted within two primary watersheds in the northern Sierra Nevada range, the American and Yuba Rivers. While previous studies addressed more specific questions pertaining to impacts from hydropower projects located within each watershed, the data collected covered a broad range of aquatic conditions (e.g. instream habitat, fish and amphibian populations, etc.) and thus provided background data for this study. Several of the study sites for this study overlapped study sites from previous studies in an effort to create a longer-term dataset of aquatic conditions that could be used for future monitoring efforts.

The remainder of this chapter is organized as follows: descriptions and information pertaining to the study sites are presented in section 1.3; methods and results pertaining to abiotic stream conditions (hydrology, water quality, temperature, geomorphology and habitat hydraulics) at each study site are presented in section 1.4; methods and results pertaining to biotic stream conditions (riparian vegetation, algae, benthic macroinvertebrates, amphibians, and fish) at each study site are presented in section 1.5; an analysis of observed relationships between abiotic and biotic conditions is discussed in section 1.6; and management implications and recommendations are presented in section 1.7.

1.2 Study Objectives

The primary objective for this study was to quantify the variability in the spring flow regime at a series of study sites located across a range of rivers with varying degrees of flow regulation and compare it to the abiotic and biotic stream conditions within each system. Study sites were selected on two unregulated river reaches, two regulated bypass river reaches where flows are diverted via upstream reservoirs, and two regulated river reaches where flows are either diverted and altered in spring or pulsed for hydropower generation (hydro-peaking). Specific sub-objectives included:

- quantifying and comparing the flow regime variability between study sites
- quantifying the geomorphic, riparian and hydraulic habitat diversity across study sites
- measuring and comparing water temperature regimes between study sites
- measuring the abundance and diversity of primary producers (algae and benthic macroinvertebrates) across study sites,
- measuring the abundance and diversity of amphibians and fish across study sites
- assessing the relationship between abiotic diversity measures and biotic abundance and diversity metrics

1.3 Study Sites

Study sites were located on six rivers ranging across the Yuba and American River watersheds, in the northern Sierra Nevada mountains, California (Figure 1.1). Rivers were selected to represent typical hydrologic and geographic conditions in the northern Sierras. All reaches consisted of riffle-pool morphology, although the South Fork (SF) Yuba contained larger substrate more consistent with cascade-pool morphology. Elevation at the study sites ranged from 196 m at the Middle Fork (MF) American to 930 m at the MF Yuba (Table 1.1). Overall, the mean elevation in the Yuba watershed was higher (838 m) than the American watershed (320 m), but within watersheds, the elevation gradient of study sites was similar. Study sites ranged from 600 m to 1000 m in length and were selected to maximize representative reach characteristics, and where possible, overlap with previous study sites associated with FERC relicensing studies or academic research.

Data collected at each study site was coordinated to overlap as much as feasible. A series of cross section transects placed 40 m apart with a random start location was established within each study site and used to document abiotic conditions and locate biotic sampling locations (Figure 1.2). Permanent benchmarks were established within each study site and detailed GPS data were collected throughout the study in coordination with various sampling efforts. All data were processed and entered into Microsoft Excel and Access databases and documented spatially in ArcGIS (Arcview 10.0, ESRI, Redlands, CA) as appropriate.

Figure 1.1: Overview map of location of study sites.

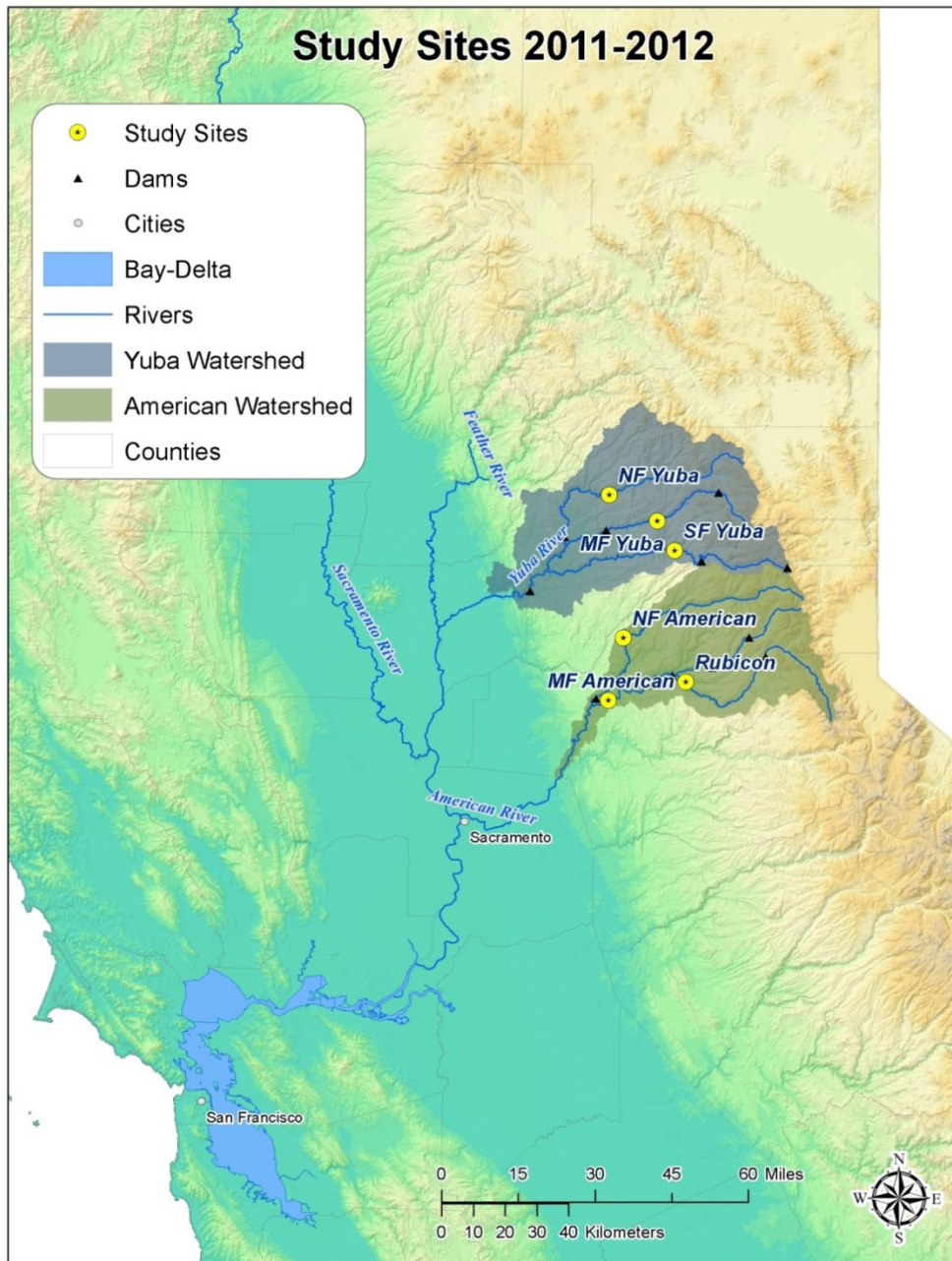


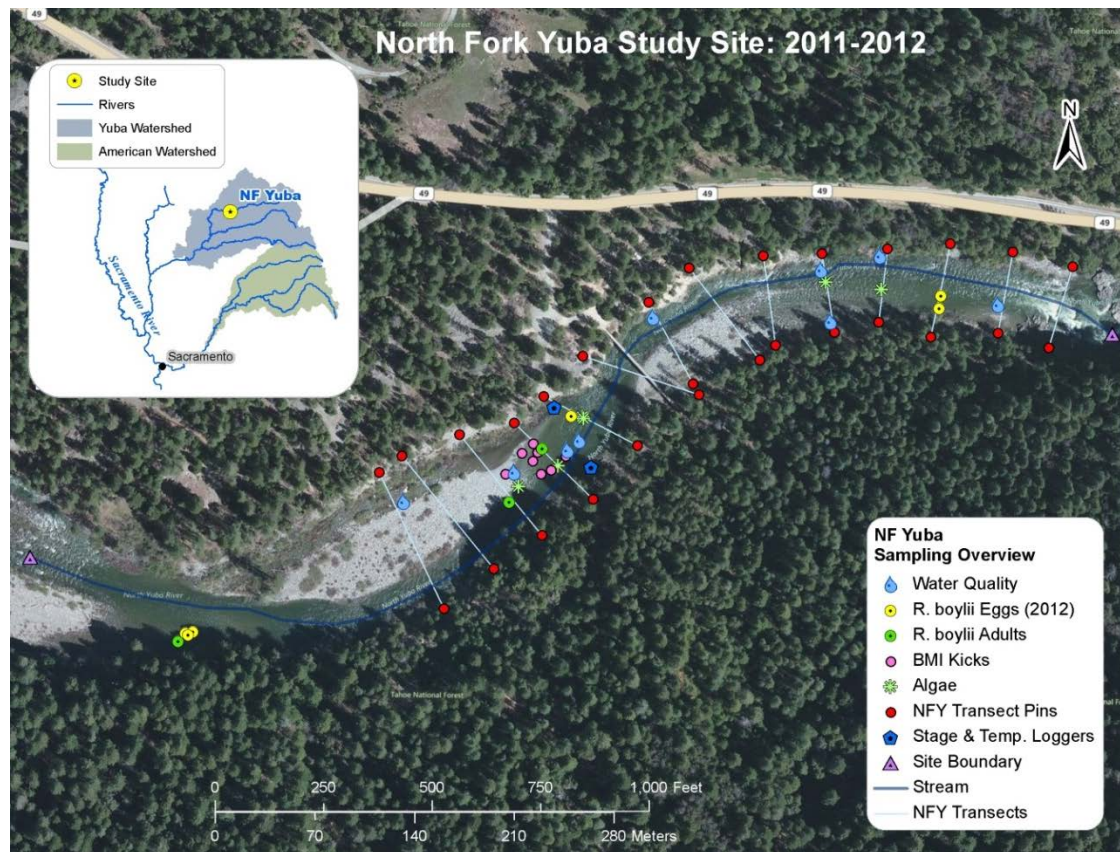
Table 1.1: Study site details.

Study Site	Flow Regime	Elevation ¹ (m)	Drainage area (km ²)	Stream order (Strahler) ²	Stream gradient (m/m)	Site length (m)
North Fork Yuba	Unregulated	705	666	5	0.011	800
Middle Fork Yuba	Regulated: <i>Bypass</i>	925	221	4	0.011	800
South Fork Yuba	Regulated: <i>Altered</i>	885	360	5	0.015	600
North Fork American	Unregulated	350	601	5	0.006	650
Rubicon	Regulated: <i>Bypass</i>	415	805	6	0.016	600
Middle Fork American	Regulated: <i>Peaking</i>	196	1572	6	0.003	1000

¹ Elevation at center of study site

² Based on USGS 1:24,000 streamlines

Figure 1.2: Detailed map of North Fork Yuba River study reach.



¹ BMI: benthic macroinvertebrates

1.3.1 Land Use

Mining activity (panning and dredging), prevalent throughout most northern Sierra Nevada rivers for over a century, occurred at all study sites with varying degrees of severity. Mining activity was heaviest at the North Fork (NF) American study site, which due to its ease of access was actively mined nearly year round. Significant disturbance associated with active panning and high-banking was observed within the NF American and MF Yuba study sites, while limited panning and sluicing were observed at the SF Yuba, NF Yuba, and Rubicon study sites. No mining was observed at the MF American study site. Evidence of suction dredging and associated equipment (i.e., plastic tubing, floats, etc.) were present at four of the study sites, though active suction dredging was not observed during study visits.

Recreation varied across study sites and largely related to ease of access. The NF Yuba and NF American, while unregulated, had the heaviest recreation use because trails and roads provided direct access to the river. Use was heaviest in the mid to late summer months, but mining was observed during every visit in 2011 and 2012 at the NF American study site (April through October). Moderately heavy recreation use was also observed at the SF Yuba study site, (including swimming, ATVs, fishing, camping, target shooting, and mining) as a dirt road runs adjacent to the river for several miles, but was not observed during every visit. The MF Yuba study site had some recreational use, but due to difficult road access, most use was largely from with mining activity. The two study sites with minimal observed recreation use were the Rubicon and MF American, likely due to difficult terrain and access. There were no road crossings in the vicinity of either the Rubicon or MF American study sites, although a footbridge provided local access to part of the Rubicon study site, and the Western States Trail ran parallel to the MF American study site up the hillslope on the left bank.

1.3.2 Management & Flow Regimes

Rivers were assessed by hydroregulation type, including bypass, peaking, altered and unregulated, across each watershed in a paired study design (Table 1.1). The NF Yuba and NF American rivers are unregulated upstream and within each study site, but both reaches eventually drain to reservoirs downstream (New Bullards Bar and Clementine, respectively). The MF Yuba and Rubicon river study sites were located in bypass reaches from which water was diverted via upstream reservoirs and rerouted to locations downstream for power generation. The SF Yuba study site was selected as an altered regulation reach, where water was diverted out of the reach (bypass), and in some years spring flows were modified such that multiple spills occurred over the dam rather than a single spill flow as typically observed on the bypass reaches. The MF American study site was located in a hydropeaking reach, where flows pulsed or “peaked” most days from late spring through late-summer or fall. The hydropeaks were timed to provide consistent whitewater boating flows for commercial rafting as well as maximize energy production during daytime hours when electricity costs were high.

1.3.3 Historical Study Data

Several study sites were selected to maximize overlap with recent studies conducted as part of the FERC hydropower relicensing process, thus providing additional historical and background data for analysis (Table 1.2). Recent FERC-related studies included surveys for aquatic amphibians and reptiles, fish populations, fish passage, benthic macro-invertebrates (BMI), instream habitat characterization, Two-dimensional (2D) modeling of instream habitat, water temperature, and water quality. Most of these studies were conducted as part of three large FERC projects: Middle Fork Project #2079 (Placer County Water Agency [PCWA]), Yuba-Bear/ Drum-Spaulding Project #2266 (Pacific Gas & Electric [PG&E], Nevada Irrigation District [NID]), and Yuba River Development Project #2246 (Yuba County Water Agency [YCWA]). The Rubicon study site had the greatest overlap in data from the PCWA project, with fish, BMI, aquatic amphibian and reptile, and instream flow studies occurring within the study site.

FERC-related aquatic amphibian and reptile studies were also completed at the MF Yuba, SF Yuba, and MF American study sites.

Table 1.2: Recent FERC-related study data available for each study site.

Study Site	Data Collected	Year	FERC Project No.	Utility
North Fork Yuba	FYLF	2012	2246	YCWA
Middle Fork Yuba	FYLF, FYLF 2D, Instream Flow ¹ , Stream Fish ¹ , BMI ¹ , Water Temperature	2008-2009	2266	PG&E NID
South Fork Yuba	FYLF, FYLF 2D, Instream Flow ¹ , Fish Passage ¹ , Water Temperature ¹	2008-2009	2266	PG&E
North Fork American	FYLF ²	2007-2008	2079	PCWA
Rubicon	2D (Fish and Frogs), Fish Population, Instream Flow, BMI, WQ	2007-2008	2079	PCWA
Middle Fork American	2D (Fish and Frogs), Fish Population, Instream Flow, BMI, FYLF ¹	2007-2009	2079	PCWA

¹ Data were collected outside of the selected study reach, but within 1 km of the site.

² Data were collected outside of the selected study reach, and was greater than 5 km from the site.

1.4 Abiotic Conditions

Data were collected at each study site to assess hydrology, geomorphology, and hydraulics as well as environmental conditions associated with precipitation, air and water temperature, and water quality. In 2011, data were collected at all study sites, while in 2012 all study sites except the MF Yuba were surveyed.

1.4.1 Hydrology

Hydrology data were compiled for each study site using existing proximal USGS gage records and stage loggers placed within sheltered locations at each study site. The gage data provided a record of the historical flow regime on each river as well as daily averaged data through the study period. The on-site stage loggers provided more detailed 15-minute data on how changes in discharge translated to changes in local stage. Rating curves were established between the stage loggers and each proximal gage where possible to verify the flow regime within each study site.

1.4.1.1 Historical Gage Data

Each of the study sites was located within approximately 30 km or less of an existing USGS discharge gaging station (Table 1.3). Four of the six study sites were located 10km or more downstream of a gage such that flows at the study site were slightly higher than those at the gage due to natural accretions from small tributaries. However, the timing and pattern of flows observed at the gage and at each study site did not significantly differ when compared on a

daily averaged time step. As a result, an assessment of historical daily flows from the gages was completed for each study site.

Table 1.3: Historical and current gage data available for each study site.

Study Site	USGS Gage Number ¹	Years of Record	Distance from Study Site (km)
NF Yuba	11413000	1931–Present	5.2 (Upstream)
MF Yuba	11408550	1987–Present	26 (Upstream)
	11408700	1957–1966	(Located At Site)
SF Yuba	11414250	1965–Present	10.3 (Upstream)
	11417000	1942–1972	3.5 (Downstream)
NF American	11427000	1942–Present	28.5 (Downstream)
Rubicon	11433200	1959–1984	28.5 (Upstream)
	PCWA Gage	1974–Present	28.5 (Upstream)
MF American	11433300	1958–2011	31.5 (Upstream)
	11433500	1911–1986	5 (Downstream)
	OXB ²	1997–Present	31.5 (Upstream)

¹ USGS Gage data available at: [http:// waterdata.usgs.gov/ ca/ nwis/](http://waterdata.usgs.gov/ca/nwis/)

² CDEC Gage data available at: [http:// cdec.water.ca.gov/](http://cdec.water.ca.gov/)

The historical flow regimes for each study site revealed similarities across watersheds, as general flow patterns from climatic conditions and differences in the spring and summer flow regimes due to regulation were observed. All sites exhibited high flows in winter and low flows in summer with annual volume of runoff varying by water year type (Figure 1.3). Very high flows were seen across all sites in the winter floods of 1964 and 1997, and the 100-year flood recurrence values were similar across basins (Table 1.3). On average, low summer flows typically occurred by mid-July at all sites and remained low and stable throughout the summer until fall storms increased flows in mid-October. Summer flows on the MF American were the exception with increased summer flows (greater than 500 cfs daily average) and daily variability due to hydropeaking. Over time, the bypass regulation on the Rubicon, SF and MF Yuba rivers created flow regimes that altered between high and low flows with little duration of flows in between. As a result, the 2-year and 5-year recurrence interval flows were lower than those observed on the unregulated systems (Table 1.3).

Figure 1.3: Mean daily hydrographs for the period of record from USGS gage data for all study sites.

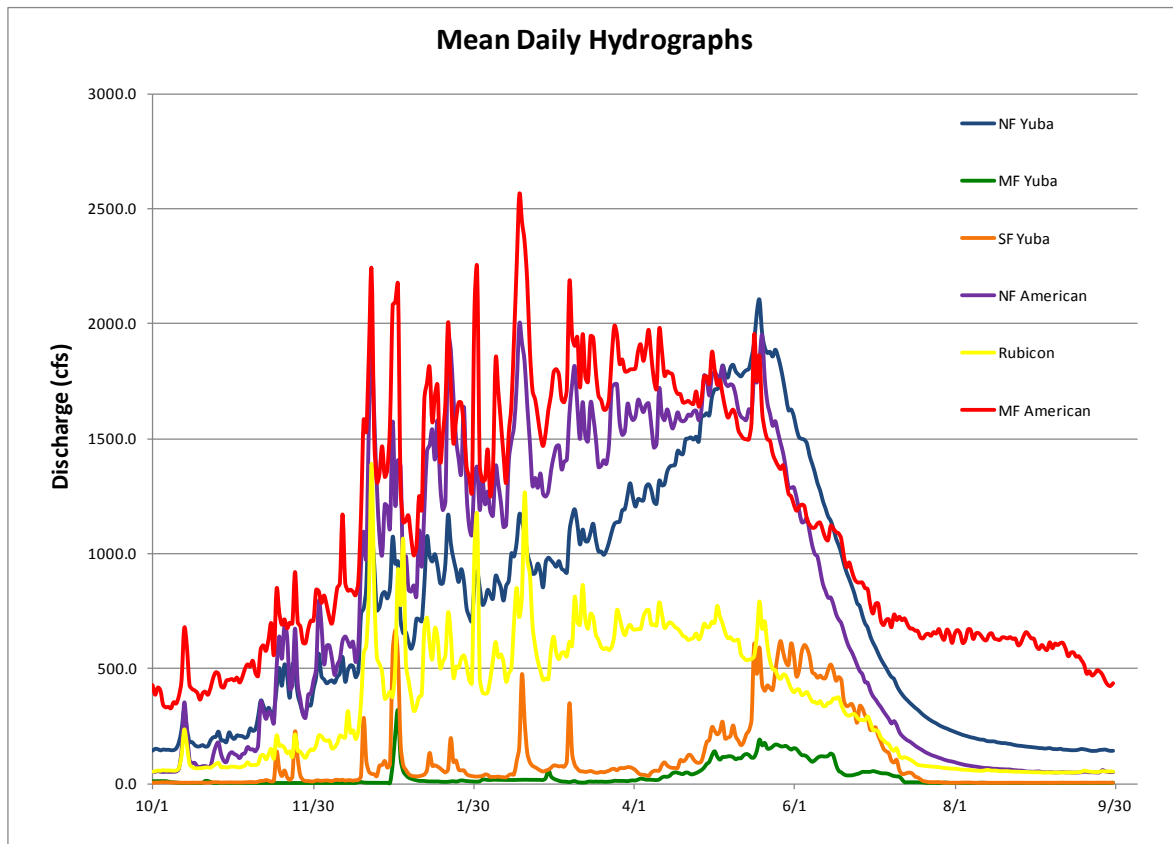


Table 1.4: Hydrologic discharge characteristics for each study site based on historical gage data available.

Study Site	Flow Recurrence Interval ¹				Mean Annual Flow (cfs)	Peak Flow of Record	
	Q ₁₀₀	Q ₁₀	Q ₅	Q ₂		Q	Year
NF Yuba	30980	15250	11080	5830	775	29600	1997
MF Yuba	44130	2260	785	90	31	6860	1997
SF Yuba	49950	10170	5280	1015	111	25400	1997
NF American	68000	27500	20275	9660	922	50100	1997
Rubicon	87130	19910	10200	2785	355	60000	1964
MF American	77500	29990	19210	8430	1125	65000	1964

¹ Recurrence interval is the yearly frequency that flow is calculated to occur, the inverse of which is the probability that flow listed will be exceeded in any given year. For example, Q₁₀₀ is the '100-year flood' or the discharge which has a 1-in-100 chance of occurring each year.

The unpredictability of abrupt flow changes in the spring and summer on the regulated rivers created inter-annual variability over time as shown by the jagged irregularity in the mean daily hydrograph (Figure 1.4). In contrast, the unregulated NF American and NF Yuba rivers remained consistent and predictable over time in spring and summer, resulting in a smooth mean annual hydrograph with little variability (Figure 1.4). Because climate was a primary driver in each of the study rivers, the average start date of the spring recession was in mid-May, with the SF Yuba typically starting in late May due to late spring spills (Table 1.5). The end date of the spring recession was calculated as the date when the daily percent decrease in flows was less than 1% over a 7-day moving average. The average end dates of the recession varied more widely from early July to mid-August due to the combined effects from regulation and water year dynamics. As a result, the duration of the spring recession ranged from 52 days on the MF American to 86 days on the NF Yuba (Figure 1.5a).

The rate of flow decrease during the recession similarly varied between the regulated and unregulated sites (Figure 1.5b). The average rate of decreasing flow during the spring recession ranged from less than 5% per day on the unregulated rivers and at the Rubicon River, to 12% per day on the SF Yuba. However, the standard deviation of the rate of flow decrease was an order of magnitude greater on the regulated SF and MF Yuba rivers compared with the unregulated rivers, and the maximum rate of decrease observed on the SF and MF Yuba rivers was 64% and 41% per day, respectively, compared to maximum rates of 7% and 12% per day on the NF Yuba and NF American rivers, respectively. The Rubicon River had similar rates of flow decrease to the unregulated rivers, likely due to tributary accretion flow during the spring.

Figure 1.4: Mean daily hydrographs from historical gage data for all study sites in spring and summer. The average start and end dates of the spring recession are delineated.

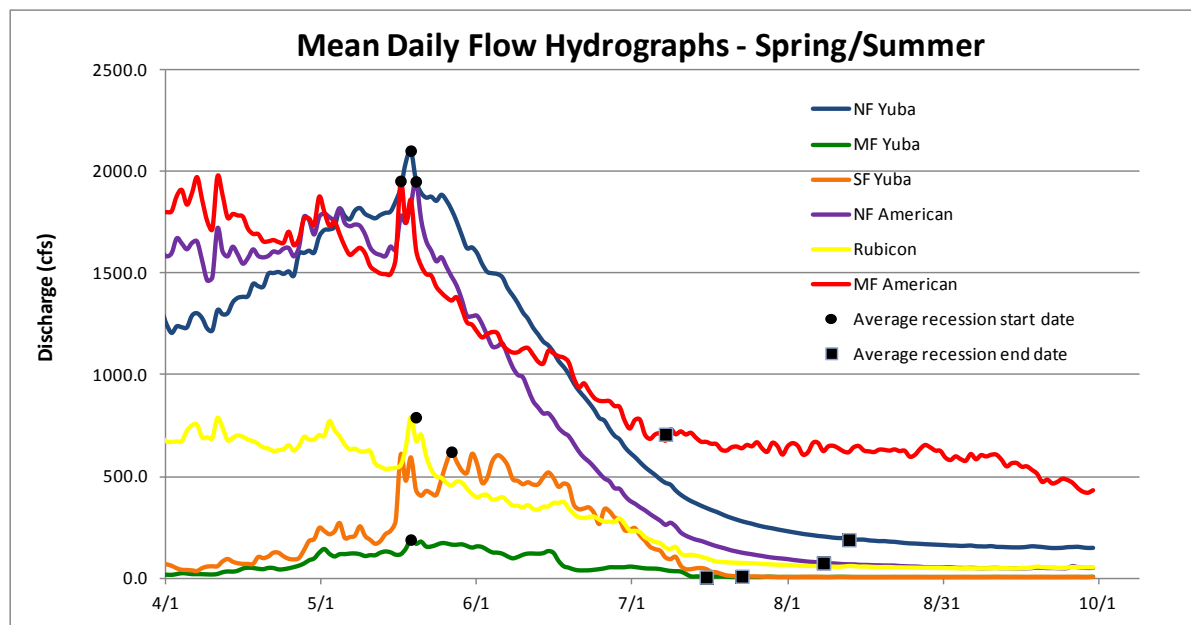
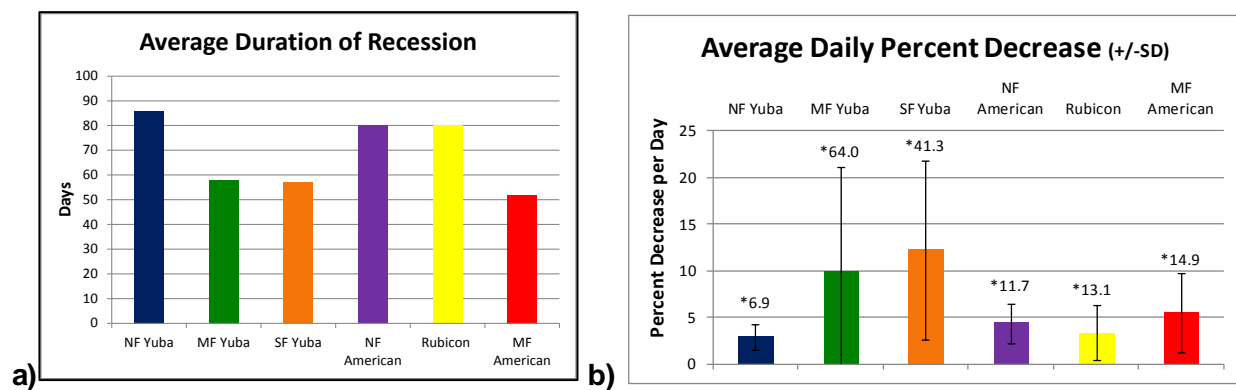


Table 1.5: Summary of historical spring recession characteristics for each study site based on mean daily flows for the period of record.

	NF Yuba	MF Yuba	SF Yuba	NF American	Rubicon	MF American
Years of Record	1931-2012	1988-2011	1967-2011	1942-2012	1959-2012	1959-2012
Start Date	19-May	19-May	27-May	20-May	20-May	17-May
Start Magnitude (cfs)	2103	191	623	1951	792	1954
End Date	13-Aug	16-Jul	23-Jul	8-Aug	8-Aug	8-Jul
End Magnitude (cfs)	190	7	11	76	76	709
Duration (Days)	86	58	57	80	80	52
Average daily percent decrease	2.9	9.9	12.3	4.4	3.3	5.5
SD of daily percent decrease	1.4	11.2	9.6	2.1	2.9	4.3
Maximum daily percent decrease	6.9	64.0	41.3	11.7	13.1	14.9

Figure 1.5: Average a) duration and b) rate of change for the spring recession at all study sites based on historical USGS gage data. Average rate of change is calculated as the percent decrease in flow per day over the duration of the recession. Error bars shows the standard deviation, and the starred values (*) indicate the maximum average daily percent change observed in the record. (see Table 1.5)



1.4.1.2 Observed Stage Data for 2011–2012

Change in stage at each study site was monitored during 2011 and 2012 using Solinst level loggers, which recorded stage and water temperature at 15-minute intervals. Loggers were placed within hydraulically responsive but stable geomorphic habitat within the study sites (Table 1.6). Because flows were high in the spring of 2011, several loggers could not be safely installed until mid-May 2011. The MF Yuba logger was removed in the fall of 2011 and was not reinstalled in 2012 due to difficulty in accessing the study site. Data were aggregated and analyzed using R (R-Development-Core-Team 2012).

Table 1.6: Solinst pressure transducer locations at study sites in 2011 and 2012.

Study Site	Date Installed	UTM Northing Z10 (m)	UTM Easting Z10 (m)
NFY	Mar. 10, 2011	4375539	673880
MFY ¹	May 12, 2011	4368064	689481
SFY	Mar. 11, 2011	4358650	695024
NFA	Jan. 13, 2011	4330724	679503
RUB	May 16, 2011	4318078	700079
MFA	Mar. 31, 2011	4311224	676115

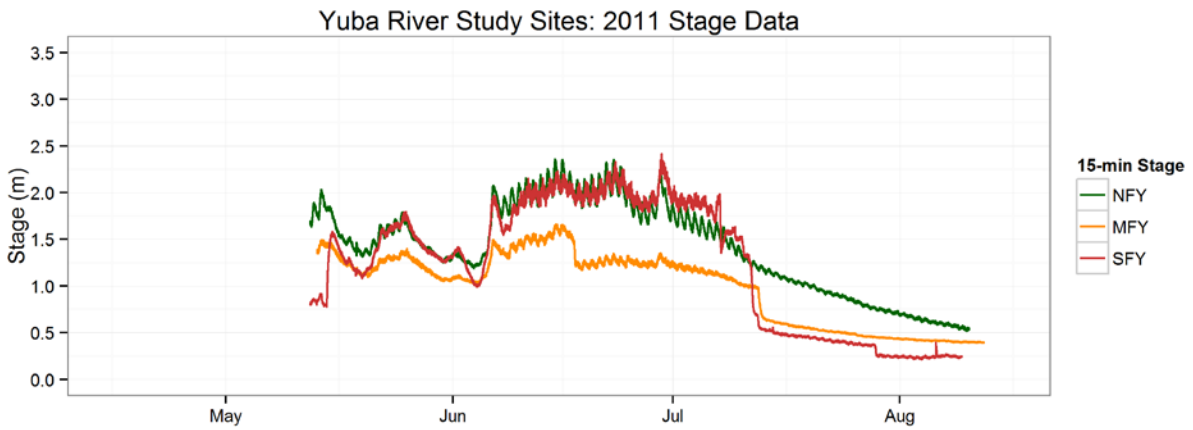
¹MFY logger removed in fall 2011 and not reinstalled in 2012 due to difficult site access.

Climatic conditions were extremely different during the two years of study with 2011 designated as a wet year, and 2012 as a below normal year. The spring of 2011 was one of the latest, coldest on record with some of the highest flows recorded in early July (Figures 1.6a, 1.7a). The spring recession began on June 22 on the unregulated rivers, a full month later than average, and lasted until early September. Every study river had high flows and spring spills, although the spills were abruptly curtailed on the MF and SF Yuba in particular. Stage decreased 0.75 m in less than 24 hours on the SF Yuba and 0.38 m in less than 12 hours on the MF Yuba (Figure 1.6a).

In 2012, a smaller snowpack and warm spring resulted in an earlier snowmelt recession on all rivers and limited spill on the regulated rivers (Figures 1.6b, 1.7b). The recession began May 2 on the unregulated rivers and the SF Yuba, and April 28 on the Rubicon and MF American, roughly three weeks earlier than average. Flows spilled on the Rubicon and MF American for several days during a late April rain storm, while two manufactured spring pulse flows were observed on the SF Yuba in May. The first flow pulse on the SF Yuba lasted for 6 days with an average daily percent decrease in flow of 31% and a maximum daily percent decrease of 38%. The second manufactured flow pulse was similar to the first, lasting for 7 days with an average daily percent decrease in flow of 34%, but with a higher daily maximum rate of decrease of 67%.

Figure 1.6: 15-minute stage data for the Yuba watershed study sites for a) 2011 and b) 2012.

a)



b)

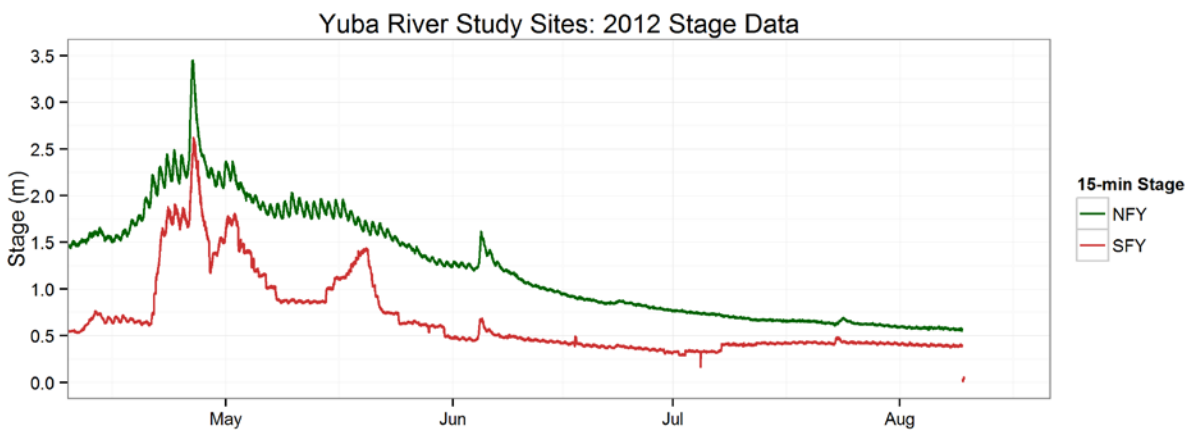
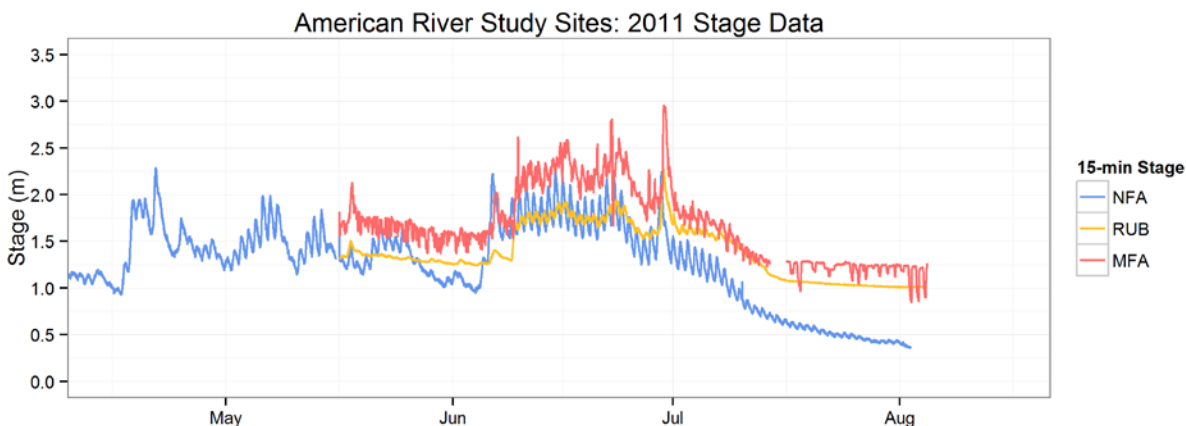
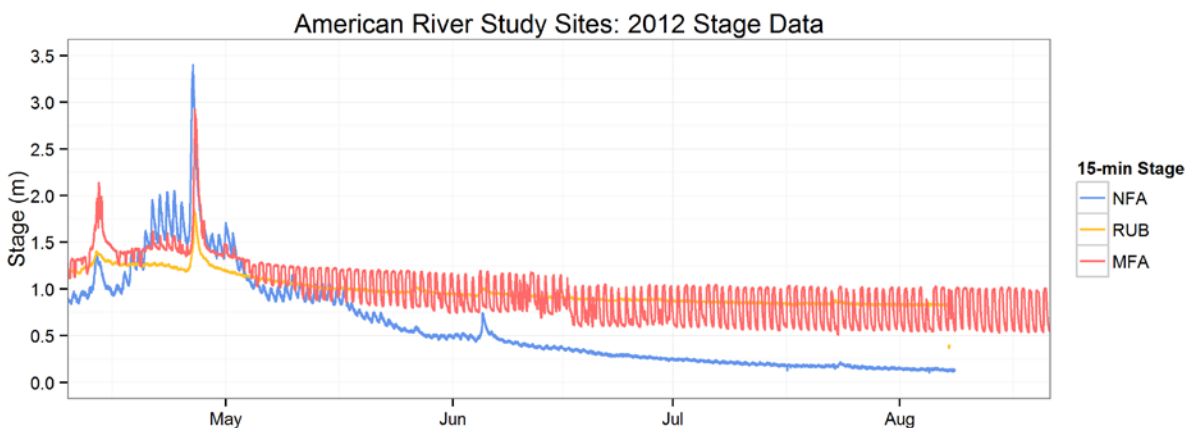


Figure 1.7: 15-minute stage data for the American watershed study sites for a) 2011 and b) 2012.

a)



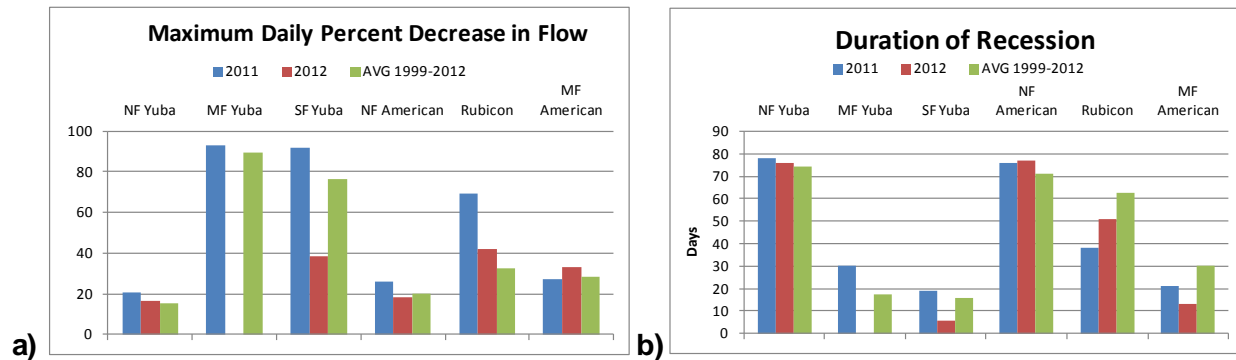
b)



The spring recession characteristics were consistent between 2011 and 2012 on the unregulated rivers, but varied between study years at the regulated study sites (Figure 1.8). The duration and rate of flow change during the spring recession on the NF American and NF Yuba rivers were consistent between study years, despite the differences in water year types, and similar to the average values for the last decade. However, the regulated rivers varied more widely, such that the short, rapid spring recessions observed in 2011 were more typical for the highly regulated SF Yuba and MF American and less typical than the decadal average for the Rubicon. Flow generally only spilled over Hell Hole dam on the Rubicon in above normal or wet year types (5 of last 14 years), and in most years, the accretion flows upstream of the study site appeared to dampen the effects of spill locally. In contrast, spills occurred frequently on the SF Yuba (11 of last 14 years), and the abrupt curtailment of spill resulting in rapid decreases in stage at the study site was more common place over the past decade. While flows spilled on the MF Yuba less often than the SF Yuba (6 of last 14 years), all of the spills were abruptly curtailed in one day similar to the flow conditions observed on the SF Yuba. However only two of the six spill years that occurred since 1999 on the MF Yuba had multiple spill events within the spring, while 7 of the 11 spill years on the SF Yuba had two or three spill events in the spring (e.g. see spring flows in 2012, Figure 1.6b). The high frequency with which the SF Yuba experienced spring spill events, both between years and within a single spring season, resulted in a spring

flow regime that was less predictable in any given year than either of the regulated bypass reaches.

Figure 1.8: Spring recession characteristics at each study site for the two years of study (2011-2012) compared to values for the past decade (1999-2012). Note stage data were not available for the MF Yuba in 2012.



1.4.1.3 Precipitation

A subset of CDEC stations within each watershed were used to summarize hourly and daily precipitation. A minimum of four stations were used for each watershed, and stations were selected based on proximity to study sites, elevation, and data collection interval. Stations used in the American watershed included: SGP, BRE, GTW, and ADR. Stations used in the Yuba watershed included: CAM, ALY, BUD, CGT, GVV, OHD, and DRC. Data were analyzed using R.

Precipitation was slightly different across watersheds with the American watershed consistently receiving less total precipitation than the Yuba, but the timing and cumulative amounts were similar over water years (Oct. 1 through Sep. 30) (Table 1.7). 2012 was a drier year than 2011, but more precipitation fell in spring and summer in 2012 than 2011.

Table 1.7: Precipitation data for study sites for 2011 and 2012.

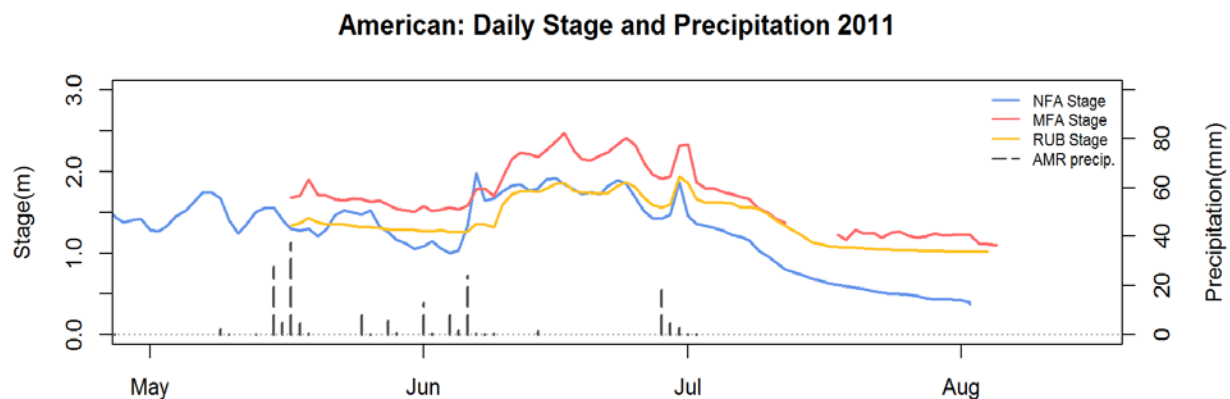
Watershed	Mean Annual Precipitation (mm) ¹	Spring-Summer Precipitation (April 1 – Sep 1)	Spring-Summer Proportion of Annual Precipitation (Spring-Summer / Mean Annual)
American (2011)	1805	170	9
American (2012)	950	201	21
Yuba (2011)	2205	196	8
Yuba (2012)	1260	261	21

¹ Averaged across 4 CDEC stations within the watershed from Oct. 1 through Sept. 30.

The timing and magnitude of any given precipitation event determined the effect of precipitation on the flow regime (Figure 1.9). In 2011, a summer snow storm occurred in late June during the spring recession, and changes in stage were observed in both watersheds at five of the six study sites. The MF Yuba had only a very slight increase in stage compared to the other study sites, suggesting the high volume of spill occurring during that time may have dampened any increases in flow due to rain. In 2012, the large April storms created significantly large increases in flow at the start of the snow melt recession at each study site, while the large increase in flow observed on the SF Yuba during late May 2012 was due to water management operations, not climatic effects.

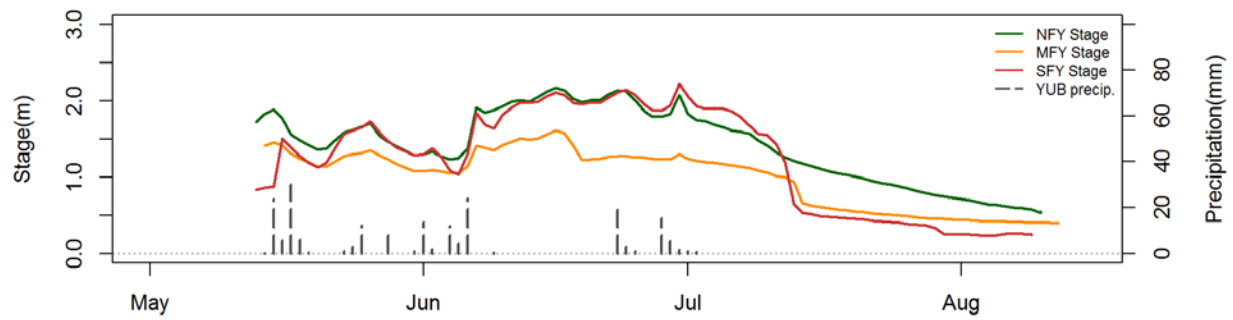
Figure 1.9: Daily stage and precipitation for the American watershed study sites in a) 2011 and b) 2012, and the Yuba watershed study sites in c) 2011 and d) 2012.

a)



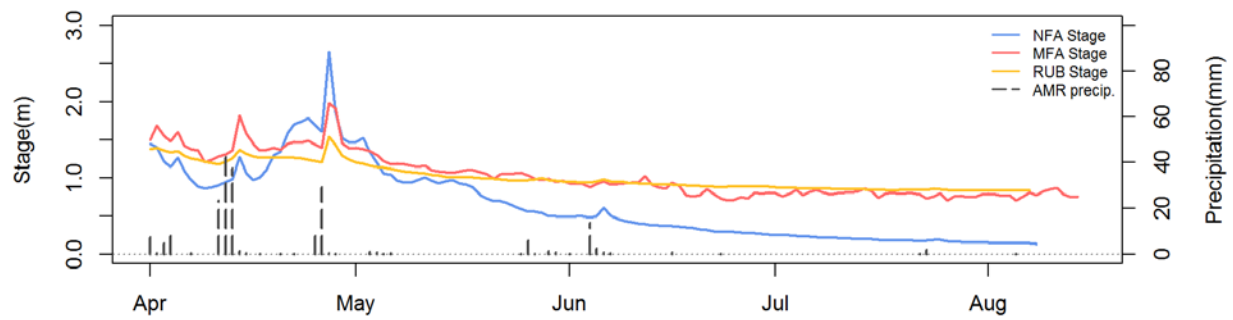
b)

Yuba: Daily Stage and Precipitation 2011



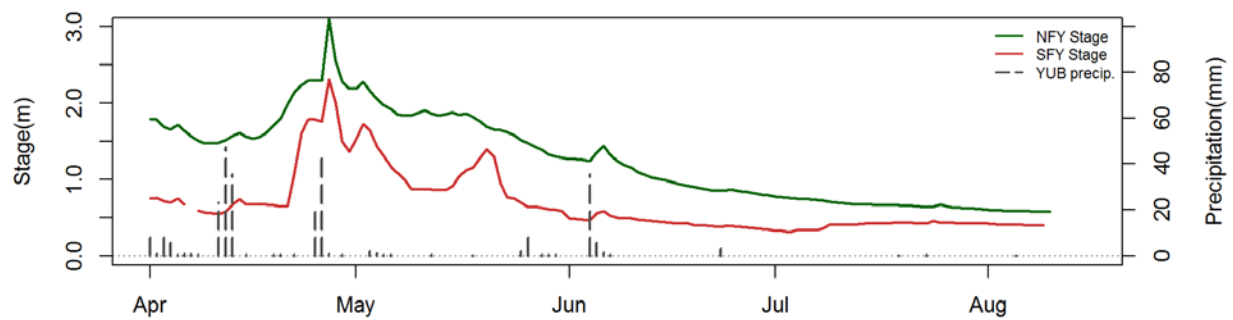
c)

American: Daily Stage and Precipitation 2012



d)

Yuba: Daily Stage and Precipitation 2012



1.4.2 Water Quality and Temperature

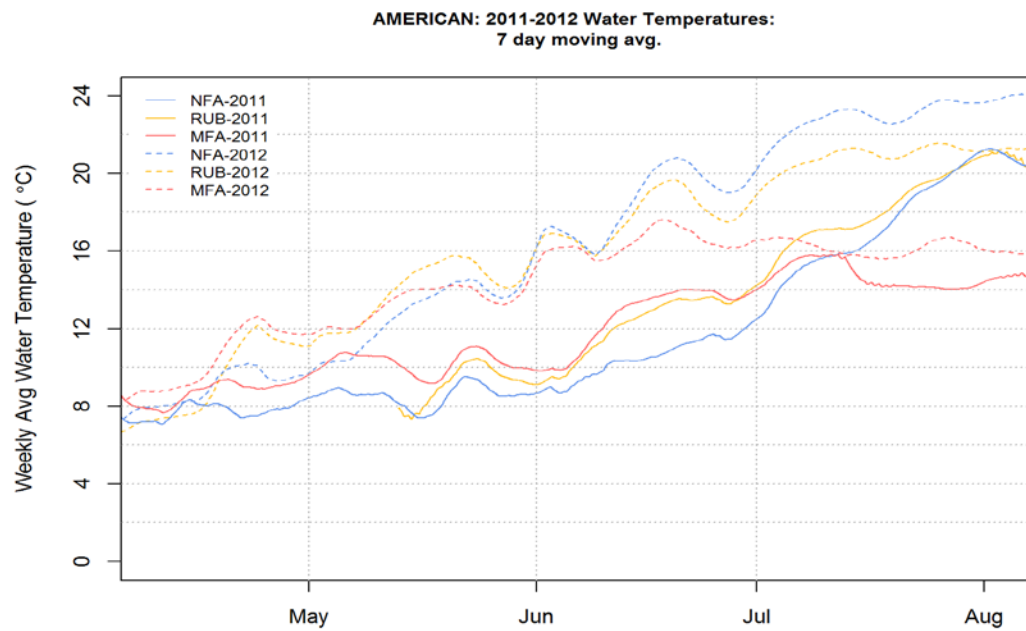
Water quality conditions were monitored at each study site in 2011, although access was limited during the early spring due to high flows. Water quality data were collected opportunistically via grab samples at each study site during each site visit in 2011, and an automatic sampler was setup at two study sites in early spring 2011 to collect more detailed data over several days of the spring recession. Air and water temperature data were recorded at 15-minute intervals using a variety of Solinst pressure transducers and Hobo temperature loggers at all study sites in 2011 and at all study sites except the MF Yuba during 2012. All temperature data were aggregated at hourly, daily, and weekly time-steps. A centered seven-day moving average (weekly average temperature) was calculated using 15-minute data. Data were aggregated and analyzed using R (R-Development-Core-Team 2012).

1.4.2.1 Water Temperatures

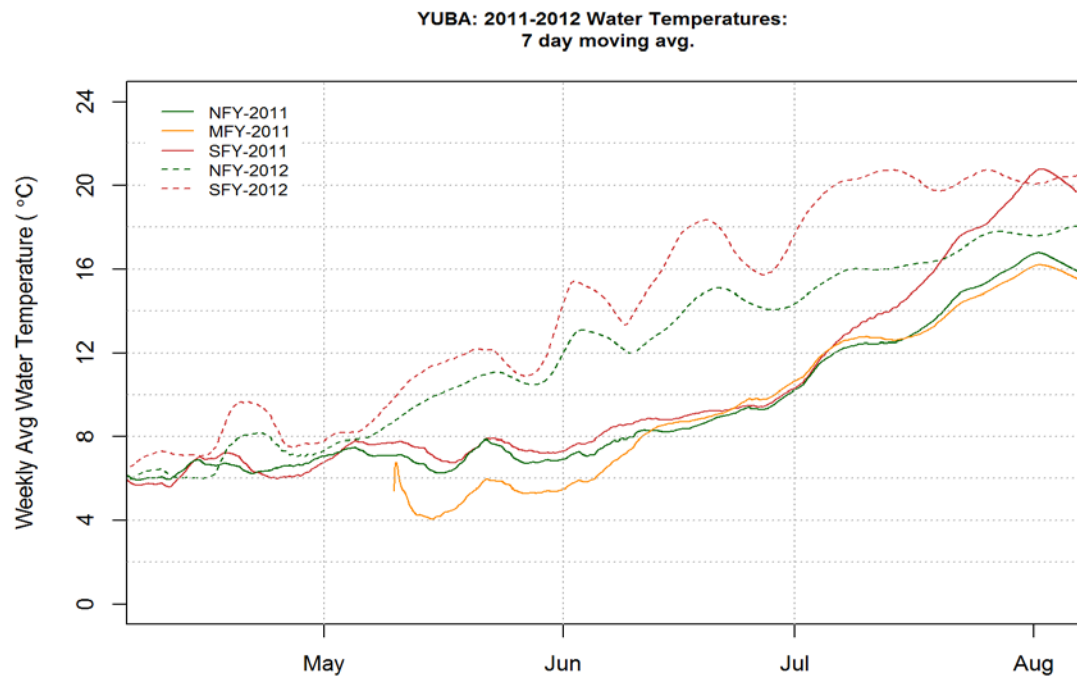
Water temperatures varied significantly between years and between rivers. 2011 was a wetter and colder water year, and therefore weekly average water temperatures were 2–6 °C cooler in 2011 compared with 2012 between early May and late July (Figure 1.10). In both 2011 and 2012, water temperatures at the Rubicon and NF American study sites continued to warm to greater than 20 °C by mid-summer, while temperatures at the MF American study site never exceeded a weekly average temperature of 18 °C due to hydropeaking-related flow releases. In both 2011 and 2012, a distinct decrease then plateau in water temperature was observed on the MF American when hydropeaking flows were initiated and cold-water releases buffered any natural seasonal warming that might have occurred. In 2012, a warmer and drier year, hydropeaking flows on the MF American began in mid-May, compared to mid-July in 2011, and thus water temperatures were fairly constant and cool by mid-June.

Figure 1.10: Weekly average water temperature at the a) American and b) Yuba watershed study sites from April through August, 2011 and 2012.

a)



b)



In general, water temperatures from study sites in the Yuba watershed were colder than the American study sites across both study years. These differences may be attributable to differences in elevation between the watersheds as the mean study elevation in the Yuba watershed was higher (838m) compared with the American (320m). Weekly average temperatures in 2011 in the NF Yuba and MF Yuba were 16–17 °C in August, while weekly average temperatures in the NF American and Rubicon were 21 °C in early August. In contrast, temperatures observed in the highly regulated SF Yuba and MF American study sites were markedly different from the other study sites within their respective watersheds, with weekly average temperatures in the SF Yuba approaching 21 °C in August 2011, and weekly average temperatures of 14–15 °C in August 2011 in the MF American.

1.4.2.2 Interactions between Air and Water Temperature

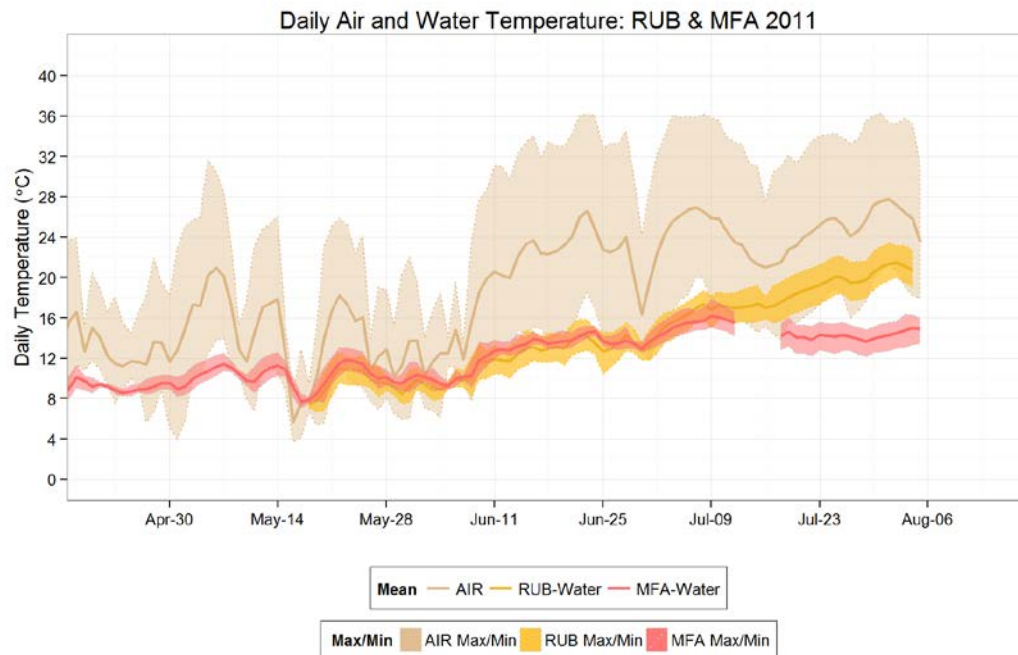
Stream water temperatures are predominantly controlled by air temperature over the stream (Beschta et al. 1987), but other factors such as relative humidity, elevation, riparian shading (Naiman et al. 1993), volume of discharge (Brown 1983), and sedimentation (Beschta et al. 1987) contribute to the variation in observed water temperature. Several of the study sites showed a strong correlation between air and water temperature throughout the year, but the most regulated sites showed the least coupling with ambient air temperatures, particularly during the summer season.

The annual temperature patterns indicated the highly regulated reaches (MF American and SF Yuba) had water temperatures that diverged with the natural thermal regimes observed on the unregulated rivers, regardless of elevation or water year (Figure 1.11). Temperatures in the MF American were decoupled from warming air temperatures due to regulated cold-water releases resulting in colder water temperatures than other study reaches within the same watershed.

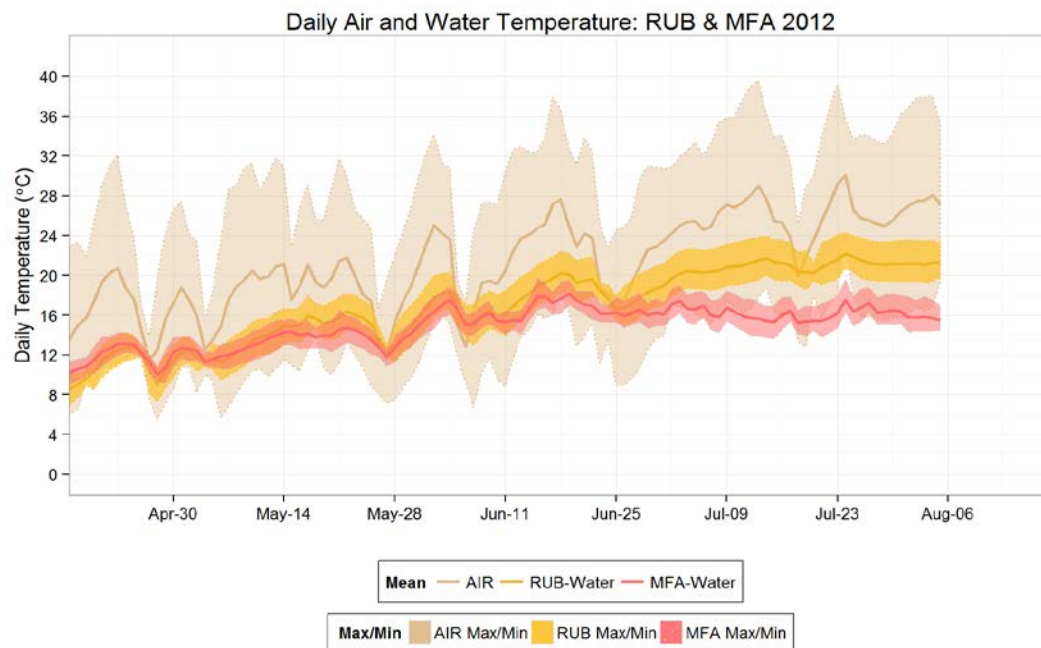
The SF Yuba water temperature patterns also diverged from natural patterns as warmer temperatures were observed in 2011 compared to 2012, with an approximately 4 °C divergence from the unregulated NF Yuba as observed in August of 2011. Contrasted with the drier and warmer 2012, differences in August weekly average temperatures between the SF Yuba and NF Yuba were approximately 2 °C, indicating water temperatures were less divergent in the drier water year.

Figure 1.11: Daily mean, maximum and minimum air and water temperatures for the Rubicon (bypass) and MF American (hydropeaking) study sites from April through August in a) 2011 and b) 2012.

a)



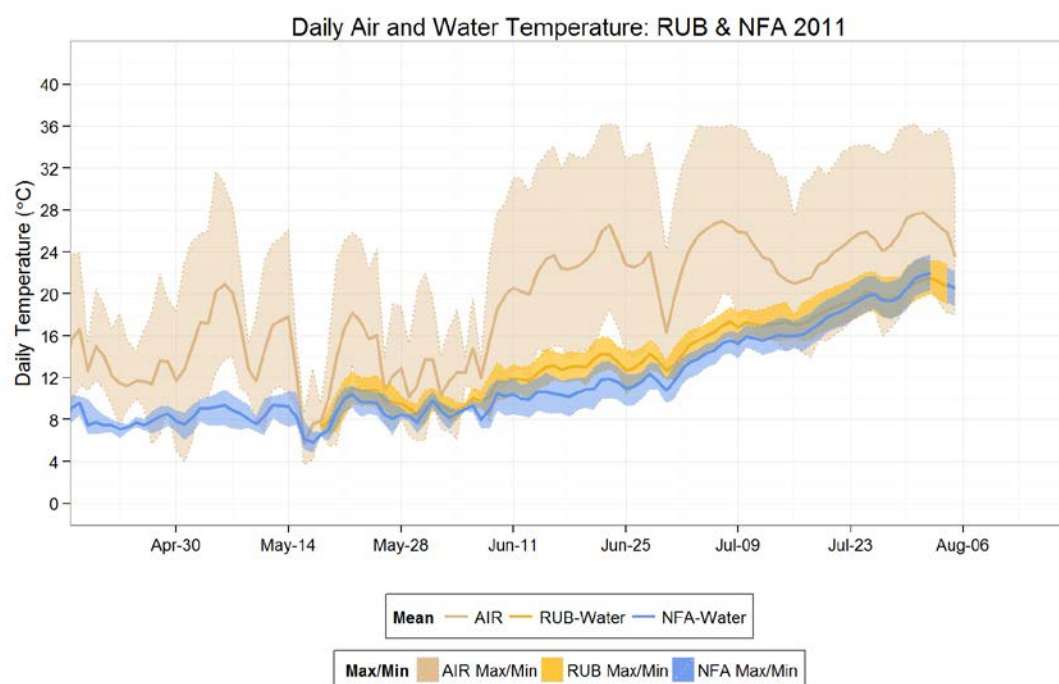
b)



Water temperatures on the MF American diverged the most from air temperatures among the study sites, primarily when hydro-peaking operations occurred. This decoupling of air and

water temperature in the MF American was observed regardless of water year type (Figure 1.11). In 2011, the daily maximum water temperatures for the MF American in the late summer (mid-July) were less than the daily minimum air temperatures in the basin. In 2012, MF American daily maximums exceeded the daily minimum air temperatures, but remained well below the daily minimum water temperature in the bypass study site on the Rubicon River, located upstream within the same watershed. In 2011, the bypass study site on the Rubicon River exhibited very similar water temperature trends to the unregulated NF American (Figure 1.12), although water temperatures were slightly warmer in the NF American study reach in 2012 compared with the Rubicon bypass reach.

Figure 1.12: Daily mean, maximum and minimum air and water temperatures for the Rubicon (bypass) and NF American (unregulated) study sites from April through August 2012.

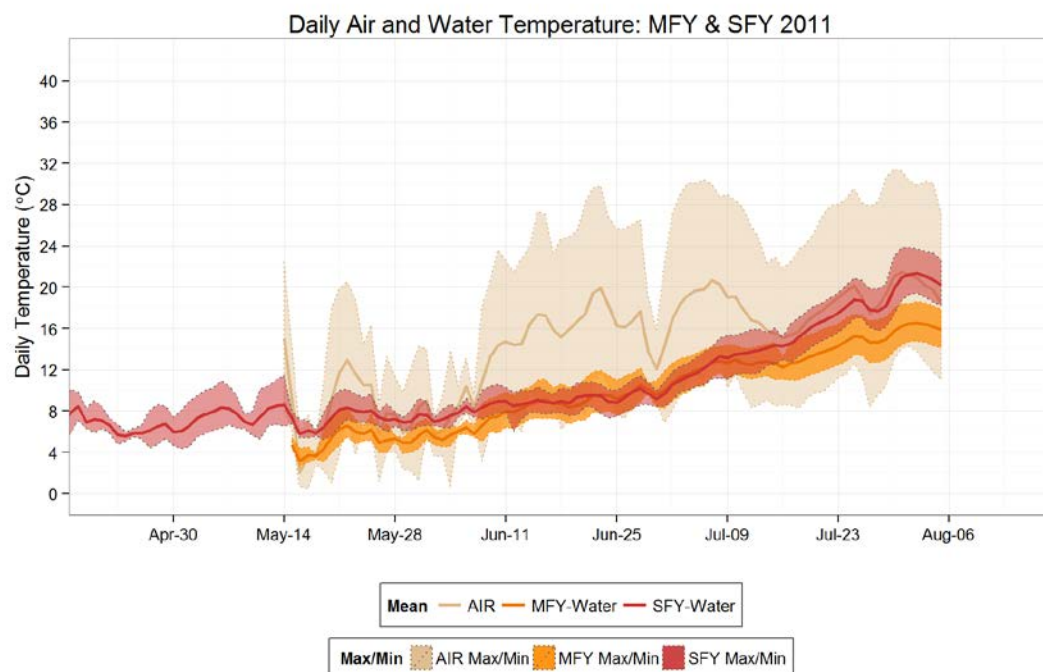


In 2012 in the American River Watershed, a divergence between the three study sites was identified in early June, when all three study sites diverged at approximately the same time the snowmelt recession ended (no snow remaining). Following snowmelt, the bypass and unregulated reaches continued to warm while the hydropeaking reach remained fairly constant with a weekly average temperature of approximately 16 °C. The maximum weekly water temperatures at the unregulated NF American exceeded the Rubicon temperatures by several degrees Celsius by mid-July in 2012. When compared to 2011, in which weekly average water temperatures in both the Rubicon and NF American study reaches remained largely synonymous, the 2012 divergence may have been related to the lack of cold-water storage or groundwater input upstream in the NF American (unregulated), while the Rubicon River bypass reach received cold water releases from Hell-Hole Reservoir, approximately 45 km upstream.

A different pattern between air temperature and water temperature was observed in the regulated study reaches in the Yuba watershed. In 2011, as air temperatures warmed in late-May and early-June, the bypass MF Yuba mean water temperatures appeared to respond more quickly to warming air temperatures compared with the SF Yuba through the end of June

(Figure 1.13). Beginning in July, daily mean water temperatures in the SF Yuba increased more rapidly than the MF Yuba daily mean temperatures, and at times exceeded the daily mean air temperature observed at the same location. Although the water temperature patterns were largely similar throughout the Yuba study sites, the unregulated NF Yuba was most similar to the MF Yuba bypass reach in 2011, and the temperature magnitude in both 2011 and 2012 was lower than the SF Yuba.

Figure 1.13: Daily mean, maximum and minimum air and water temperatures for the Yuba River watershed at the MF Yuba and SF Yuba study sites from April through August 2011.

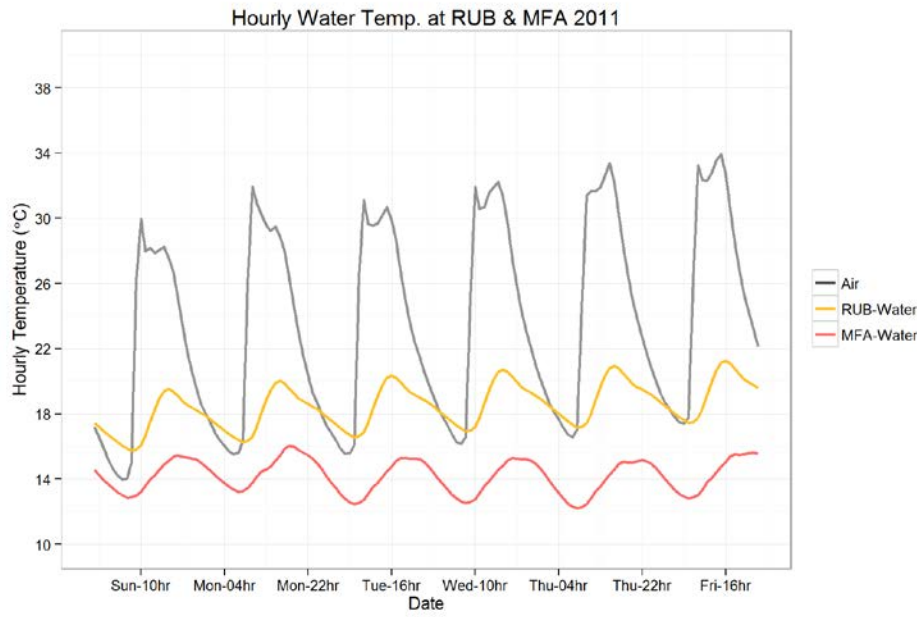


Differences in air and water temperature between years were significant, as 2011 was categorized as a wet water year by DWR and 2012 was a dry water year. Diurnal fluctuations in air temperature were comparable between years, ranging up to 20 °C daily in July and August; however, water temperatures were generally cooler in 2011 compared with 2012. One notable exception was the SF Yuba, which was the only study reach with 2011 mean weekly average water temperatures exceeding temperatures from 2012 (in August). The weekly average temperature in the Rubicon River was consistent between years with approximately equivalent temperatures observed in August in 2011 and 2012; however the maximum weekly average temperature observed occurred in August 2012.

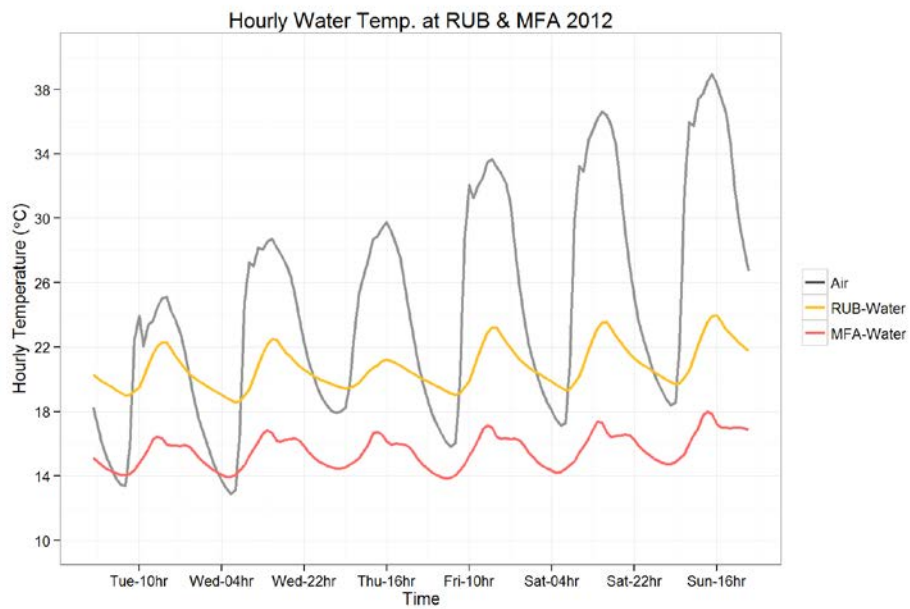
The diurnal fluctuations of stream temperature in the MF American were similar in amplitude and wavelength to the Rubicon River in both 2011 and 2012, and generally show similar patterns compared with air temperatures, however, several significant differences were observed (Figure 1.14). The primary difference was that the overall magnitude of hourly water temperature in the MF American was approximately 4–7 °C less than the Rubicon and NF American once peaking flow operation began, regardless of water year type. Greater divergence in magnitude was observed in 2012 compared with 2011. For example, the daily diurnal range in water temperature in late July at the Rubicon was 19–23 °C and 15–18 °C at the MF American.

In addition, warmer, drier conditions in 2012 appeared to affect the shape of the peak in diurnal water temperatures in the MF American. This was due to a lag in the arrival of the peaking flow pulse at the study site, which was approximately 35 km downstream of the powerhouse release point. Flows were released in the morning, typically around 7:00 am, and reached the study site downstream in approximately eight hours. Consequently water temperatures at the MF American study site had sufficient time to warm and equilibrate with air temperatures as the flow pulse reached the site. Although the pulse water temperatures warmed during the travel time, they remained cooler than the water temperatures at the study site. Displacement and mixing of these two phases at the MF American was clearly visible in 2012 as a decrease in water temperature (approximately 1 °C) followed by a plateau during the warmest period of the day. In contrast, water temperatures at the Rubicon and NF American continued to increase throughout the day until air temperatures began to decline in the evening.

Figure 1.14: Hourly mean air and water temperatures for a five day period in mid-July on the Rubicon and MF American study sites in a) 2011 and b) 2012.



a)



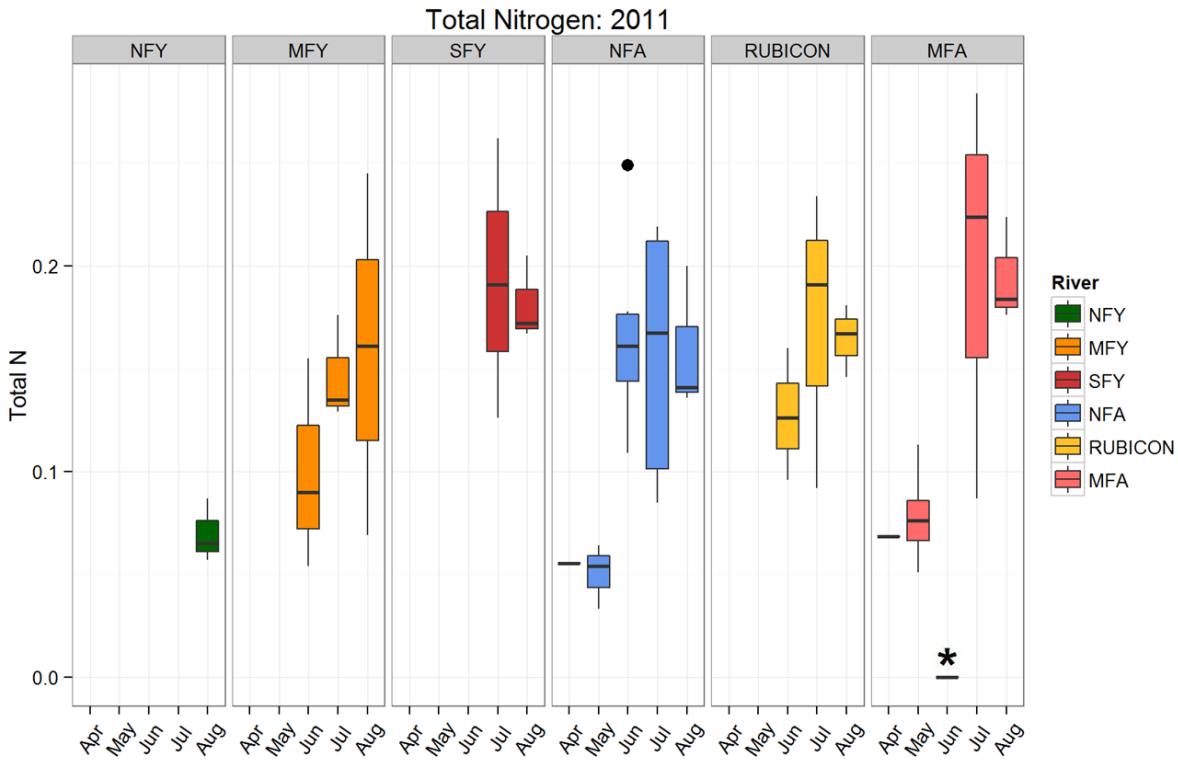
b)

1.4.2.3 Water Quality

Water quality data were collected in 2011 to assess potential differences between regulated and unregulated rivers during the spring snowmelt period of the hydrograph. Sampling was collected monthly via grab samples on an opportunistic basis in the spring and summer of 2011. In addition, autosamplers were installed on the NF American and MF American, and samples were collected sub-daily for several weeks during the spring-summer of 2011. At each study site, samples were collected in triplicate in acid-washed and pre-rinsed 1L bottles. Grab samples were stored in the dark, on ice, and transported to the lab for processing within 24 hours of collection. Autosampler samples were stored within the autosampler on ice, in the dark and were removed every three days and transported to the lab for analysis. Total suspended solids (TSS), turbidity, total phosphorus (TP) and total nitrogen (TN) were analyzed. TSS were determined by filtering ~500 mL of water through a pre-combusted, pre-weighed, GF/F glass fiber filter and then reweighed after drying (Clesceri et al., 1998). TN was determined spectroscopically following oxidation with 1% persulfate followed by determination using the vanadium chloride method (Doane and Horwath, 2003). TP was determined spectroscopically following oxidation with 1% persulfate followed by determination using the ammonium molybdate method (Clesceri et al., 1998).

In 2011, TN amounts varied across rivers, however similar monthly trends were observed in the three American watershed study sites (Figure 1.15). Mean TN increased from low values in May to high values in July, followed by a decrease in August. The highest mean TN was observed in July in the MF American, and the lowest in the NF American in May. Monthly patterns were similar in the Yuba Rivers with mean TN highest in July and August. The pattern of increasing TN from May through July followed by a decline in August correlated with spring flows, which peaked in late-June, and then attenuated or were regulated by early-July.

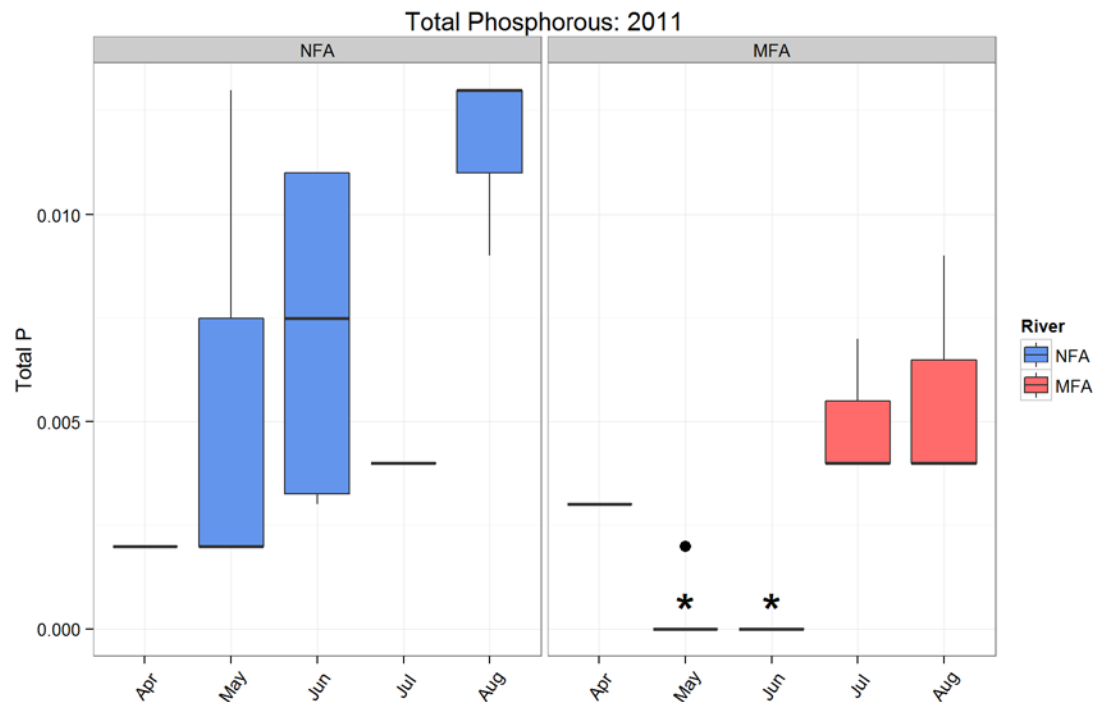
Figure 1.15: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) of total nitrogen in 2011 at all study sites.



¹ Asterisk indicates sample values were below limit of detection [LOD (<0.001 mg/ L)].

Data on TP was limited and could not be compared across all rivers in the study due to variable samples across months and rivers. However, the NF American and MF American data were suitable for monthly comparisons. Overall, TP concentrations were higher and showed greater variability in the NF American (Fig 1.16). The pattern of monthly TP increase and decrease differed between the NF American and MF American, with concentrations generally increasing through summer on the NF American while decreasing then increasing on the MF American. Both study sites showed peak TP concentrations in August, although TP was higher in the NF American. In general, the MF American had a greater proportion of samples with TP values below the limit of detection, indicating potential TP limitation during some proportion of the summer.

Figure 1.16: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) for total phosphorus in 2011 in the North Fork American and Middle Fork American Rivers.



¹ Asterisk indicates sample values were below limit of detection [LOD (<0.001 mg/ L)].

Further analysis of the NF American and MF American water quality data showed the peak magnitude of TSS occurred at both study sites in June during the high flow runoff period (Figure 1.17) indicating a strong relationship between TSS and discharge. However, the NF American and MF American showed different relationships between TSS and TP. On the NF American, TP peaked in June in conjunction with peak TSS, and then again in August, suggesting TP may be derived largely from sediments and organic particulate matter. In contrast, on the MF American, the lack of a peak in TP in June during high flows suggests the dominate P-fraction may be comprised largely of soluble reactive inorganic phosphorus (orthophosphate) or soluble organic phosphorus rather than organic particulate matter.

Patterns of TSS in the Yuba study sites were similar to those observed in the American study sites, with peak magnitudes in June and low TSS values observed thereafter (Figure 1.18). Similar to other water quality parameters, this pattern correlates with flow patterns observed at the study sites where stream discharges peaked during June and receded in July and August.

Figure 1.17: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) of total suspended solids in 2011 in the North Fork American and Middle Fork American Rivers.

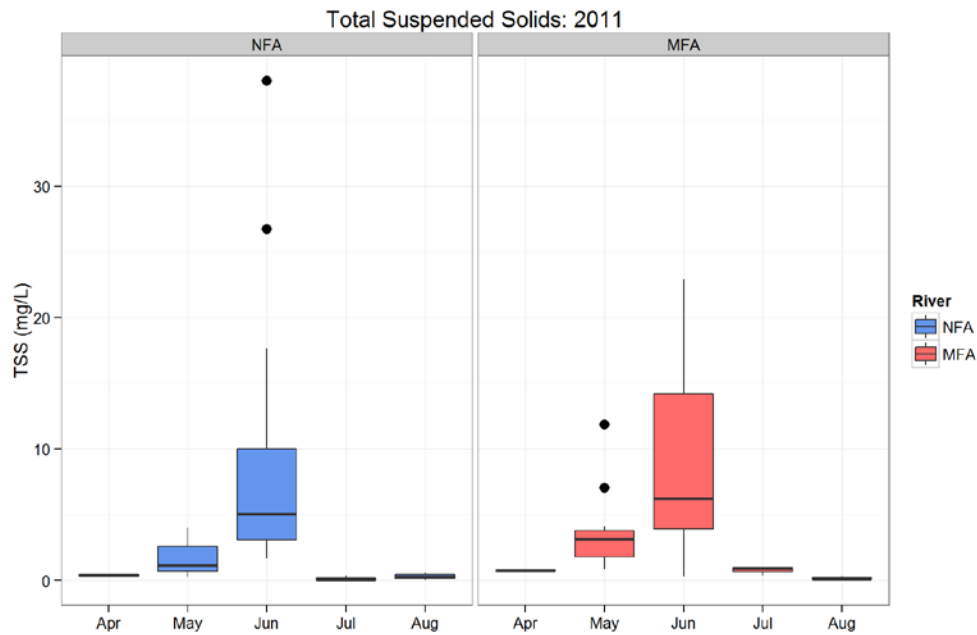
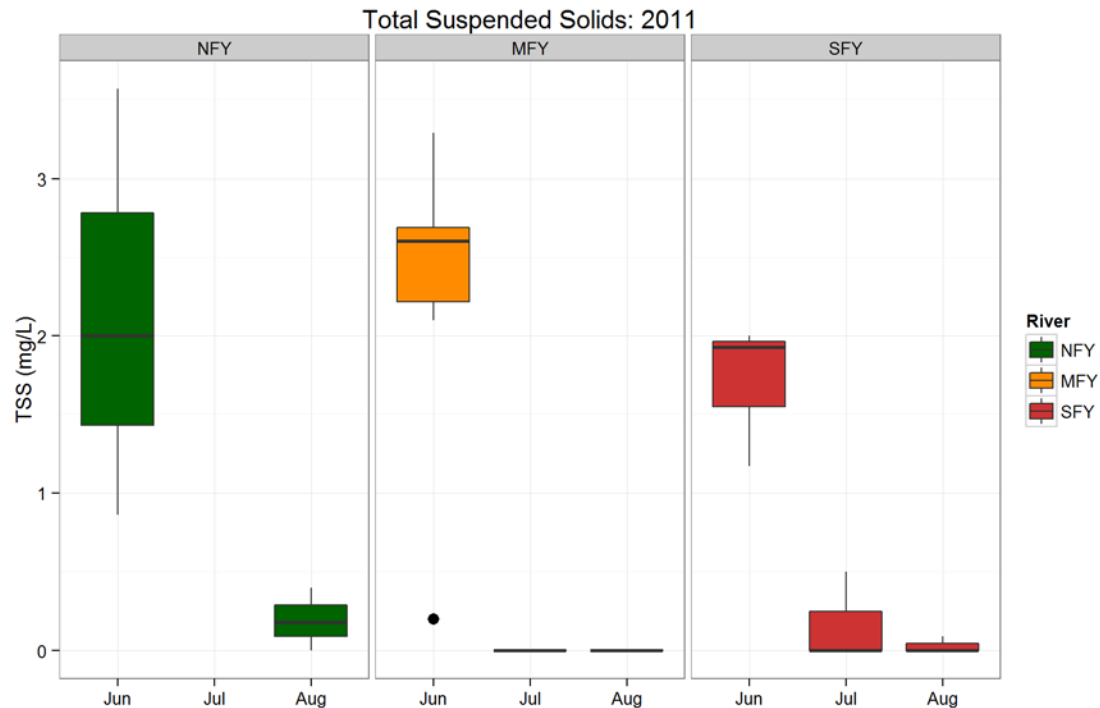


Figure 1.18: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) of total suspended solids in 2011 in the Yuba Rivers.



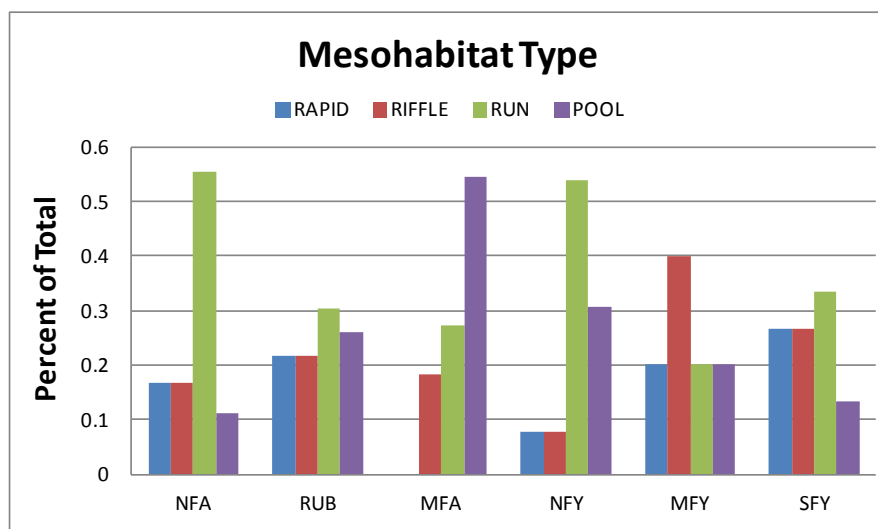
1.4.3 Geomorphology

In order to characterize the basic morphology of each study site, a set of permanent cross-section transects were placed within each study site. Cross-sections were selected using a random starting point along the thalweg stream line within the first 40m of the selected study reach, and then subsequent cross sections were selected at 40 m intervals along the thalweg. Cross-sections were monumented using a Trimble GPS and pins were epoxied to stable bank locations for all future visits. Larger reach-scale geomorphic features such as mesohabitats were delineated in the field and transferred to ArcGIS. Comparative measures such as channel slope, entrenchment ratio, valley width and mesohabitat length were calculated from the field and GIS data. A comprehensive geomorphic analysis of each site was beyond the scope of this project, but detailed geomorphic data is available for each of the regulated study sites within the FERC relicensing study reports (PCWA, 2010; NID and PG&E, 2011). For this study, basic channel morphology was collected in the field and used to provide context for the hydrologic and biotic analyses.

The reach-scale morphology of each study site was generally similar across study sites encompassing at least two bar-riffle-pool units as per the study design. Consequently, each study site was comprised of four primary mesohabitat unit types: rapid, riffle, run and pool (Hawkins et al 1993). The distribution of these types within each study site varied however, depending on factors such as channel bed slope, valley width and degree of entrenchment (Figure 1.19). The unregulated NF Yuba and NF American were dominated by lower gradient run habitat (> 50% each) and pool habitat (30% and 10%, respectively). The MF American was also dominated by lower gradient pool habitat (55%), but with less than 30% of the site containing run habitat. In contrast, the remaining regulated sites were dominated by higher gradient rapid and riffle habitat (40-60%).

A slightly steeper channel gradient in the SF Yuba and Rubicon study sites contributed to the higher prevalence of rapid habitat when compared to the other study sites, and the moderately confined nature of the channels (average valley width of 37 m and 36 m, respectively) provided limited space for deposition. Coarse boulder-dominated channel bars occurred in areas where valley width increased allowing for deposition of lateral bars. The MF Yuba similarly had a confined channel (average valley width of 32 m), moderate gradient and was dominated by coarse boulder and large cobble substrate, thus exhibiting a higher prevalence of rapid and riffle habitat. Each of these three regulated reaches exhibited limited sediment supply conditions with coarse bed substrates, little sand deposition in the pools and deposition of moderately sized gravel and cobble material predominantly along the edges of pools and in pool tailouts. Large boulder substrate particularly dominated the SF Yuba study site, where debris from past gold mining operations remained.

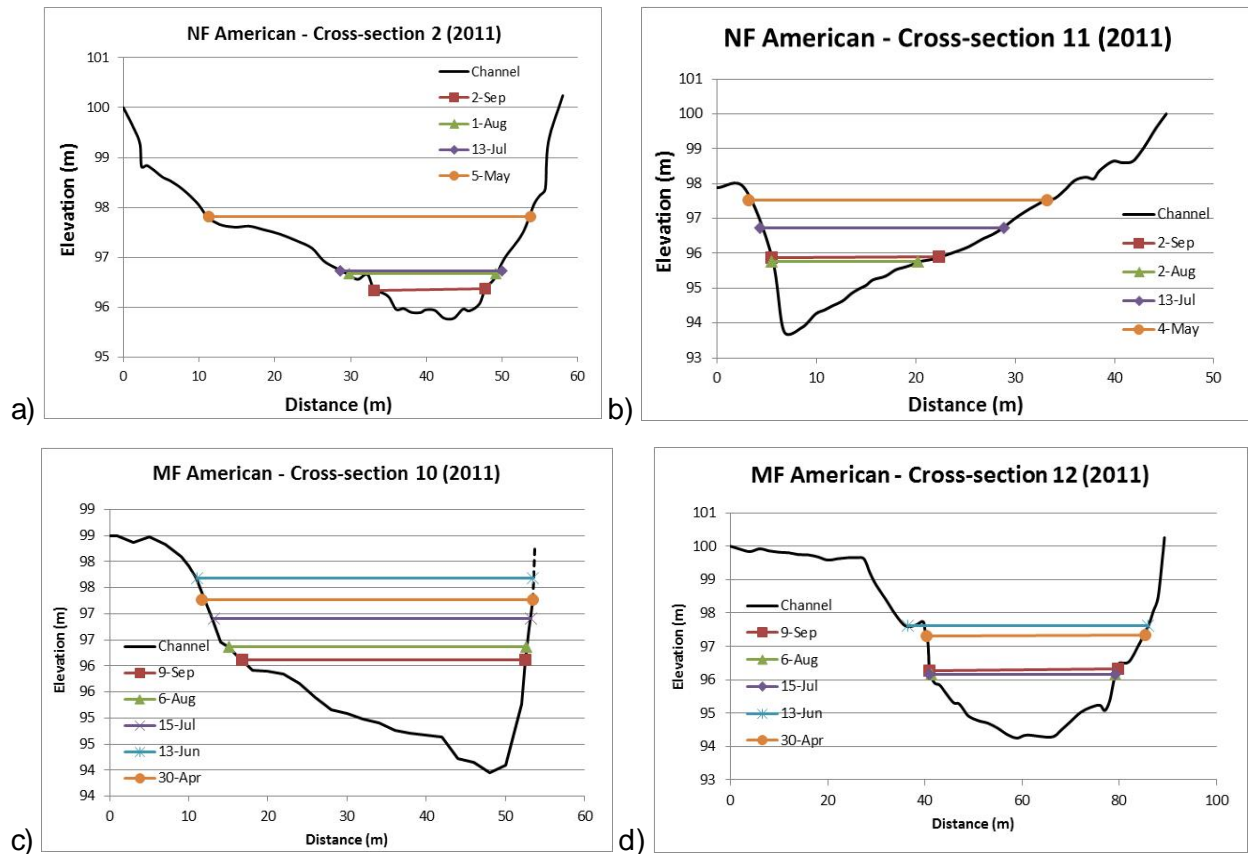
Figure 1.19: Percent of total habitat within each study site comprised of one of four primary mesohabitat types: rapid, riffle, run and pool.



The lower gradient and wider valley widths observed on the NF American, MF American and NF Yuba study sites contributed to the dominance of pool and run habitat. Average valley widths ranged from 44m on the NF American to 62 m on the NF Yuba to 150 m on the MF American. On the unregulated sites, active lateral channel bars occurred where local valley width increased, and substrates were more heterogeneous reflecting a wide distribution of sand to boulder from an abundant sediment supply. The MF American morphology was dominated by historical channel bar terraces that infrequently flooded due to moderate incision in the main channel. The entrenchment ratio at the MF American study site averaged 1.7 in comparison to an average of 1.2 at the NF American study site, and in some locations ranged to almost double that observed on the NF American. As a result, long deep pools paralleled the large channel terraces with riffles occurring where the bars transitioned laterally across the channel.

The cross-section morphology thus differed between the more active unregulated sites and the less active regulated sites. Channel bars on the MF American, SF Yuba and MF Yuba were typically stabilized by a band of mature vegetation lining the water's edge, which typically reduces bank erosion and promotes channel narrowing (Petts and Gurnell 2005). In contrast, the unregulated NF American and NF Yuba typically exhibited channel bar shapes that were more asymmetric in profile with mature vegetation occurring along the back of the bars further from the active channels that experience erosion and deposition annually. Cross-section profiles reflected these differing channel bar characteristics (example shown in Figure 1.20). As stage decreased from high flows in May 2011 on the NF American to low flows in September, both depth and width decreased through time as flows receded over the asymmetric channel bars (Figure 1.20a, b). High flows in April 2011 on the MF American did not exceed the main channel dimensions and extended only onto the upstream head of the channel bars before returning quickly to the main channel. As a result, flows were contained within the main channel next to the bar and water depth decreased while width remained constant as flows decreased into summer (Figure 1.20 c, d).

Figure 1.20: Channel cross-section profiles across a) left bank bar on NF American, b) right bank bar on NF American, c) left bank bar on MF American, and d) left bank bar on MF American. Horizontal color lines indicate water surface elevation at the associated survey date in 2011.



1.4.4 Hydraulics

Previous studies have shown that the composition and range of hydraulic habitat within a stream can determine the composition of biota, particularly benthic macroinvertebrate communities, within the stream (Lancaster and Hildrew, 1993; Pastuchova et al., 2008), suggesting that streams with a diversity of hydraulic habitat across space and time support diverse biota (Dyer and Thoms, 2006; Yarnell et al., 2010). Methods for quantifying hydraulic habitat diversity however have been highly variable, ranging from analyses of categorical variables, such as surface flow types (Dyer and Thoms, 2006), to calculations of coefficient of variation of hydraulic parameters, such as depth and velocity, at a single point in time (Gostner et al 2013). In order to assess the diversity of hydraulic habitat in each study reach, both across space (throughout the reach) and across time (as flows change from spring to summer), a novel approach was taken to quantify the observed distribution of measured depth and velocities across the potential full range of values. Study reaches where depths and velocities spanned the greatest range of available hydraulic habitat niches through time were considered to be the most hydraulically diverse, and thus potentially to support the greatest diversity of biotic communities.

Hydraulic field data were collected at each of the monumented cross-sections within each study site at each visit. During each visit, water depth and velocity were measured at 1 m increments along each transect, from the edge-of-water to the maximum wadeable location (approximately 1.20 m in depth or 1.5 m/s in velocity during high flows in the spring). If measurement points were located on a boulder or dry area above the water surface larger than 0.5 m², they were

recorded as “dry” (depth = 0.0 m, velocity = 0.0 cm/ s). If the dry feature was smaller than 0.5 m², the measurement was taken on the downstream side of the feature. At each point along the transect, total depth of the water column was measured with a wading rod, and mid-column velocity was measured using a Marsh McBirney Flow Meter (Hach Company, Loveland, CO).

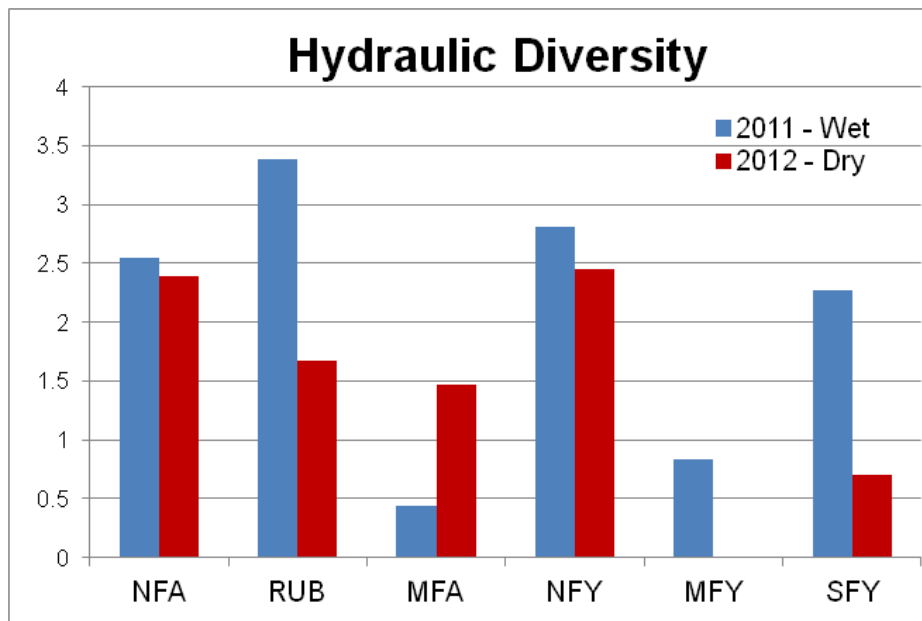
The diversity of hydraulic habitat was quantified using a variance to mean ratio of nearest neighbor distance between measured depths and velocities as they plotted across the range of potential depths and velocities. By plotting the depth versus the velocity of each measured point, a sampling space was created of the potential range of wadeable depths (0-120 cm) and velocities (0-150 cm/ s). The distribution or dispersion of measured points within the sampling space was then quantified by calculating the ratio of the variance to the mean of nearest neighbor distances between each set of points (Upton and Fingleton 1985). Mean and variance were calculated as:

$$Mean = \frac{\sum x_i}{n}, \quad Variance = \frac{\sum x_i^2 - \frac{(\sum x_i)^2}{n}}{n-1}$$

where x_i was the distance between each point and its nearest neighbor, and n was the total number of points within the sampling space. Larger distance values indicated greater dispersion across the sampling space, and thus a greater diversity of hydraulic values for the associated time period.

Hydraulic diversity remained high and consistent through time at the unregulated sites, but was highly variable through time at the regulated sites. When data were pooled across cross-sections and across sampling dates within a year for each study site, dispersion values were highest at the unregulated study sites, and the Rubicon and SF Yuba study sites in 2011 (Figure 1.21). Values were lower in 2012 at most sites and in general at the regulated MF American and MF Yuba sites. Higher sustained flows in 2011, a wet year, allowed flows to occupy much of the cobble bars on the Rubicon and SF Yuba increasing the hydraulic diversity, while in 2012, a dry year, flows were confined to the main channels at regulated sites. The channel morphology of the unregulated sites was typically more asymmetric in cross-section than the regulated sites, allowing for a greater range of depths and velocities to occur at any given flow (see previous discussion in section 1.4.3).

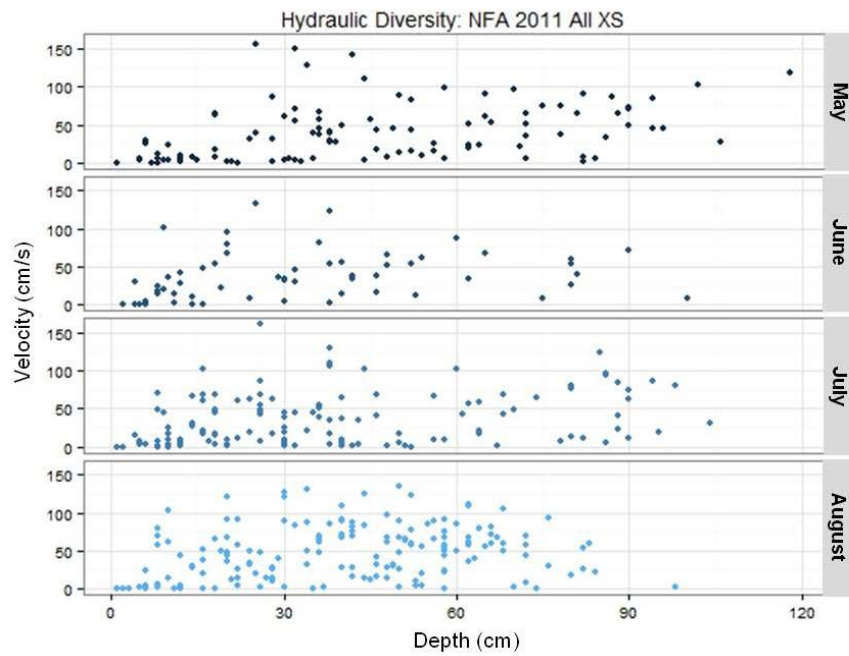
Figure 1.21: Dispersion of depths and velocities across all cross-sections from May to August at each study site. Higher dispersion values indicate a higher hydraulic diversity.



When the hydraulic data were assessed on a monthly time scale in order to better discern changes in diversity as flows decreased into summer, the influence of differing channel cross-section morphology was evident. Measured hydraulic values ranged across the spectrum of potential values (0-120 cm in depth and 0-150 cm/ s for velocity) at the NF American in May 2011 when flows averaged 2500 cfs, and remained dispersed as flows increased to about 3000 cfs in June and decreased to an average of 500 cfs in July and 100 cfs in August (Figure 1.22a). Conversely, on the MF American where the main channel is U-shaped rather than asymmetric, measured hydraulic values ranged from 0-120 cm in depth in May 2011 (average of 2500 cfs), but velocities were largely below 50 cm/ s. As flows declined through time on the MF American (average of 3500 cfs in June, 1500 cfs in July, and 1000 cfs in August), hydraulic values were less dispersed and contracted towards low velocities (< 50 cm/ s) and shallow depths (< 50 cm) (Figure 1.22b). In 2012, lower flows (average 1000 cfs in May, 500 cfs in June, 100 cfs in July) resulted in lower observed depths in all months on the NF American, but the range of observed depths and velocities remained high through time even as flows decreased (Figure 1.23a). On the MF American in 2012, flows remained constant averaging 800 cfs from May until August. As a result, observed depths and velocities remained consistently below 100 cm and 25 cm/ s, respectively (Figure 1.23b). The calculated hydraulic diversity values for each month at each study site reflected these patterns, with consistently high diversity across months and years on the NF American, but decreasing diversity on the MF American after high flows in May and more variation in diversity across years (Figure 1.24).

Figure 1.22: Distribution of wadeable depths and velocities at all measured cross-sections by month at a) NF American and b) MF American study sites in 2011.

a)



b)

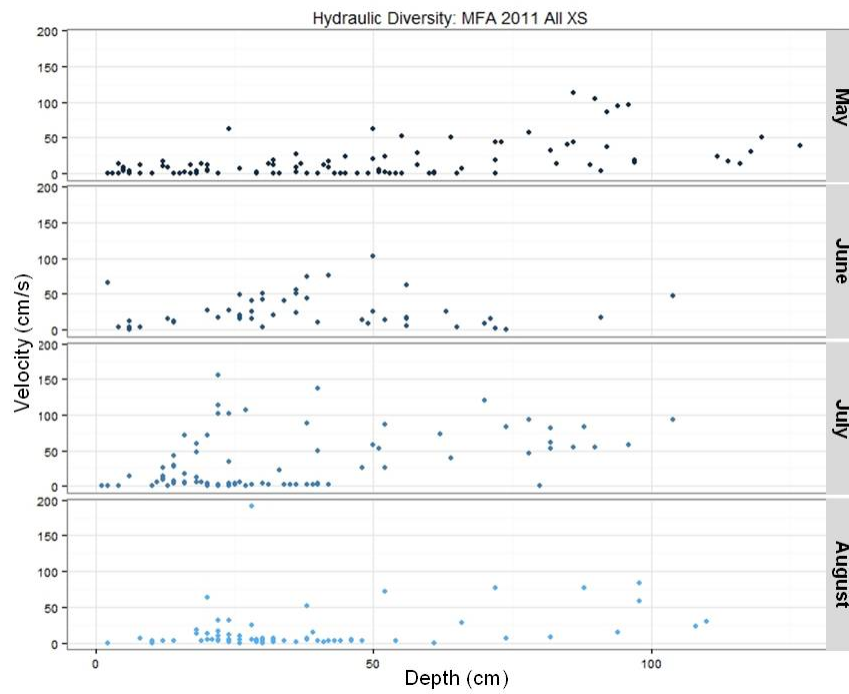
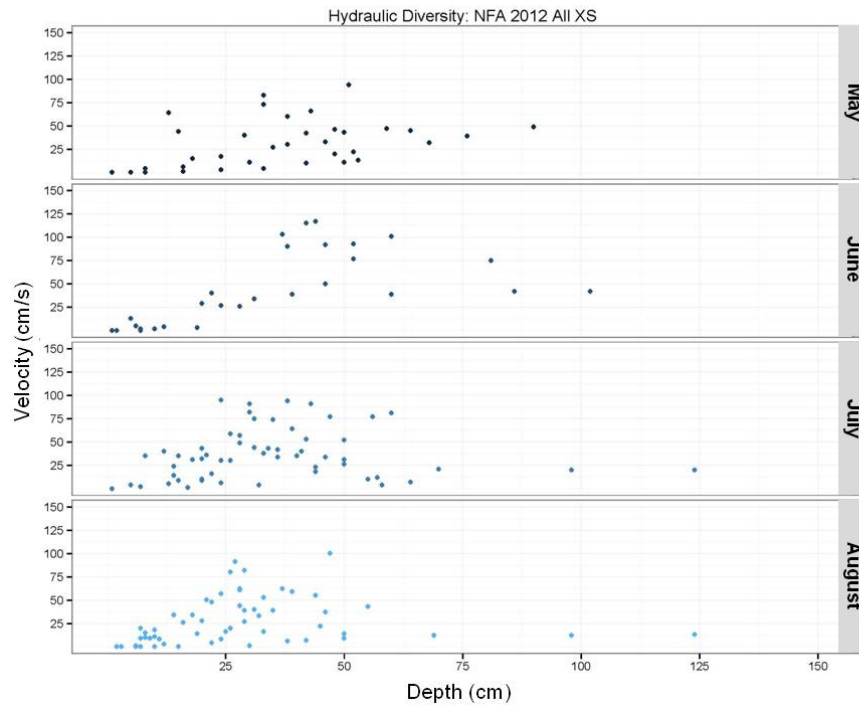


Figure 1.23: Distribution of wadeable depths and velocities at all measured cross-sections by month at a) NF American and b) MF American study sites in 2012.

a)



b)

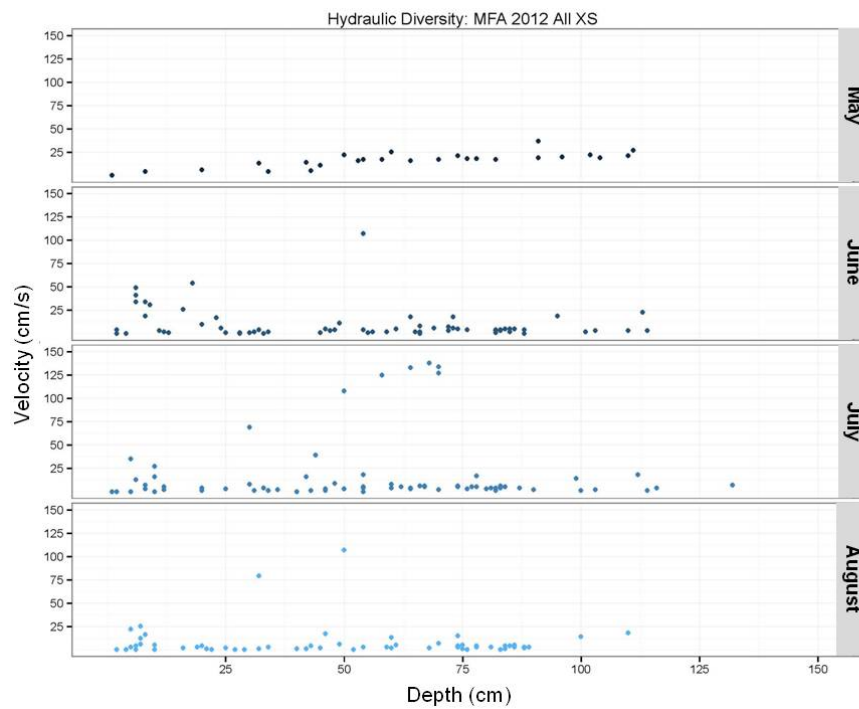
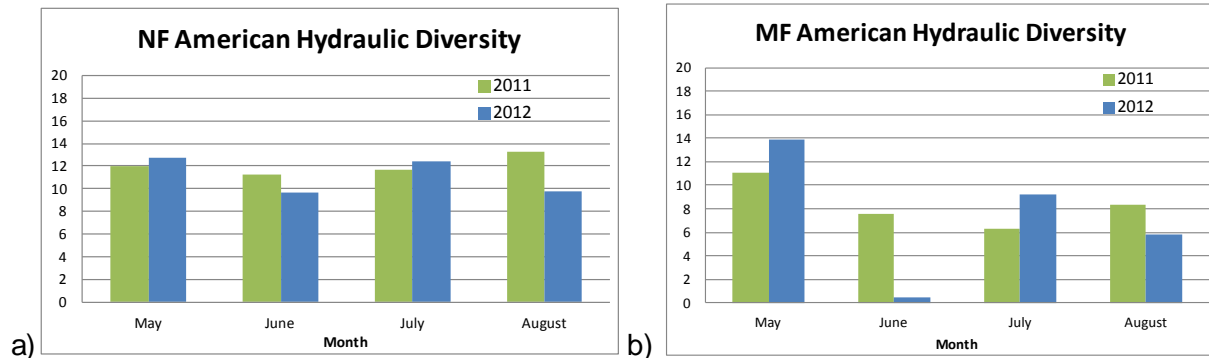


Figure 1.24: Dispersion of depths and velocities across all cross-sections by month at a) NF American and b) MF American study sites. Higher dispersion values indicate a higher hydraulic diversity.



1.5 Biotic Conditions

Data were collected at each study site to assess the riparian zone and primary productivity in the stream as well as the abundance and diversity of key aquatic indicator groups, including benthic macroinvertebrates, foothill yellow-legged frogs, and fish. In 2011, data were collected at all study sites, while in 2012 all study sites except the MF Yuba were surveyed.

1.5.1 Riparian Vegetation

The riparian zone along river reaches serves as a crucial interface between the aquatic and terrestrial realms of the larger watershed. Riparian vegetation serves not only as a structural element in the river system providing habitat for various terrestrial species, but contributes carbon and nutrients to the aquatic system fueling the primary productivity in the stream.

Each study reach was digitized at a scale of 1:1500 for vegetation communities within the riparian zone and the immediate upland area. The riparian zone was designated as anything adjacent to the river and polygons were digitized into the upland communities to create a small buffer zone for each of the study reaches. Digitized polygons were further informed by field surveys and visual inspection of communities in the field during June 2012.

For each of the six reaches in the study, California Native Plant Society (CNPS) rapid assessments with full species lists and photos were collected along at least four of the established monitoring cross-sections at each reach. CNPS Rapid assessments were conducted for vegetation starting at the river's edge and continued into upland vegetation within the riparian zone. A GPS point was taken for each survey.

To assess differences between study sites, overall alpha diversity, nativity, species distributions, and community turnover was investigated for each survey location and study reach. For the purposes of this analysis, a survey location was considered an individual survey along a transect, and a reach included all of the species contained within each survey location at that reach. Between reach species nativity and turnover (Sorensen's dissimilarity) were analyzed using a oneway analysis of variance (ANOVA) and Tukey's HSD to look at pairwise differences. To assess community differences between reaches and between river basins, the "metaMDS" routine in the Vegan Package in R was used to calculate community membership based on Sorensen Bray-Curtis distance. In this case, membership was calculated on a metacommunity basis, or as a collection of all of the survey locations within a river reach. Community differences were tested for significance using the package "Adonis" routine which is a multivariate analysis of variance (MANOVA) for community distance metrics like beta-diversity (Oksanen 2011).

1.5.1.1 Vegetation Types

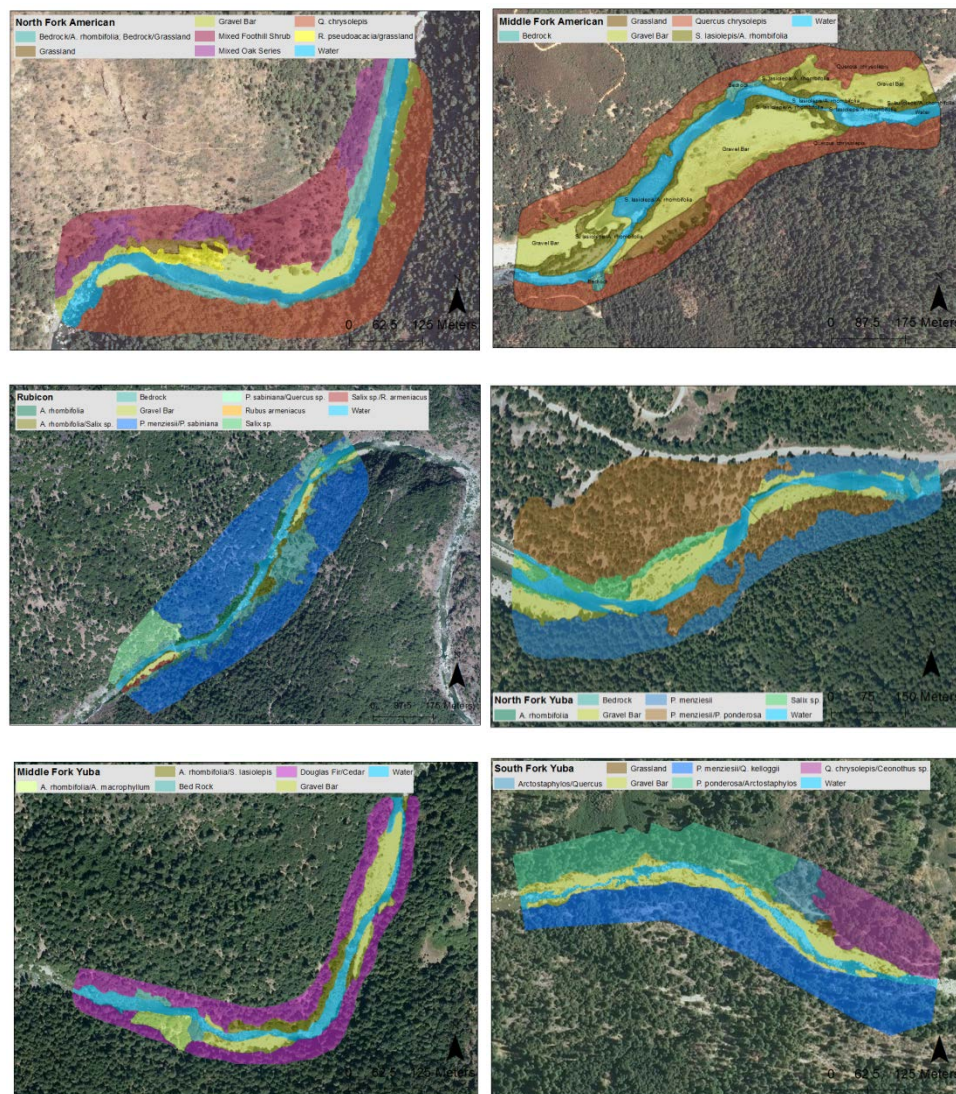
Twenty-six habitat and vegetation types were delineated for the six river reaches (Table 1.8). Each study site contained either gravel bar or steep areas of bedrock near the channel which usually contained willow and/ or alder species (Figure 1.25). Gravel bar vegetation was usually comprised of a few herbaceous species, like *Brickellia californica*, and young willow shoots. Some of the reaches contained stretches of non-native grassland at the edge of the riparian zone, especially in study sites where channel incision was prevalent.

Table 1.8: List of vegetation types delineated for all study reaches with canopy structure, common name of dominant species (where applicable), and dominant species name or habitat feature.

Structural Layer	Common Name	Habitat/Species
Low Vegetative Cover		Bedrock
		Bedrock/ <i>A. rhombifolia</i>
		Bedrock/Grassland
		Gravel Bar
		Water
Grassland		Grassland
Shrub	Himalayan blackberry	<i>Rubus armeniacus</i>
	Manzanita	<i>Arctostaphylos/Quercus</i>
		Mixed Foothill Shrub
Tree	White Alder	<i>A. rhombifolia</i>
		<i>A. rhombifolia/A. macrophyllum</i>
		<i>A. rhombifolia/S. lasiolepis</i>
		<i>A. rhombifolia/Salix sp.</i>
	Douglas Fir	<i>P. menziesii</i>
		<i>P. menziesii/C. decurrens</i>
		<i>P. menziesii/P. ponderosa</i>
		<i>P. menziesii/P. sabiniana</i>
		<i>P. menziesii/Q. kelloggii</i>
	Ponderosa Pine	<i>P. ponderosa/Arctostaphylos</i>
	Foothill pine	<i>P. sabiniana/Quercus sp.</i>
	Oak	Mixed Oak Series
	Canyon live oak	<i>Q. chrysolepis</i>
		<i>Q. chrysolepis/Ceonothus sp.</i>
	Black locust	<i>R. pseudoacacia/grassland</i>

	Willow	<i>Salix sp.</i>
	Willow/Himalayan blackberry	<i>Salix sp./R. armeniacus</i>

Figure 1.25: Digitized vegetation maps of the six study reaches.

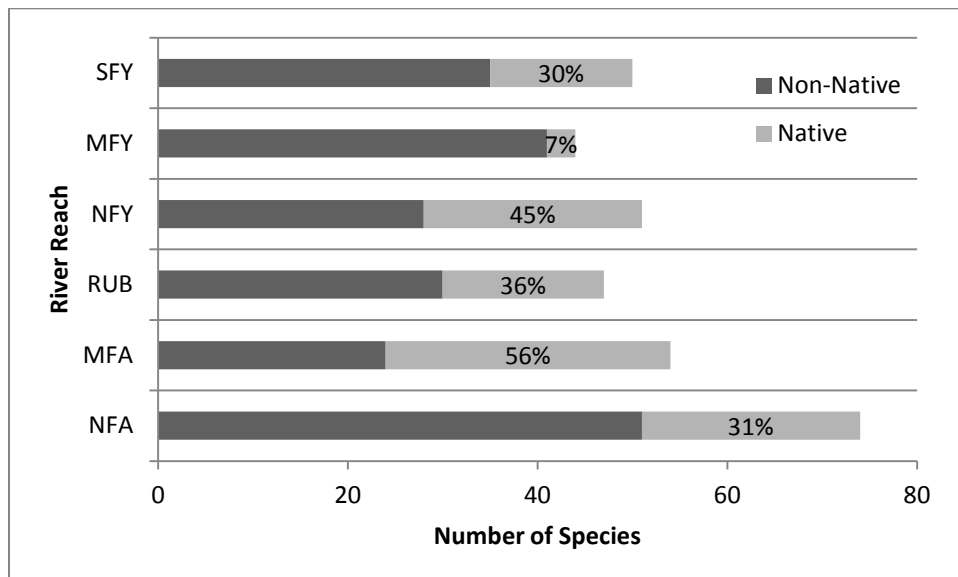


1.5.1.2 Diversity, Nativity, and Community relationships

In total, 147 distinct plant species were identified in all six reaches (species lists available upon request). Per survey species richness, which is a measurement of the alpha diversity contained in each community sampled, was highest at the NF Yuba and lowest at the Rubicon; however, these differences were not statistically significant ($F_{(5,41)}=0.87$, $p=0.51$). The MF Yuba had the highest number of non-native species (11 species), and the Rubicon had the fewest non-native species (5 species) per survey ($F_{(5,85)}=2.24$, $p=0.057$). Communities on the MF Yuba had the highest number of native species (13 species) per survey, while communities on the MF American were the least native (6 species) ($F_{(5,41)}=2.4$, $p=0.053$).

When looking at the total alpha diversity, or the metacommunity diversity, of each study site however, rather than richness per survey, the NF American had the highest total number of species, and the MF Yuba had the least (Figure 1.26). The NF American contained the most non-native species, while the MF American contained the most native species. The species contained within the MF Yuba reach were 93% non-native, compared to approximately 70% non-native species on the SF Yuba, Rubicon and NF American study sites. The MF American was the only study site where native species dominated.

Figure 1.26: The total number of unique species at each of the six river reaches split into their non-native and native components.



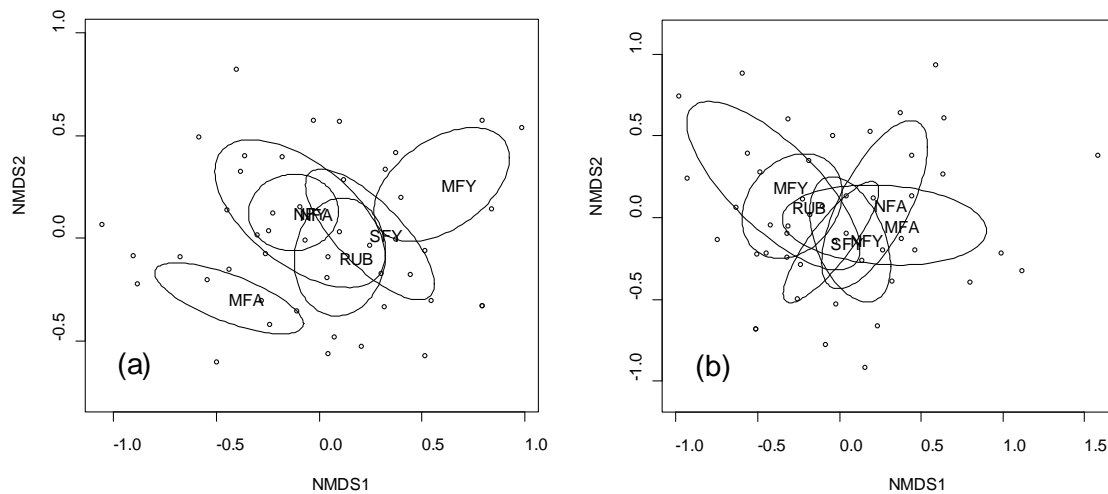
The NF American study site contained a high degree of community heterogeneity compared to the other sites, with between survey turnover approaching 80% compared to the within reach (or between survey) dissimilarities (Table 1.9). Both the MF American and MF Yuba were highly dissimilar to all other sites (Table 1.9 and Figure 1.26). At the MF Yuba, this may have been due to the high percentage of non-native species (93%, Figure 1.26), while the MF American contained the highest percentage of native species (56%).

Table 1.9: ANOVA and Tukey HSD of Sorensen (Bray-Curtis) similarity between and within (†) reaches ($p < 0.0001$). Higher values indicate higher rates of dissimilarity. Study sites that are not connected by the same letter are considered to be significantly different from each other.

Reach Comparison		Mean
MFA to MFY	A	0.89
MFY to NFA	A B	0.88
MFA to SFY	A B C	0.85
MFA to NFA	A B C D	0.84
MFY to NFY	A B C D E	0.84
MFY to RUB	A B C D E	0.83
NFA to RUB	B C D E F	0.81
MFA to RUB	B C D E F	0.80
MFA to NFY	C D E F	0.80
NFA to NFA †	B C D E F G	0.79
MFY to SFY	B C D E F G	0.79
NFY to SFY	C D E F G	0.78
NFA to NFY	D E F G	0.77
RUB to SFY	E F G	0.76
NFY to RUB	E F G	0.76
NFA to SFY	E F G	0.76
MFA to MFA †	F G H	0.73
MFY to MFY †	E F G H I	0.72
RUB to RUB †	G H I	0.70
SFY to SFY †	H I	0.63
NFY to NFY †	I	0.62

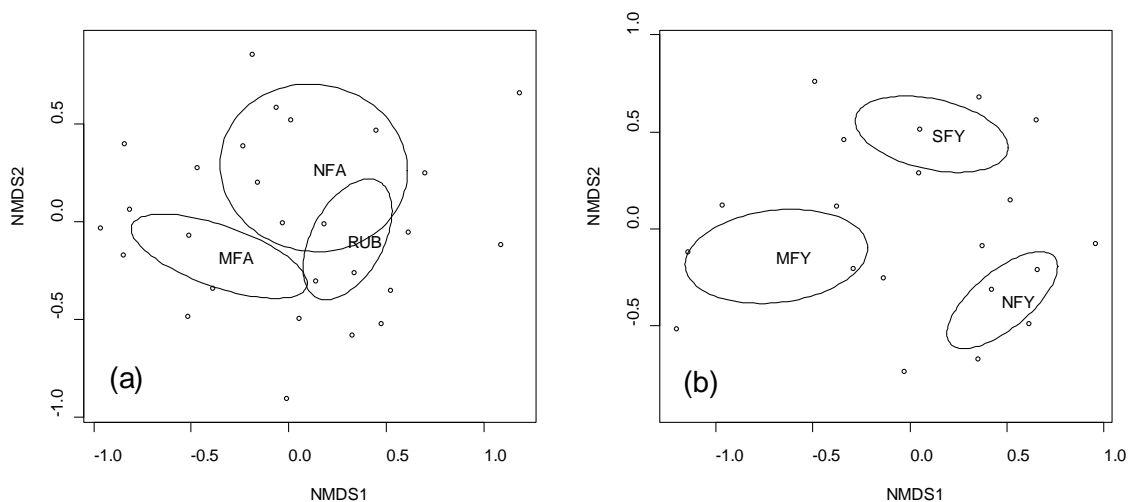
The dissimilarities between the MF Yuba and MF American study reaches versus the other study reaches were driven primarily by the presence of non-native species (Figure 1.27a). When only native species from each survey were plotted, the differences between metacommunities were less distinct (Figure 1.27b).

Figure 1.27: Plotted NMS ordination of a) all species at each river reach showing separation between the MF American and all other reaches, and separation of the MF Yuba and most other reaches ($p=0.004$), and b) only native species. Community dissimilarities in both a) and b) are significant to the $p=0.004$ level.



To discern the differences between reaches within the same river system, the NMS ordination was plotted for the American watershed study reaches and the Yuba watershed study reaches separately. The MF American study site shared little similarity to the NF American and Rubicon study sites (Figure 1.28a), but the three American study sites clustered more closely than the Yuba watershed study sites (Figure 1.28b).

Figure 1.28: Plotted NMS ordination of a) American watershed study reaches and (b) Yuba watershed study reaches. Community dissimilarities in both (a) and (b) are significant to the $p=0.004$ level.



1.5.2 Algae

Algae were sampled in 2011 and 2012 to characterize potential differences in biomass between regulated and unregulated rivers. Samples were collected monthly from each river at three different cross-sections. Due to higher flows in 2011, algae samples were only collected in June, July and August, and the MF Yuba was not sampled in 2012. At each study site during each visit, 3-4 cross sections were selected for algae sampling. At each cross-section, five rocks were randomly selected within the wadeable area, a 3x3 cm area from each rock was scrubbed and rinsed with a small volume of water (50-100 mL), and finally composited into a single sample for the selected cross-section. Samples were then placed on ice in a dark cooler until further processing was possible.

In the lab, samples were filtered using Whatman™ 47 mm glass microfiber filters and dried for 24–48 hours before burning. Total dry mass and ash-free dry mass (AFDM) (mg/ cm²) were calculated to measure total biomass (total dry mass – AFDM) within each sample. To determine whether biomass was statistically different by river and month, two-way analysis of variance (ANOVA) tests were conducted, and *post-hoc* single site ANOVA tests were completed to assess differences by month within each river independently.

To determine whether the invasive diatom *Didymosphenia geminata* (“didymo” or “rocksnott”) was present within each study site, a 200 uL aliquot of each composite sample was taken prior to filtering during the 2012 sampling effort. *D. geminata* is a large freshwater diatom that grows abundant extracellular mucopolysaccharides (stalked material) and has been identified as an invasive nuisance species on a global scale. Each aliquot was examined under a light microscope at 100-times magnification to determine presence or absence of the distinct *D. geminata* cells.

1.5.2.1 Biomass

Algal biomass was significantly greater at the SF Yuba and MF American study sites compared to all other study sites in 2011 and 2012 (Table 1.10). The volume of biomass on the MF American was an order of magnitude greater than all other rivers, and abundance patterns were similar between years (Figures 1.29 – 1.30). The lowest biomass was observed on the MF Yuba; however, samples were only available from 2011 in this study reach. Mean monthly biomass was comparable between the unregulated NF Yuba and NF American rivers in 2011 and 2012, although values were lower at all sites in 2012. The biomass values at the Rubicon were most similar to the unregulated sites, although lower in 2011 and higher in 2012.

Table 1.10: Mean monthly algal biomass (Total Dry Mass – AFDM) by river for 2011-2012.

River	2011 Biomass (mg/cm ²)	2012 Biomass (mg/cm ²)
NFY	1.5818	0.7405
MFY ¹	0.4998	NA ¹
SFY	3.0680	4.6797
NFA	2.0307	0.5424
RUB	0.9508	1.2697
MFA	81.7616	12.7610

¹ Samples only collected in 2011 at this study site

Figure 1.29: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) for algal biomass (mg/cm²) at each study site in 2011.

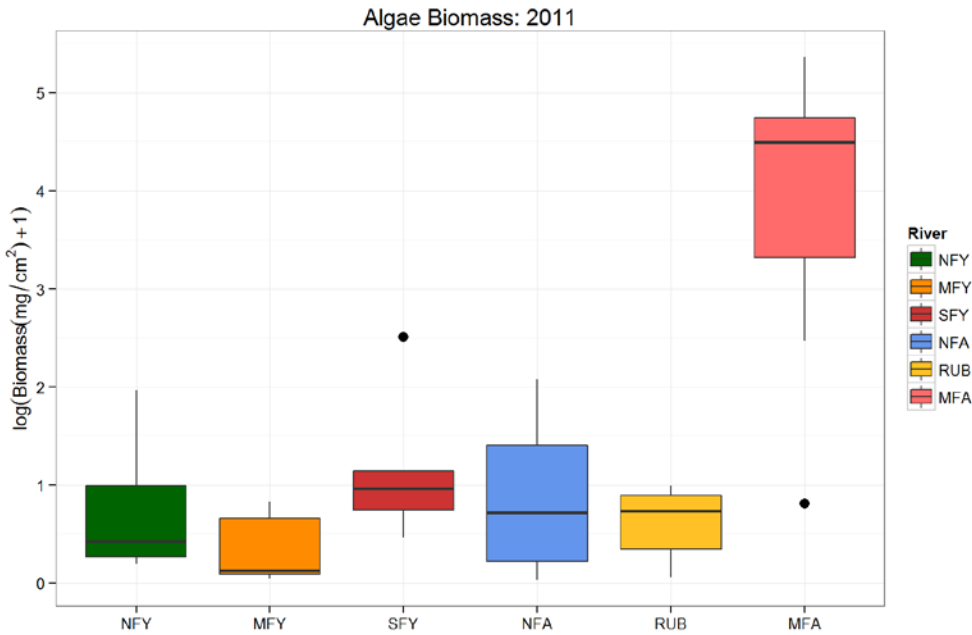
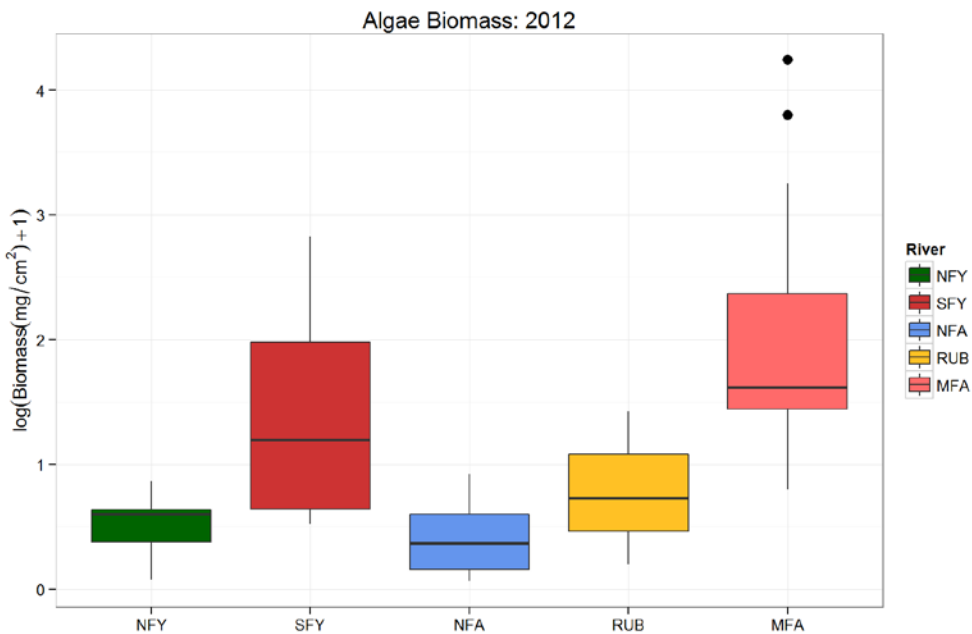
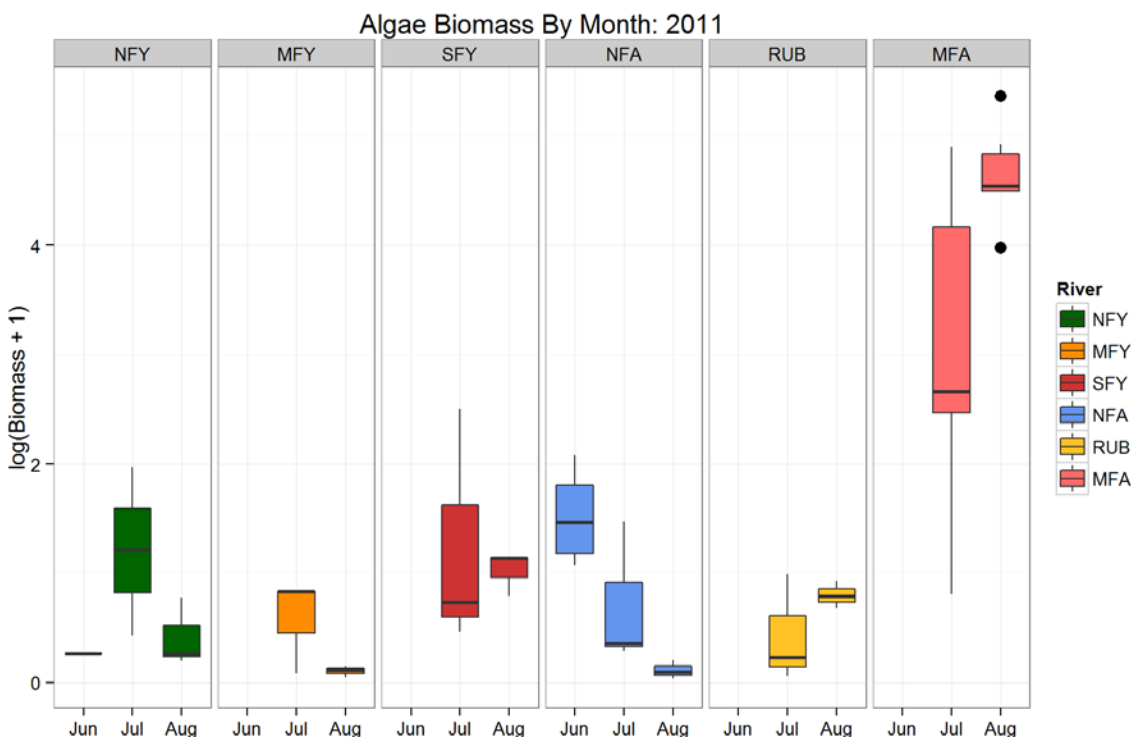


Figure 1.30: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) for algal biomass (mg/cm²) at each study site in 2012.



In 2011, only three months of data were available for temporal analysis (Jun–Aug), however general decreases in biomass occurred between the July and August samples in the NF Yuba, MF Yuba, and NF American, corresponding with the late snowmelt recession (Figure 1.31). The opposite pattern was observed in the Rubicon, SF Yuba and MF American rivers, where biomass increased between July and August.

Figure 1.31: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) for algal biomass (mg/cm²) by month at study sites in 2011.

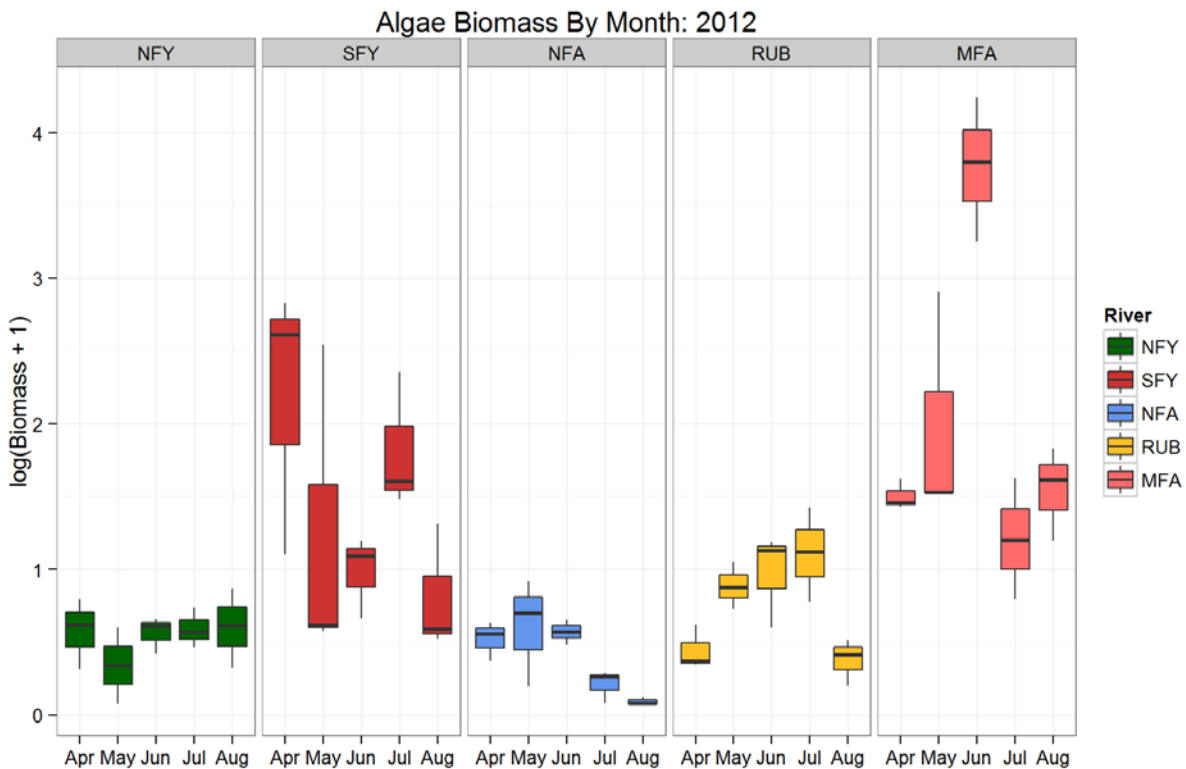


In 2012, algal samples were collected for five months between April and August in order better detect potential seasonal trends between rivers (Figure 1.32). A two-way ANOVA of algal biomass across river and month was highly significant between rivers and between months (Table 1.11). Trends in monthly biomass on the NF American were similar between 2011 and 2012 with a peak in May and June (associated with peak snow melt periods) followed by a gradual decline in biomass in the later summer months. On the Rubicon study reach, algal patterns in 2011 were similar to the NF American, but in 2012, biomass increased from April through July before sharply declining in August potentially due to senescence of algal growth late in the summer. The NF Yuba did not show significant differences in total biomass between months in 2012. Monthly biomass patterns on the SF Yuba and MF American differed from the other study reaches within the same watershed. Large increases and decreases in biomass from month to month were observed on the SF Yuba, and a general increase in biomass through June followed by a sharp decrease in biomass in July was observed on the MF American.

Table 1.11: Independent comparisons of 2012 algal biomass and sample month within each study site, $\alpha=0.05$, p-values (=highly significant, *=significant).**

River	Df	Sum Sq.	Mean Sq.	F-value	Prob. > F (p-value)
NFY	4	2.114	0.5285	1.079	0.417
SFY	4	7.463	1.8657	1.963	0.176
NFA	4	10.703	2.676	6.882	0.006**
MFA	4	15.85	3.963	12.12	<0.001**
RUB	4	5.675	1.418	6.247	0.009**

Figure 1.32: Boxplot of median, 25%-quartile, 75%-quartile, and whiskers showing 1.5 * inter-quartile range (approx. 95% CI) for algal biomass (mg/cm²) by month at study sites in 2012.



1.5.2.2 Invasive Diatom (*Didymosphenia geminata*)

The freshwater benthic diatom *Didymosphenia geminata* can thrive in a wide range of stream conditions. *D. geminata* has been documented in water temperatures from 4 to 27 °C, and across a wide range of depth and velocities (from 0 m/ s to velocities greater than 1.2 m/ s) (Kilroy et al. 2005, Spaulding and Elwell 2007). Research has shown that proliferations of *D. geminata* are largely due to the growth of stalk material which consists of extracellular polymeric substances that may be stimulated in oligotrophic rivers with high light levels (Kirkwood et al. 2007, Kilroy and Bothwell 2011). This invasive diatom may be one of few documented periphytic alga that blooms in oligotrophic conditions, and has the ability to form potentially ecologically disruptive algal blooms because the growth can cover entire substrates (Kirkwood et al. 2007, Rost et al. 2011).

D. geminata was visually observed in the SF Yuba and MF American study sites and has been documented in the SF Yuba, MF Yuba, and MF American previously (Spaulding and Elwell 2007, Rost et al. 2011) (Figure 1.33). Analysis of 2012 algae samples showed presence of *D. geminata* cells in the SF Yuba and MF Yuba during all visits and at all cross sections sampled, thus contributing to the significantly higher biomass observed at these study sites (Figure 1.32 above). Spaulding and Elwell (2007) observed the biomass of *D. geminata* was measured to be 250 times greater than chlorophyll *a* biomass, largely due to the impact of the extracellular stalks, not the actual diatom cells. Additionally, blooms of *D. geminata* may generate biomass and chlorophyll *a* values many times those found in non-bloom conditions, and the biomass produced can occur at levels indicative of a biologically impaired river (Spaulding and Elwell 2007). Therefore, patterns in biomass in the SF Yuba and MF American were likely dominated by biological interactions of *D. geminata* with water temperature, light intensity, nutrient levels, and flow regimes, which effect growth of extracellular stalk material.

Occurrence of *D. geminata* blooms has been more significantly associated with lower mean discharge and less variation in discharge commonly observed in regulated flow regimes (Kirkwood et al. 2007). Flood events or days since last high flow can be an effective hydrologic predictor of *D. geminata* presence and abundance (Kilroy et al. 2005, Kirkwood et al. 2009, Miller et al. 2009). In order to reduce biomass, flows must be large enough to mobilize substrates to scour cells from rock surfaces (e.g. in particular, saltation of the bed load or bed disturbance may be most important for controlling growth of *D. geminata*) (Larned et al. 2007, Spaulding and Elwell 2007, Miller et al. 2009), and several studies have shown *D. geminata* abundance decreased following large flood events (Kilroy et al. 2005, Kirkwood et al. 2007, Miller et al. 2009). Without variability in flow and the corresponding mobilization and scour of the substrate, stable conditions may allow *D. geminata* to out-compete other periphyton species. Recent research has shown locations downstream of dams where flows were consistently stable were more likely to have higher *D. geminata* abundance and bloom frequency than in unregulated rivers (Kirkwood et al. 2007, Kirkwood et al. 2009).

Figure 1.33: *D. geminata* cells with characteristic features (black arrow indicates 2-5 stigmata) observed in SF Yuba study site.



1.5.3 Benthic Macroinvertebrates

Previous FERC studies in both the Yuba and American watersheds at or near the study sites have sampled for benthic macroinvertebrates (BMI) during a single visit, typically during fall months (i.e., September on the MF Yuba or October on the Rubicon). This study sought to assess spatiotemporal differences within and among study sites during the spring and summer. Therefore benthic macroinvertebrates were sampled at each study site in 2011 in June, July and August and in each month from April to August in 2012. Results from 2012 sampling were not included in the following section as identification and analysis had not been completed at the time of this report.

1.5.3.1 BMI Methods

Four kick samples were collected at each of three randomly selected transects within the same 50 m reach of stream during each site visit in 2011 and 2012. A standard kick net (500 μ m mesh) was placed immediately downstream of the target sample area and approximately 0.10 m² of the streambed was vigorously disturbed for one minute. The twelve individual kick samples (four kicks over three transects) were combined in a bucket and the entire sample was elutriated to remove sand, silt, and gravel. The composite sample was subsequently preserved in 95% ethyl alcohol and returned to the laboratory for processing and identification.

Macroinvertebrate samples for taxonomic determination were obtained by randomly subsampling, using a Wildco plankton splitter to reach a minimum count of 500 organisms. If the entire sample contained less than 500 organisms, all organisms were identified. Large and rare taxa were excluded from subsequent quantitative analyses, but included in the taxonomic list generated for each sample period. Aquatic macroinvertebrates were identified to genus level whenever possible using Merritt and Cummins (2008), Thorp and Covich (2001), Smith (2001), Wiggins (1996), as well as various taxonomic-specific references. Ostracoda, Oligochaeta, and Arachnida were identified to class, while Chironomidae were identified to family. Specimens in poor condition or in very young instars were left at the next highest taxonomic level.

Several metrics can be calculated to assess the response of BMI communities to changes in flow regime. Table 1.12 provides a description of the metrics used for this report and the anticipated response to flow regulation. Previous studies have shown certain metrics are more effective at discriminating between unregulated and regulated sites. Rehn (2009) identified seven metrics which were largely independent (minimal auto-correlation) and form the basis for a hydropower index of biotic integrity (IBI) for streams and rivers influenced by hydropower projects. However, the most downstream site included in the hydropower IBI dataset was only 3 km from a dam, and all of the sites were located above elevations of 888 m, making comparisons difficult with larger mid-elevation rivers, such as those in this study. Therefore, to more accurately characterize potential differences between regulated and unregulated study sites, comparisons of multiple metrics were used describe study sites (Table 1.12).

Table 1.12: Description of BMI metrics and expected responses under flow regulation.

Macroinvertebrate Metric	Metric Description	Anticipated Response to Flow Regulation
Total Density (number / m ²)	Total number of macrobenthos per square meter	Decrease
Total Richness	Total number of distinct taxonomic groups or richness found in sample	Decrease
Percent EPT	Percent of macrobenthos in orders Ephemeroptera, Plecoptera, and Trichoptera	Decrease
Percent Grazer	Percent of macrobenthos that grazes upon epilithic biofilms (periphyton)	Variable
Percent Sensitive Taxa	Percent of macrobenthos with tolerance values of 0–2, (range 0–10), 0 being highly intolerant and 10 being highly tolerant	Decrease
Percent Chironomidae	Percent of macrobenthos in the family Chironomidae (midge larvae)	Increase
Percent Collector-Gatherer and Collector-Filterer	Percent of macrobenthos that collect and gather or filter fine particulate organic matter	Increase
Percent Predator	Percent of the macrobenthos that capture and consume other animals	Variable
Shannon's Diversity	Measure of community structure defined by the relationship between the number of distinct taxa and their relative abundances (range from 0 to infinity, least to most diverse)	Decrease

1.5.3.2 BMI Results & Discussion

During the June–August sampling period (2011), analysis showed changes in the benthic macroinvertebrate communities between unregulated and regulated rivers. In addition, the type of flow regulation (bypass or hydropeaking) also appeared to affect the invertebrate communities between rivers. Trends in the invertebrate communities over all sample periods

(June, July, and August) for each river are discussed below, followed by discussion of temporal shifts between individual rivers.

Changes in both benthic macroinvertebrate diversity and density were observed over the six study sites during 2011. The unregulated NF American exhibited the greatest invertebrate richness (both taxa richness and Shannon's diversity) and number of sensitive species when compared with the other study sites (Figure 1.34). Both the MF Yuba (bypass reach) and NF Yuba (unregulated) also showed high invertebrate diversity and a strong contribution of sensitive species to their respective assemblages. Conversely, the more regulated rivers (SF Yuba and MF American Rivers) showed the lowest diversity values among all sites during the study period, and sensitive species were more infrequent in these river systems. Benthic invertebrate density (count / m²) was comparable between rivers, with the MF American and MF Yuba generally showing higher densities throughout the study period. Patterns relating to regulation and operation type were similar across watersheds despite significant differences in elevation between the study sites in the Yuba and American watersheds. The unregulated study sites within each watershed, the NF Yuba and NF American, generally had the highest diversity, richness, and percent sensitive taxa while the most regulated sites, the MF American and SF Yuba, had the lowest.

The EPT index measures the percent contribution of Ephemeroptera, Plecoptera, and Trichoptera to a benthic invertebrate assemblage. These orders of aquatic insects are known to be sensitive to environmental stress and perturbation and therefore, are often used to assess the relative condition and health of lotic communities (Merritt and Cummins 2008). The unregulated NF Yuba showed the greatest contribution of EPT taxa to its assemblage (Figure 1.34). EPT taxa were also found to significantly contribute to the assemblage dynamics of the NF American, MF Yuba, and Rubicon, but exhibited far lower values for the SF Yuba and MF American. Conversely, the SF Yuba and MF American exhibited elevated contributions of chironomids when compared with the unregulated and bypass streams. Chironomids, or non-biting midges, are generally more tolerant organisms that exhibit fast lifecycles enabling them to colonize and succeed in disturbed habitats.

Comparison of functional feeding group metrics showed similar trends and also provided insight on the types of carbon sources available for uptake by particular macroinvertebrates. Functional feeding guilds appeared to fluctuate with river type (Figure 1.35). Grazers were more strongly associated with unregulated and bypass sites, while collector-gatherers dominated both the more regulated sites accounting for over 85% of the entire assemblage.

Figure 1.34: Boxplots of BMI metrics calculated from compilation of all data from 2011 sampling.

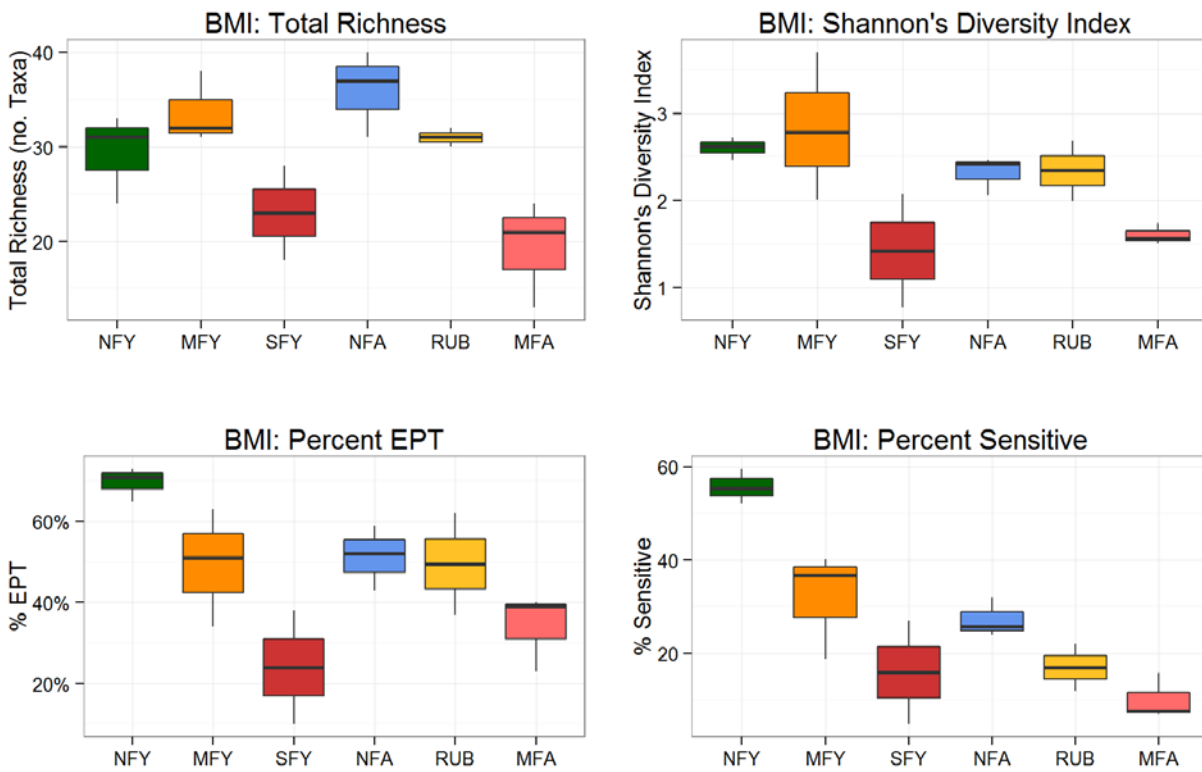
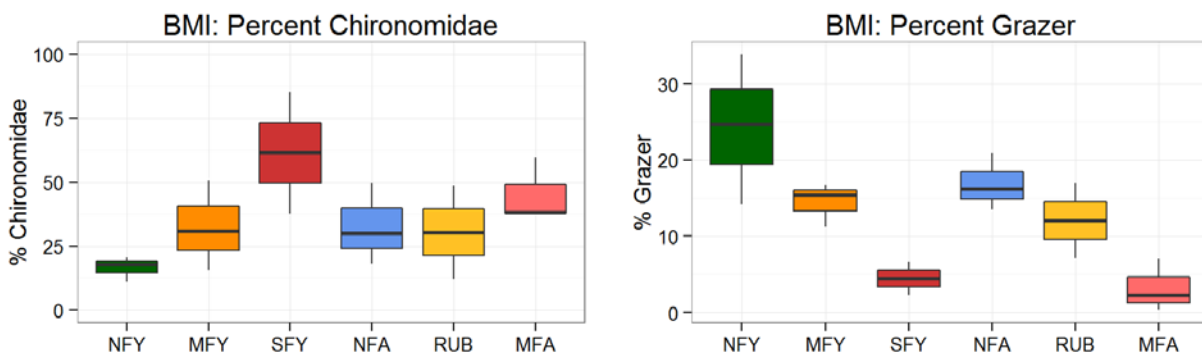
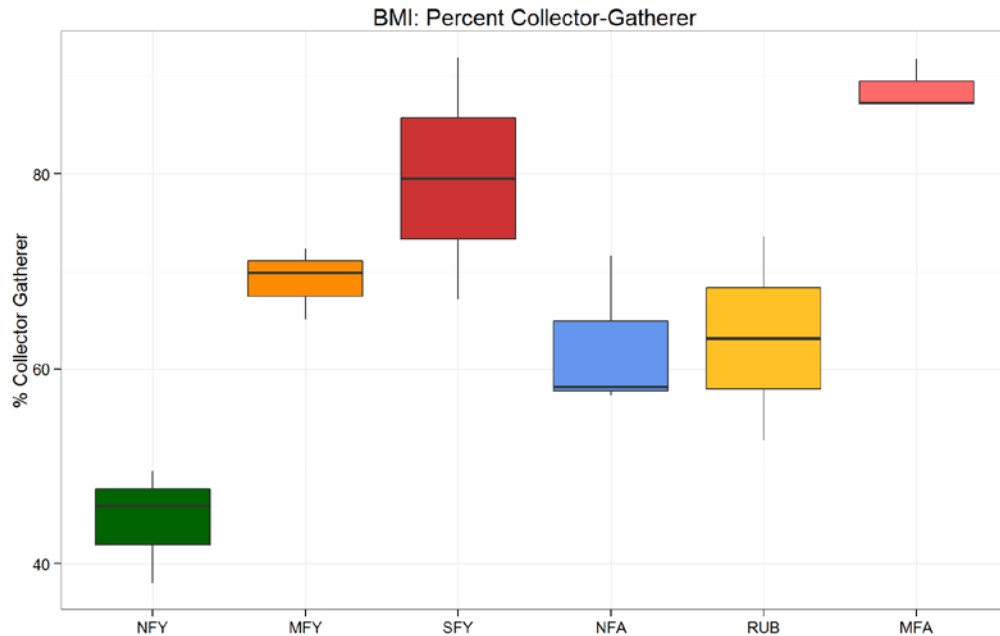


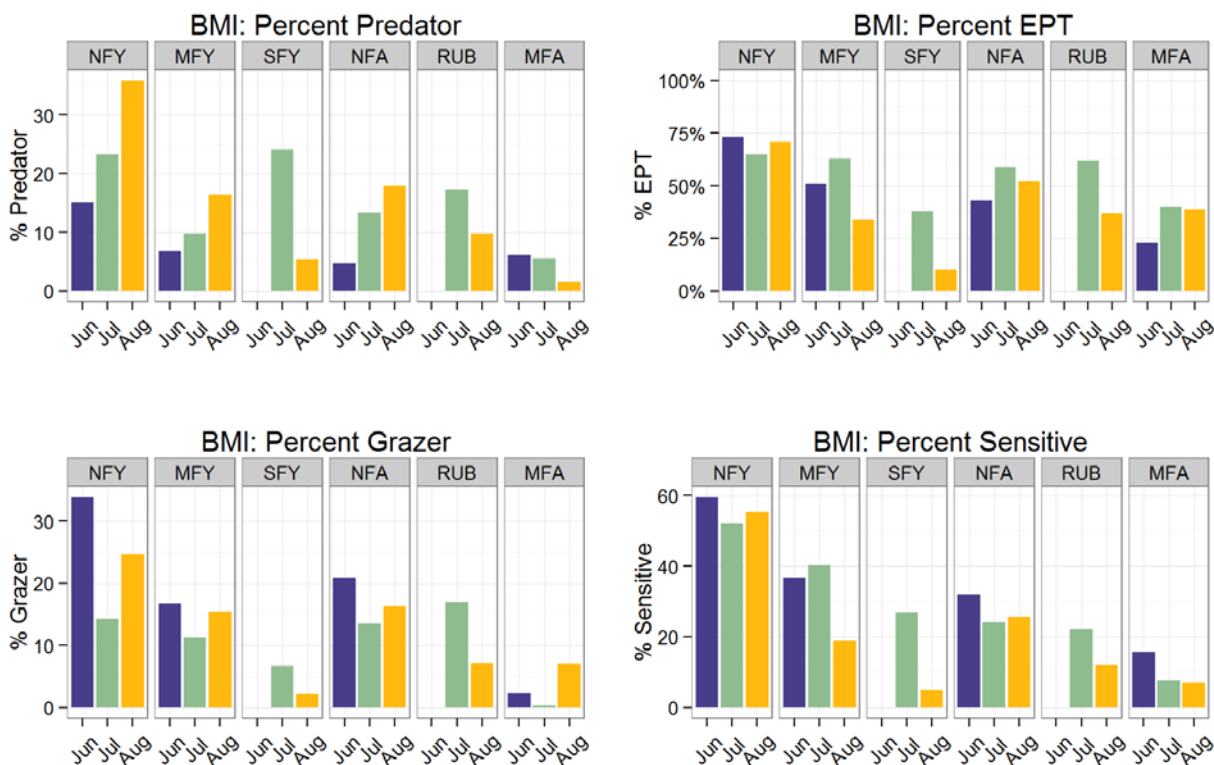
Figure 1.35: Functional feeding group boxplots, across three sampling dates in 2011.





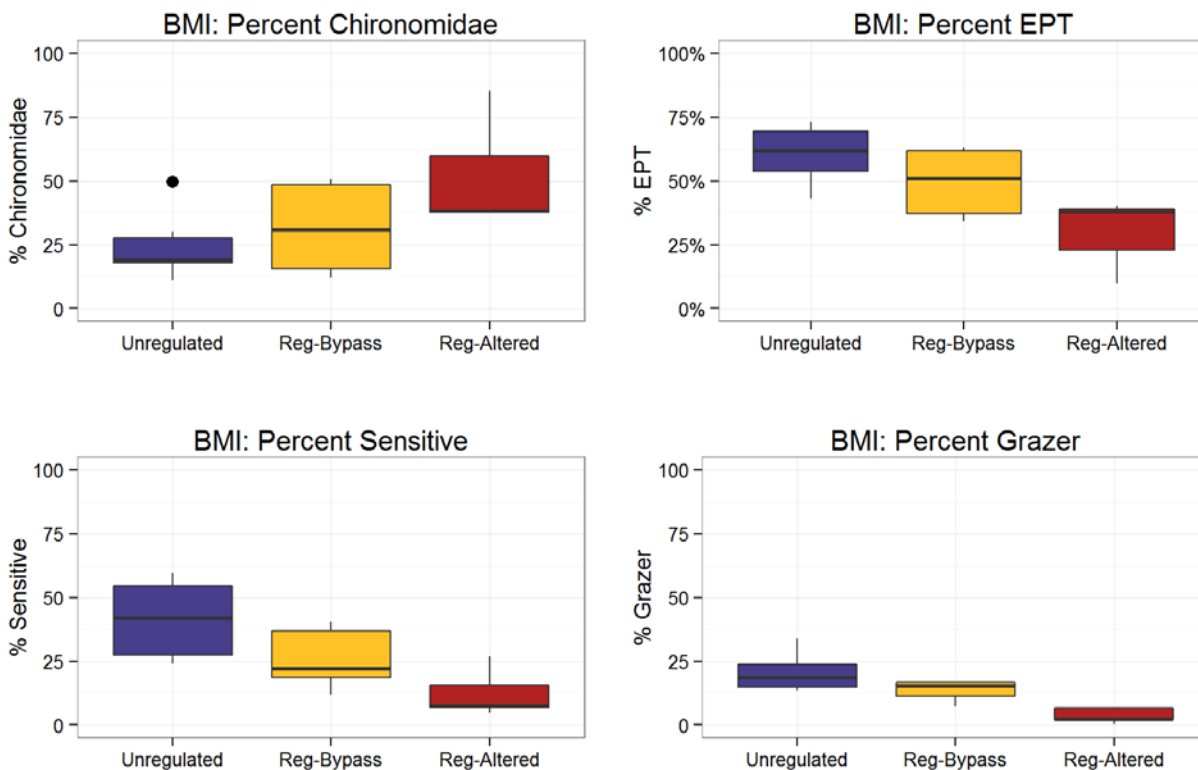
Analyzing BMI metrics by month provided a unique temporal comparison of changes in macroinvertebrate assemblage dynamics across watersheds and operation types during 2011 (Figure 1.36). The unregulated sites generally showed a strong pattern of increasing predator contribution to the assemblage through time, suggesting that decreasing flows through time may condense available habitat for prey and increase foraging efficiency by predators. Predator contribution on the SF Yuba and MF American decreased significantly during the same period suggesting that altered flows may be negatively affecting this feeding guild. The unregulated reaches also showed similar trends in grazer dominance through time. For both the NF Yuba and NF American, an increase in the relative proportion of grazers in each assemblage during the August lower flow time period was observed. This suggests that the snow melt recession has an integral role in the establishment of benthic algal resources which are then capitalized on by grazing invertebrates in unregulated systems. The MF American showed a similar trend, however, the percentage of grazers was much lower compared to other study sites. The Rubicon and SF Yuba had significant decreases in grazing taxa during the same spring-summer period. Finally, the relative contribution of sensitive taxa trended similarly between unregulated sites with slight declines observed from June to July followed by increases during August. This pattern was in direct contrast to those observed in the bypass reaches (MF Yuba and Rubicon), as well as the SF Yuba, which showed sharp declines from July to August. The decline in sensitive species correlated in time with observed reductions in stage and a truncation of the spring recession.

Figure 1.36: Boxplots of BMI metrics calculated by month for data collected in 2011.



Given the similar trends in the relationship between BMI metrics and degree of flow regulation within each study watershed, rivers with similar types of flow regulation were combined and assessed. The reaches with the greatest flow regulation (altered sites SF Yuba and MF American) had the lowest percent EPT, Shannon's diversity index, percent sensitive species, total richness and percent grazers. Across watersheds, the unregulated study sites (NF Yuba and NF American) had the highest percent sensitive taxa and percent EPT (Figure 1.37). Kruskal-Wallis rank-sum tests showed differences in the metrics between unregulated and altered study sites were statistically significant for percent sensitive (Kruskal-Wallis, $p < 0.022$), percent grazer (Kruskal-Wallis, $p < 0.005$), and percent EPT (Kruskal-Wallis, $p < 0.018$), while percent Chironomidae were biologically significantly different (Kruskal-Wallis, $p < 0.092$). The statistical differences between unregulated and altered sites indicated the impacts of regulation, and not elevation, were significant factors in the patterns observed in the BMI data. The results also indicated bypass reaches (Rubicon and MF Yuba) exhibited patterns in macrobenthos that were not significantly different from unregulated sites nor from the altered sites. Rather, BMI communities in bypass study sites appeared less affected by regulation than those in the altered sites.

Figure 1.37: Boxplots of BMI metrics calculated by level of flow regulation for data collected in 2011.



1.5.4 Foothill Yellow-Legged Frogs

Visual encounter surveys (VES) for foothill yellow-legged frogs (*Rana boylei*) (FYLF) were conducted in 2011 and 2012, with the primary focus on breeding (detection of egg masses). Surveys generally occurred between May and August, with more frequent (bi-weekly) visits in May and June during the breeding period followed by monthly visits in July and August when tadpoles were present. Because 2011 was a wet year with a late snowmelt, breeding extended into July. Surveys were completed at each of the six study sites in 2011, and all study sites except the MF Yuba in 2012.

Visual encounter surveys involved two surveyors wading along each side of the river channel and visually scanning the shallow water habitat for egg masses and a snorkeler slowly swimming the deeper edgewater to examine the deeper crevices and concealed locations (Heyer et al. 1994). Surveyors walked and snorkeled upstream to minimize substrate disturbance and maximize egg mass detections because often egg masses were attached on the downstream side of the substrate. Similarly, because many egg masses were tucked up underneath boulders out of view, the visual search effort was supplemented by feeling around and underneath large boulders, cobbles, and overhanging bedrock shelves. Wading surveyors were limited to depths less than 1.2 m due to the physical constraints and safety concerns of working in rivers at high flows, while snorkelers examined all areas where they could safely swim. During summer surveys post-breeding, two surveyors waded all river margins < 1.2 m in depth to search for tadpoles. Tadpoles were typically located at shallower depths so snorkelers were not used (Bondi et al., 2013).

At each FYLF lifestage observation, data on substrate, depth, and general habitat use were collected. For egg mass locations, water temperature was also recorded at the exact egg mass location. When possible, the developmental phases of both egg mass and tadpole observations were determined using a Gosner staging chart (Gosner 1960). Coordinates for all observations were collected in Universal Transverse Mercator (UTM) with a handheld GPS receiver using Zone 10 NAD83 datum, and were averaged for approximately 30 seconds per location to increase accuracy (presumed accuracy $\pm 3\text{m}$). All points were then mapped using ArcGIS (Arcview 10.0, ESRI, Redlands, CA).

1.5.4.1 Post-metamorphic life stages

Observations of FYLF at each study site were highly variable through time and between years, with differing patterns between rivers and across months (Figure 1.38). Across all visits, adult and juvenile FYLF were most commonly observed in the NF American River, with the highest number of observations occurring in June and July in 2011 and in May in 2012. The timing of observations correlated with the approximate initiation of breeding during the snowmelt recession. Conversely, only one juvenile FYLF was observed at the regulated hydropeaking MF American study site during the entire two year project period (Figure 1.39). In general very few juveniles were observed in 2012 compared with 2011, and most juveniles were observed at three of the six study sites (NF American, Rubicon, and SF Yuba). The SF Yuba was the only study site where more juveniles were observed than adults, and most juveniles were found in seeps and small ephemeral tributaries that occurred along the site, particularly in 2011 when these locations remained wetted for much of the summer.

Figure 1.38: All *Rana boylei* adults observed each visit month at study sites during 2011-2012.

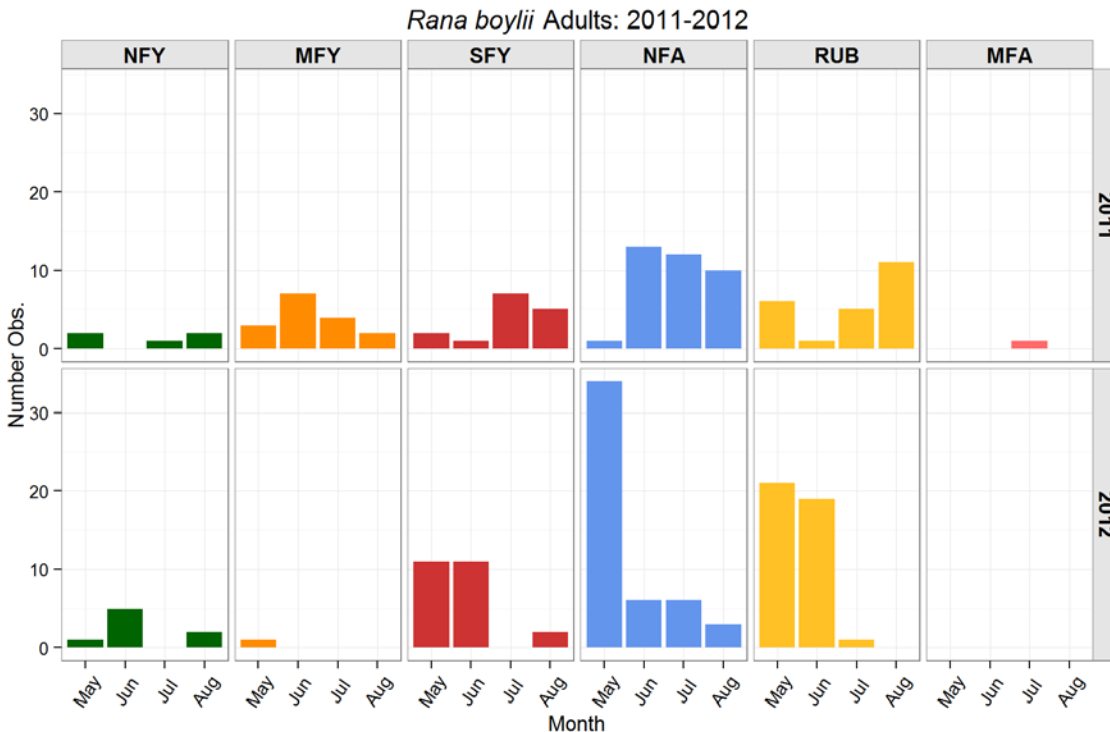
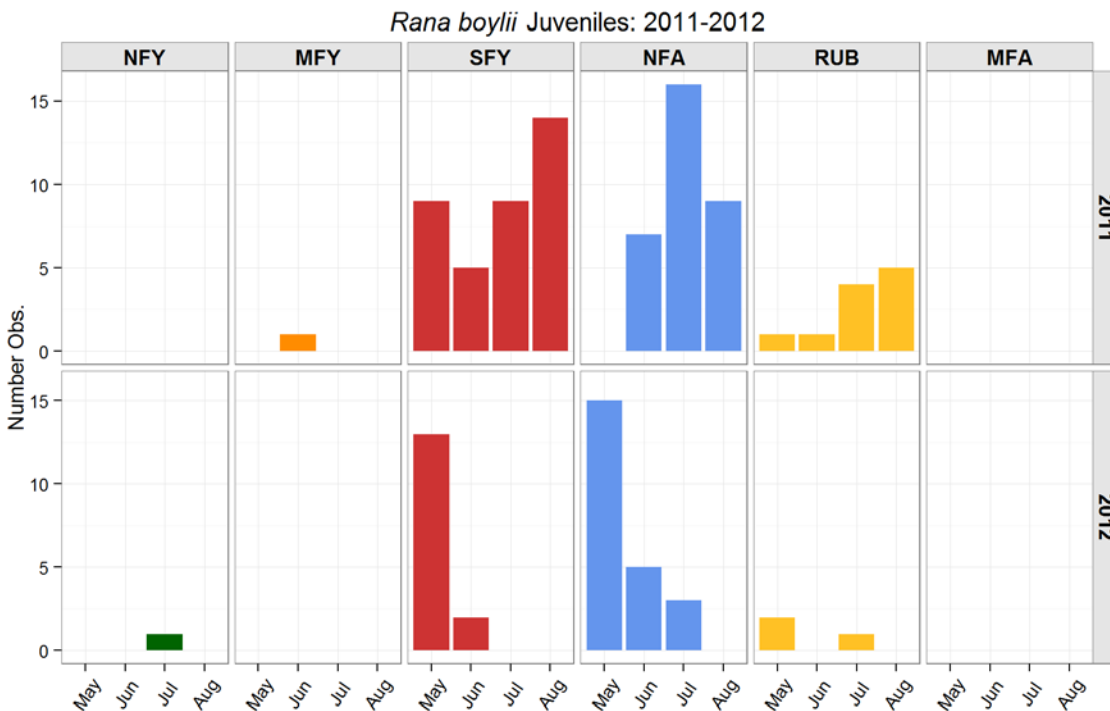


Figure 1.39: All *Rana boylei* juveniles observed each visit month at study sites during 2011-2012.



1.5.4.2 Egg Masses and Tadpoles

The number of FYLF egg masses observed within the study sites was variable in 2011 and 2012 (Table 1.13). The 2011 surveys yielded egg masses at three of the six study sites (NF American, Rubicon, MF Yuba), and signs of breeding (tadpole presence) at one additional study site (the SF Yuba). In 2012, egg masses were observed during site visits in four of the six study sites (NF American, Rubicon, NF Yuba, MF Yuba) and tadpoles were observed in the SF Yuba in August, however, comprehensive egg mass counts were not conducted at the MF Yuba so it was not included in the 2012 analysis. Tadpoles were observed in the SF Yuba in July and August of 2012 yet no egg masses were identified during extensive visual and snorkeling surveys (Table 1.13). Compared to data from previous surveys from the same study reaches, the maximum number of eggs masses observed in 2011 and 2012 at the NF American was comparable (14 egg masses observed in 2009, Bondi et al., 2013). A total of 24 egg masses were observed in 2009 at both the Rubicon and MF Yuba, which was comparable to the maximum observed in the Rubicon in 2012, but less so for the MF Yuba in 2011 (Figure 1.40, Table 1.13). No signs of breeding were observed (eggs or larvae) in the MF American in 2011 or 2012 but breeding was documented in American Canyon (a tributary that flows into the MF American approximately 3-4 km upstream of the study site) in 2011 and 2012.

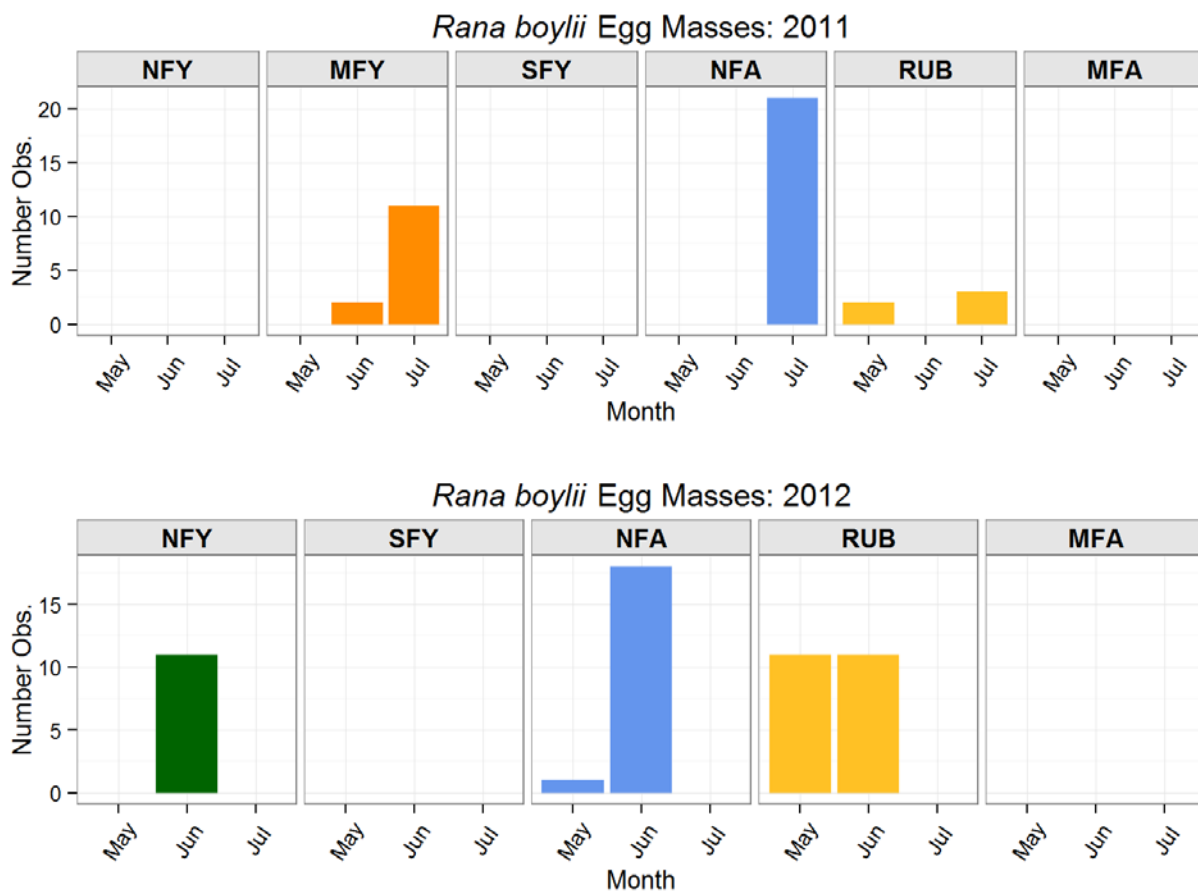
Table 1.13: Total number of FYLF egg masses observed during 2011 and 2012 surveys at study sites.

River	Number of Egg masses observed in 2011	Number of Egg masses Observed in 2012
NFY	0	11
MFY ¹	13	N/A ¹
SFY	0 ²	0 ²
NFA	21	19
MFA	0	0
RUB	5	22

¹ Surveys only conducted in 2011 at this study site

² Evidence of breeding (tadpole presence) was documented during late summer visits

Figure 1.40: Number of new FYLF egg masses observed each month within study sites in 2011 and 2012.



Inter-annual differences were evident at many of the study sites, particularly at the NFY and Rubicon. In 2011, few FYLF egg masses were observed in the Rubicon River and no egg masses were observed in the NF Yuba study site. However, in the dry water year of 2012, higher numbers of egg masses were observed at both study sites.

The Rubicon bypass reach experienced a prolonged period of spill in 2011, starting in mid-June and ending in early-July. Prior to the spill, two egg masses were observed during a late-May visit to the study site. Subsequent visits during the spill period revealed these egg masses had been scoured from oviposition locations, and three new egg masses were identified in July after spills had subsided. Conversely, no egg masses were observed at the NF Yuba in 2011, but the snowmelt recession did not begin until mid-July and as flows remained high, mean weekly water temperatures did not exceed 16 C° until August. FYLF tadpoles require temperatures of 16 C° or greater for several months in order to successfully metamorphose (Kupferberg et al., 2012b), and conditions in 2011 in the NF Yuba study reach largely remained thermally unsuitable for breeding and rearing for much of the summer.

1.5.4.3 Timing of FYLF Breeding

Initiation of breeding for FYLF in 2011 at study sites was some of the latest on record for the Sierra Nevada, followed by earlier than average breeding in 2012. The initiation of breeding was over a month earlier in 2012 compared with 2011, however in both years the timing of breeding was closely tied with the snowmelt recession and warming water temperatures in the unregulated reaches (Figure 1.41). These results support the idea that FYLF breeding is cued in response to the seasonal spring flow patterns and thus is highly plastic from year to year (Peek et al., in prep). In the Mediterranean climate of California, a broad range of hydroclimatic conditions, from very dry to very wet, resulted in significant differences in the magnitude and timing of precipitation and correlated shifts in water temperature from year to year. In the Sierra Nevada, FYLF have evolved to breed in synchronicity with seasonal spring snowmelt, generally timing egg deposition to occur during the predictable period of runoff represented by the descending limb of the hydrograph (Kupferberg 1996, Lind et al. 1996, Kupferberg et al. 2008, Yarnell et al. 2010, Kupferberg et al. 2012a, Yarnell et al. 2012). Although large differences in flow timing and magnitude were observed at study sites in 2011 and 2012 (leading to highly disparate breeding timing) (Figure 1.41), these cues responsible for triggering the initiation of breeding, such as water temperatures exceeding 10°C, remained predictably constant in the unregulated rivers (Table 1.14). Conversely, in the regulated bypass reaches, such as the Rubicon study site, misleading cues, such as prematurely warm, stable flows prior to snowmelt-driven spill, can lead to the initiation of breeding before high flows have finished for the season (Figure 1.42).

Figure 1.41: Timing and approximate duration of FYLF breeding at the unregulated NF American study site in 2011 and 2012, with stage colored by water temperature.

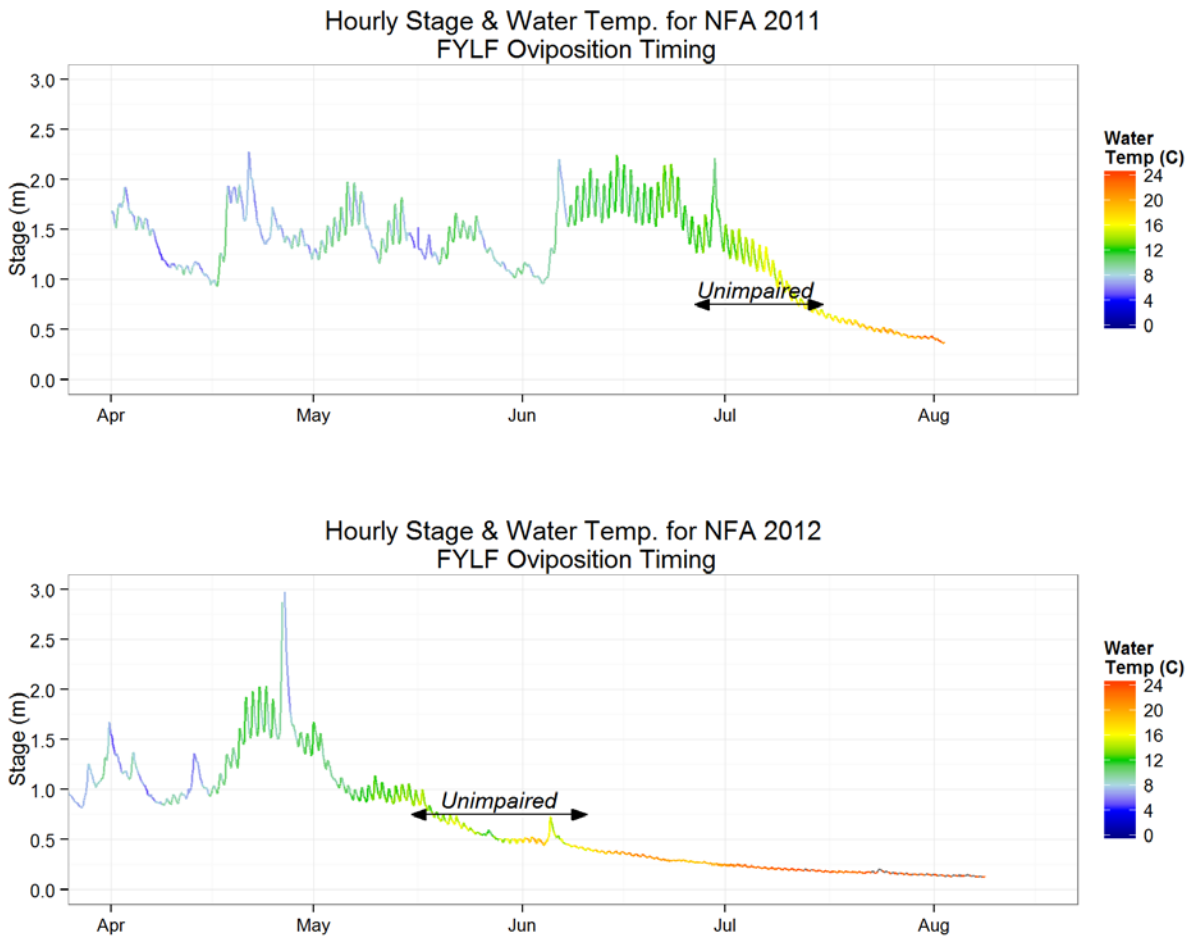


Table 1.14: Summary of initial and estimated oviposition dates (based on Gosner staging of eggs) with associated mean weekly water temperatures for 2011 and 2012.

Year	Study Site	First Egg Masses Observed	Weekly Average Temperature on Observed Day (C°) ¹	Estimate of Initiation of Oviposition	Mean Weekly Average Temperature on Estimated Initiation Day (C°) ¹
2011	NF Yuba	n/a ²	12.7 (July 15)	n/a ²	n/a
2011	MF Yuba	7/18	13.2	7/1	10.7
2011	SF Yuba	n/a ³	14.6 (July 15)	n/a ³	n/a
2011	NF American	7/13	15.9	6/26	11.5
2011	Rubicon	5/31 (pre-spill) 7/12 (post-spill)	9.1 17.2	5/24 (pre-spill) 6/30 (post-spill)	10.4 14.1
2011	MF American	n/a ²	14.5	n/a ²	n/a
2012	NF Yuba	6/5	12.7	5/15	10.1
2012	MF Yuba ⁴	5/23	n/a ⁴	5/15	n/a ⁴
2012	SF Yuba	n/a ³	12.6 (May 20)	n/a ³	n/a
2012	NF American	5/25	13.7	5/18	15.6
2012	Rubicon	5/21	15.7	5/7	12.4
2012	MF American	n/a ²	15.7	n/a ²	n/a

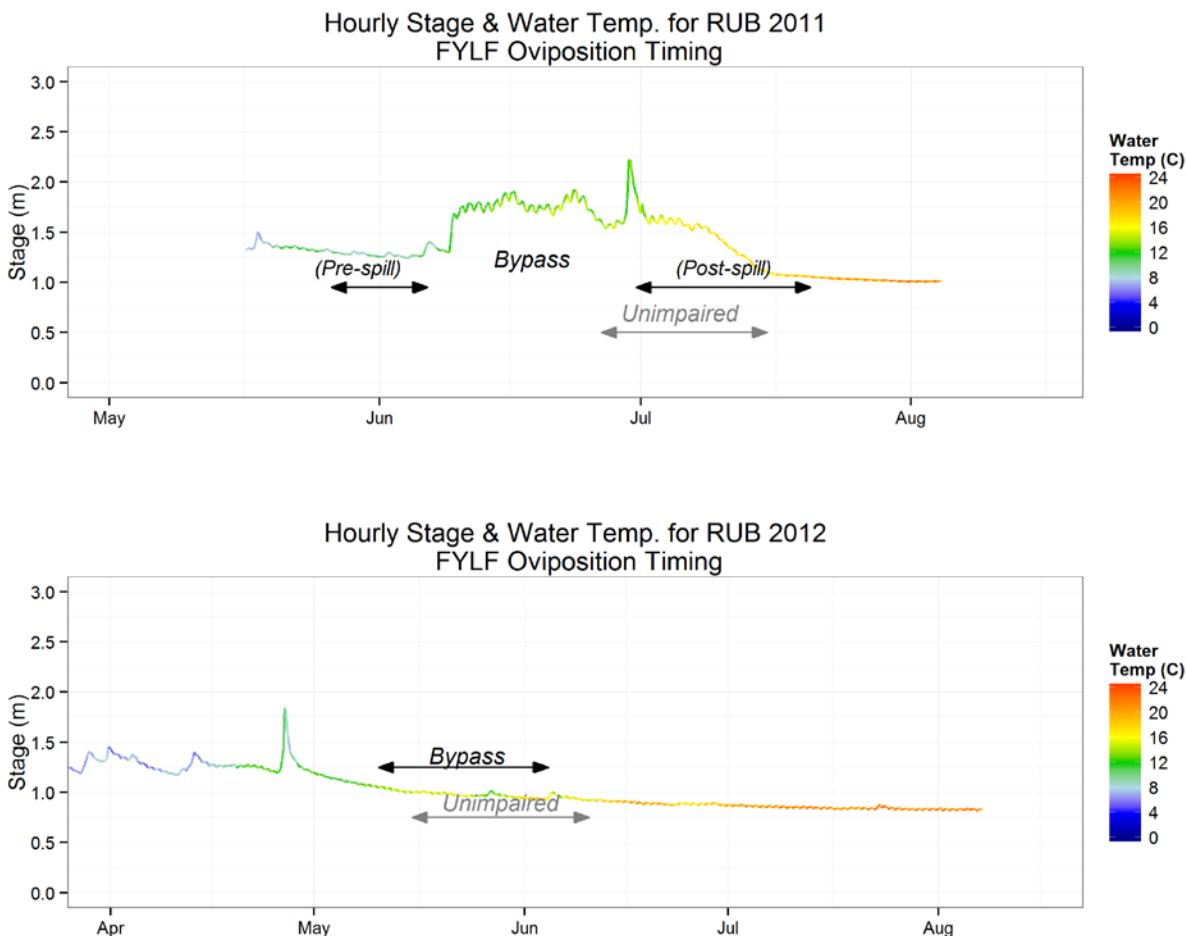
¹ If no eggs observed, weekly average water temperature from comparable date was used for each year

² No egg masses observed in the study site

³ Evidence of breeding (tadpole presence) was documented during late summer visits

⁴ Eggs observed during a single visit in May, full surveys were not completed at this study site and no logger data available in 2012

Figure 1.42: Timing and approximate duration of FYLF breeding at the Rubicon bypass study site in 2011 and 2012, with stage colored by water temperature.



1.5.5 Fish

Snorkeling surveys for fish were conducted in 2011 to determine presence-absence within each study reach. As 2011 was a wet year, surveys could not be safely conducted until July. One snorkel pass was used at each study site, from upstream to downstream, utilizing two snorkelers per pass. At the MF American, average river width required a third snorkeler. Each study site was snorkeled once in July and once in August, prior to all other survey work at the site in order to reduce potential disturbances at the site.

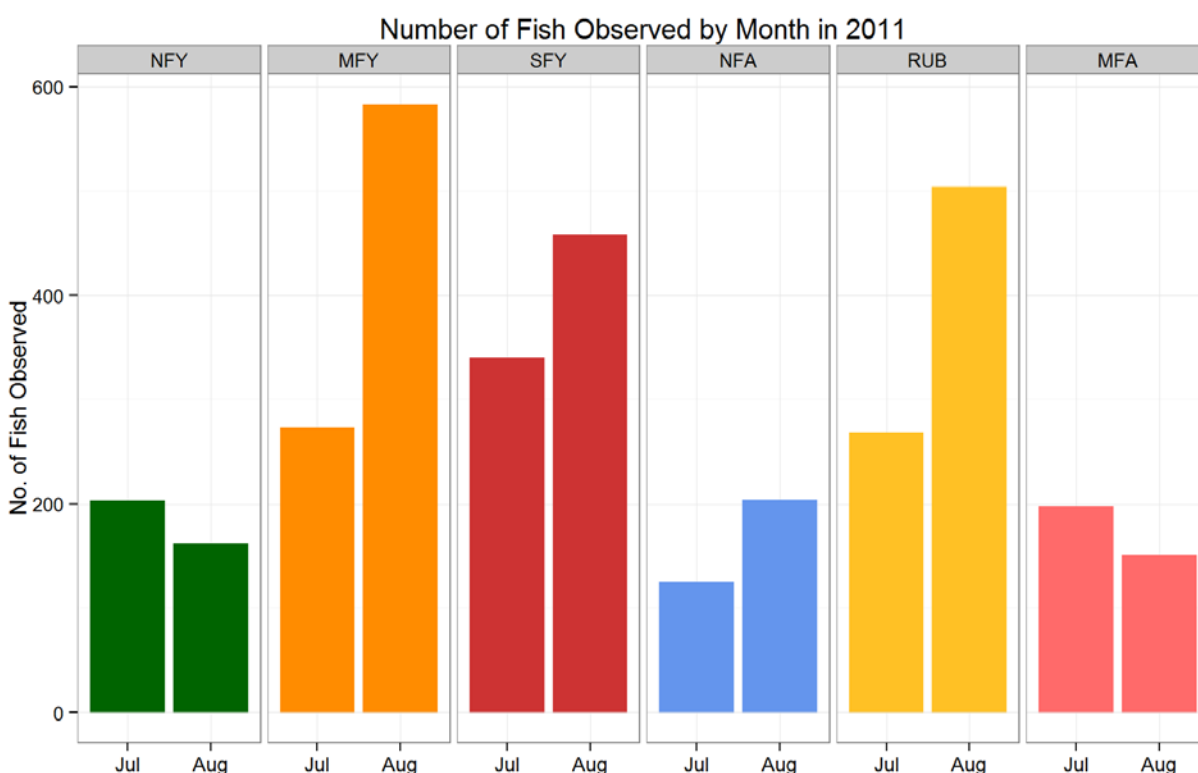
Visibility was measured with a Secchi disk, and varied across study sites, with a higher mean visibility in August (6.2 m) compared to July (4.9 m), and ranging from 2.0–7.6 m. The MF American had the lowest visibility and deepest pools (many exceeding 4 m), therefore fish observations likely underestimated the total number of fish present at the study site during the snorkel survey. Qualitative assessment of the composition of cover at each study site showed little difference in dominant cover types. One exception was the SF Yuba, which was dominated by larger boulder substrate that provided approximately 60% of the cover at the study site. All other study sites were comparable in cover type and abundance.

Invasive signal crayfish (*Pacifastacus leniusculus*) were observed at all study sites, across both months in 2011. Invasive small-mouth bass were observed in the NF American study reach

during snorkel surveys in 2011, but no other invasive fish were observed at any other study site. Fish assemblages were similar across all study sites, consisting mainly of salmonids (rainbow and brown trout), Sacramento suckers, Sacramento pikeminnow, and riffle sculpin (Figure 1.43). As part of several FERC hydrorelicensing aquatic studies, surveys of stream reaches at or within a mile of study sites documented only one additional species: speckled dace was observed at the Rubicon River study site (PCWA 2010, Aquatics 6.2).

The number of fish observed in July ranged from 125–340 (mean=235), with the fewest observed in the NF American and the most observed in the SF Yuba (Figure 1.43). In August, the number of fish observed ranged from 151–583 (mean=344) with the fewest observed in the MF American and the most observed in the MF Yuba. The unregulated study sites had two of the lowest mean number of fish observations over the two sample periods (NFY=183, NF American=165). The MF American also had a low mean number of fish observed (mean=175), however water visibility and river depth made fish observation difficult within the study site.

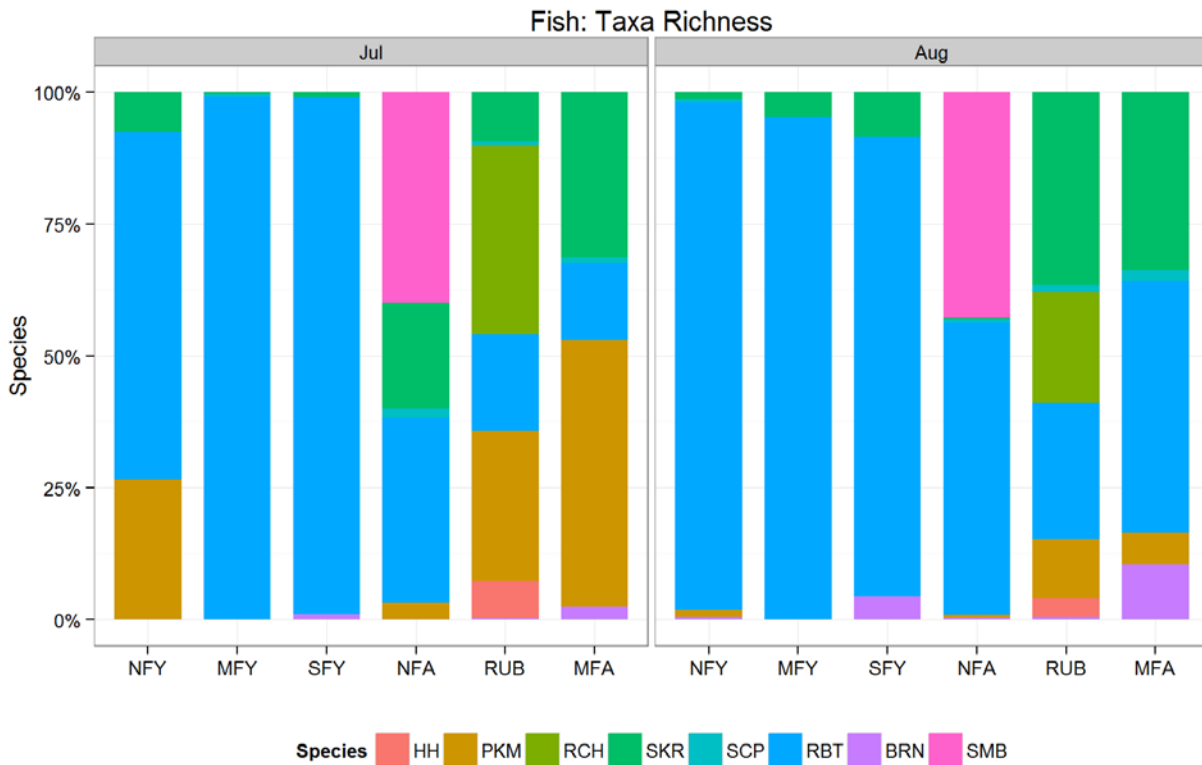
Figure 1.43: Number of fish observed during 2011 snorkeling surveys by month.



Rainbow trout dominated the Yuba River reaches, with few other species observed at the NFY, MF Yuba, and SF Yuba (Figure 1.44, Table 1.15). In the American River reaches, Sacramento pikeminnow and Sacramento Sucker were predominantly observed in the MF American and Rubicon, while rainbow trout and small-mouth bass were observed in the NF American. More Sacramento pikeminnow were observed in July compared with August, which correlates with the later snowmelt recession observed in 2011. Sacramento pikeminnow are native spring-breeding fish, and in small-to-medium sized streams, they typically move upstream into the nearest riffle to spawn in April and May (Moyle 2002). In 2011, the spring snowmelt recession did not begin until late-June and early-July, consequently there may have been more spawning adults moving through study sites in July compared with August (Figure 1.44). The diversity of fish species observed within watersheds and rivers varied across months, and was highest in the Rubicon River (n=7). Of the native spring-breeding fish, Sacramento Sucker in the

unregulated reaches and hardhead and California roach in the Rubicon site, were more prevalent in July during the spring recession than in August.

Figure 1.44: Fish species diversity observed during 2011 snorkeling surveys by month.



¹ HH = hardhead, PKM = Sacramento pikeminnow, RCH = California roach, SKR = Sacramento sucker, SCP = riffle sculpin, RBT = rainbow trout, BRN = brown trout, SMB = small-mouth bass.

Table 1.15: Fish species observed during 2011 snorkeling surveys at study sites.

Species	NFY	MFY	SFY	NFA	RUBICON	MFA
Sacramento sucker	●	●	●	●	●	●
Sacramento pikeminnow	●			●	●	●
Hardhead					●	
California roach					●	
Riffle sculpin	●			●	●	●
Rainbow trout	●	●	●	●	●	●
Brown trout	●	●	●	●	●	●
Smallmouth bass ¹				●		

¹ Invasive non-native fish species

Fish assemblages showed little difference between month and study site within the same watershed. Comparisons across watersheds indicate slightly higher species diversity in the American watershed (n=7) versus the Yuba watershed (n=5), and species diversity within the regulated reaches in the Yuba was the lowest observed (n=3) (Table 1.15). However, more broad scale data from FERC relicensing studies indicated comparable species were observed across the Yuba and American watersheds in different hydroregulation operation regimes (PCWA 2010, NID and PG&E 2011). The predominant species that occurred in these streams included rainbow trout, brown trout, Sacramento sucker, Sacramento pikeminnow, and riffle sculpin. These results indicate fish assemblages within the regions studied (across a similar elevation band across the foothills of the Sierra Nevada) may be less sensitive to differences in flow regime.

1.6 Relationships between Abiotic and Biotic Conditions

It is well established within the scientific community that abiotic and biotic stream conditions are intricately linked with feedbacks occurring at multiple spatial and temporal scales (e.g. Petts, 2000; Naiman et al. 2008, Yarnell et al., 2010). Previous studies quantifying various specific relationships between abiotic and biotic stream factors have contributed to a weight of evidence within the scientific literature that streams with greater hydrogeomorphic diversity support more diverse biotic assemblages (e.g. Palmer et al. 2000; Patsuchova et al., 2008; Miller et al 2010).

The results from this study qualitatively support the concept that stream reaches with a high native biodiversity are sustained by a heterogeneous, yet predictable stream environment. As high spring flows slowly recede and transition into the low flow channel, the variability of hydraulic conditions as water passes over diverse topography and substrate creates a gradually shifting mosaic of habitats that allows a variety of native species to reproduce, disperse and flourish (Yarnell et al. 2010). The unregulated study sites exhibited the highest diversity in hydraulic habitat in space and time, the highest diversity in primary productivity, and provided the most predictable spring flow regimes. Conversely, the study sites with the most altered flow regimes exhibited the lowest and least consistent hydraulic diversity, the lowest diversity

in primary productivity, and the least predictability in spring flow regime. These differences between unregulated and altered study sites were observed in both study years, regardless of water year type. The regulated bypass study sites however, presented greater variability from year to year, with high hydraulic diversity in wet years and low hydraulic diversity in dry years. Similarly, spring flow regimes were less predictable in wet years due to the abrupt curtailment of spill, and as a result, the bypass study sites exhibited moderate levels of biotic diversity, intermediary to the other study sites.

A more direct comparison between the abiotic and biotic conditions at each site was explored by plotting the relationship between the hydraulic diversity index and biotic metrics such as the EPT index. For the American watershed, a positive correlated relationship occurred between the hydraulic diversity and the EPT Index (Figure 1.45). Similar to results observed by Pastuchova et al. (2008), the relationship suggests diverse hydraulic niches support diverse benthic macroinvertebrate assemblages. A similar but less robust relationship existed between the number of observed FYLF egg masses at each study, a metric of biotic diversity, and the hydraulic diversity (Figure 1.46). FYLF are known to select hydraulically stable instream locations for laying egg masses (Kupferberg 1996), and have been shown to be select diverse hydrogeomorphic reaches where a variety of hydraulic habitat conditions exist at any given flow magnitude (Yarnell, 2005). While statistically limited due to small samples sizes, these results contribute to the weight of evidence that diverse abiotic stream conditions contribute to high instream biodiversity.

Figure 1.45: Relationship between monthly EPT index and monthly hydraulic diversity index in 2011 for the American watershed study sites.

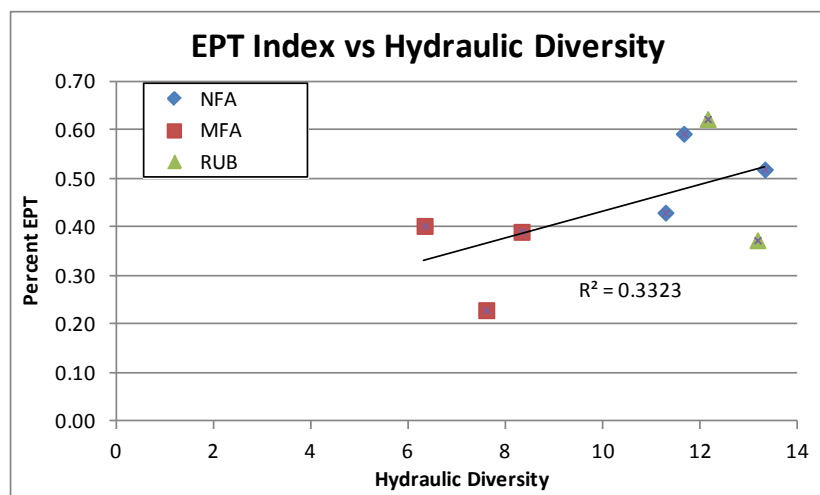
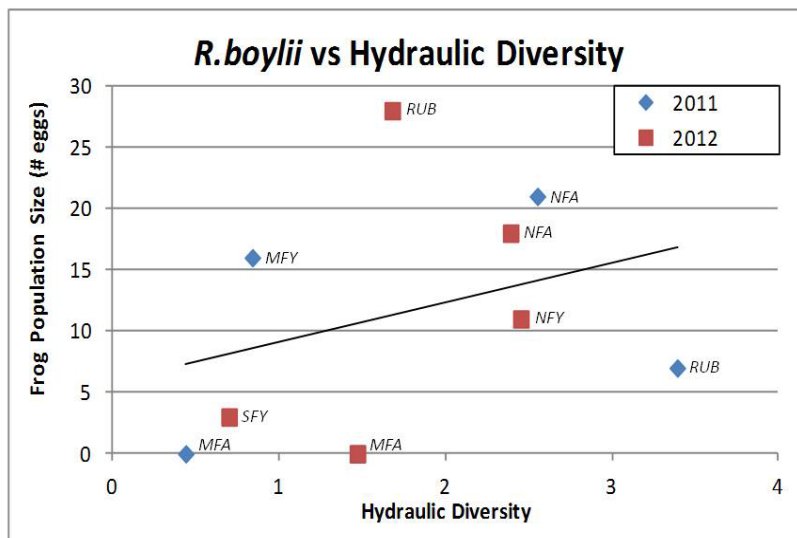


Figure 1.46: Relationship between number of FYLF egg masses and annual hydraulic diversity index. Data includes all study sites in 2011 and 2012 where known FYLF populations could be accurately assessed.



1.7 Management Implications and Recommendations

The results from this study provide qualitative and quantitative data supporting a variety of previous studies indicating the importance of a natural flow regime for native species adapted to the unique seasonal flow patterns of California's Mediterranean climate (Gasith and Resh, 1999; Lytle and Poff, 2004; Yarnell et al., 2010). Regulated flow regimes where key environmental cues and instream habitat conditions required by native species are altered or eliminated often do not support the more diverse biotic assemblages observed in rivers with unregulated flows, as seen in the results of this study. However, the study results also provide information for resource managers regarding the extent to which varying degrees of flow regulation may impact instream biota, and thus increased understanding of those aspects of the flow regime that are most likely to contribute to the maintenance of instream biodiversity.

For regulated rivers, restoration of key elements of the flow regime known to provide distinct ecological cues for native species, such as the spring snowmelt recession, can greatly contribute towards the maintenance of stream biodiversity. Specifically, replicating the timing and gradual rate of change of spring recession flows in all water year types can increase hydraulic habitat diversity and mimic the predictable flows that native species use to cue their reproduction. For the FYLF, the gradual spring recession of river flow coincides with warming water temperatures, providing a reliable and distinct environmental cue that triggers the onset of breeding. While the cue is consistent across years, the timing of the cue varies from year to year due to hydroclimatic patterns, such as the differences observed between 2011 and 2012 in this study. This plasticity around a hydrologic cue allows FYLF to effectively select the most stable seasonal period for breeding and rearing even if that period may shift inter-annually. However, ecological cues (recession rate and water temperature) in rivers that are regulated are often dampened or eliminated completely by local operating conditions. As regulated flows diverge from natural hydroclimatic patterns, native aquatic species like the FYLF are more susceptible to sudden changes in flow, such as was observed at the Rubicon River study site in late May 2011 when late season snowmelt caused spill to occur and early egg masses were scoured away (Figure 1.42). Ultimately, FYLF and other native species require conservation of the environmental cues under which they have evolved, and more effective management

requires mimicking these flow-related cues appropriately so that critical breeding periods reflect seasonal and annual hydroclimatic conditions.

Regulation of flows can occur in a variety of ways, and the degree and extent to which flows are altered can affect the potential for improvement. Bypass reaches have the highest potential for improvement in that the single act of restoring the spring snowmelt recession can create a managed flow regime that most mimics a natural flow regime throughout the year. However, more fully regulated reaches can be improved by creating a flow pattern that mimics the natural seasonality of high and low flows and provides more gradual transitions from one to the other.

While improvements to managed flow regimes that better mimic the natural timing and pattern of spring flows can create the hydraulic habitat conditions that promote instream diversity, other factors associated with regulation must be considered. Diurnal fluctuations in water temperature associated with flow can have strong influences on biota within aquatic systems (Ward and Stanford 1982), particularly for aquatic organisms with lower tolerances for critical maximum temperatures (Moyle 2002, Welsh and Hodgson 2008). The observed diurnal temperature shifts in the MF American study site represent a reduction in potential thermal energy that may be biologically important for many aquatic organisms, for example, western pond turtles. Western pond turtles were observed in the downstream end of the MF American study site in 2011 and 2012 during snorkel surveys as well as during visual encounter surveys for frogs. As poikilotherms, western pond turtles require ample basking time for thermoregulation, and temperature is an important component for physiological processes involved in digestion in turtles and also in larval frogs (Duellman and Trueb 1986, Reese and Welsh 1998). For those aquatic species sensitive to changes in thermal regimes, such as the Western pond turtle or FYLF, warm-water habitat below cold-water release dams may be restricted to the downstream-most reaches regardless of flow regime.

In many regulated rivers, the impetus for improving flow regimes and prescribing environmental flows is driven by a variety of factors including potentially conflicting habitat needs for multiple aquatic species of interest. More often than not, resource management decisions tend to consolidate around flow requirements for emblematic fish species such as trout at the expense of other native aquatic species (Lind et al., 1996). As an indicator of biodiversity, fish abundance and diversity can be misleading, as was seen in this study where no trend was observed between the degree of flow regulation and fish presence or diversity. A management approach focused on mimicking the seasonality, timing and rate of change observed in natural flow regimes, particularly during the ecologically important springtime, will be better suited to providing the range of instream habitats required by all native species as well as limiting the ability of non-native species to succeed in a flow environment to which they were not adapted. Preserving the natural stream processes that create and support native biodiversity provides the best strategy for building ecological resiliency and limiting species loss in the face of future climate warming.

1.8 References

- Bartholow, J.M. 1989. Stream temperature investigations: field and analytic methods. Instream flow information paper no. 13. Biological Report 89(17). U.S. Fish and Wildlife Service, Fort Collins, Co.
- Beschta, R. L., R. E. Bilby, G. E. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forest Interactions. Pages 191-232 in E. O. Salo and T. W. Cundy, editors. Streamside Management: Forest and Fishery Interactions. University of Washington, Institute of Forest Resources.
- Brown, G. W. 1983. Water Temperature. Forestry and Water Quality. O.S.U. Book Stores, Corvallis, Or. Pages 47-57.
- Bondi, C.A., S.M. Yarnell, and A.J. Lind. 2013. Transferability of habitat suitability criteria for a stream breeding frog (*Rana boylei*) in the Sierra Nevada, California. Herpetological Conservation and Biology 8(1): 88–103.
- Clesceri, L.S., L.A. Greenberg, and A.D. Eaton. 1998. Standard methods for the examination of water and wastewater, 20th edn. APHA, AWWA.
- Cullis, J. D. S., C. A. Gillis, M. L. Bothwell, C. Kilroy, A. Packman, and M. Hassan. 2012. A conceptual model for the blooming behavior and persistence of the benthic mat-forming diatom *Didymosphenia geminata* in oligotrophic streams. Journal of Geophysical Research-Biogeosciences 117(G2): 1-11.
- Doane, A. and W.R. Horwath. 2003. Spectrophotometric determination of nitrate with a single reagent. Anal Lett 36: 2713–2722.
- Duellman, W. E. and L. Trueb. 1986. Biology of Amphibians. John Hopkins University Press, Baltimore.
- Dyer, F.J. and M.C. Thoms. 2006. Managing river flows for hydraulic diversity: An example of an upland regulated gravel-bed river. River Research and Applications 22: 257-267.
- Gasith, A. and V.H. Resh. 1999. Streams in Mediterranean climate regions: Abiotic influences and biotic responses to predictable seasonal events. Annual Review of Ecology and Systematics 30: 51-81.
- Gosner, K. 1960. A simplified table for staging anuran embryos and larvae with notes on identification. Herpetologica: 183-190.
- Heyer, W. R., M. A. Donnelly, R. W. McDiarmid, L.A. C. Hayek, and M. S. Foster. 1994. Measuring and monitoring biological diversity. Standard methods for amphibians. Smithsonian Institution Press, Washington DC.
- Kilroy, C, T. Shelder, and J. Sykes. 2005. Likely environments in which the non- indigenous freshwater diatom can survive, in New Zealand. National Institute of Water and Atmospheric Research, New Zealand. Consultancy Report 2005-043. 34 pp.
- Kilroy, C. and M. Bothwell. 2011. Environmental Control of Stalk Length in the Bloom-Forming, Freshwater Benthic Diatom *Didymosphenia Geminata* (Bacillariophyceae). Journal of Phycology 47: 981-989.
- Kirkwood, A. E., T. Shea, L. Jackson, and E. McCauley. 2007. *Didymosphenia geminata* in two Alberta headwater rivers: an emerging invasive species that challenges conventional views on algal bloom development. Canadian Journal of Fisheries and Aquatic Sciences 64: 1703-1709.
- Kirkwood, A. E., L. J. Jackson, and E. McCauley. 2009. Are dams hotspots for *Didymosphenia geminata* blooms? Freshwater Biology 54: 1856-1863.
- Kupferberg, S.J. 1996. Hydrologic and geomorphic factors affecting conservation of a river-breeding frog (*Rana boylei*). Ecological Applications 6: 1332-1344.

- Kupferberg, S.J., A.J. Lind, S.M. Yarnell, and J.F. Mount. 2009a. Pulsed Flow Effects on the Foothill Yellow-legged Frog (*Rana boylei*): Integration of Empirical, Experimental and Hydrodynamic Modeling Approaches. Final Report to the California Energy Commission, PIER, CEC 500-2009-002, 189 pp.
- Kupferberg, S., A. Lind, and W. Palen. 2009b. Pulsed flow effects on the foothill yellow-legged frog (*Rana boylei*): Population modeling. Final Report to the California Energy Commission, PIER, CEC 500-2009-002a, 92 pp.
- Kupferberg, S. J., W. J. Palen, A. J. Lind, S. Bobzien, A. Catenazzi, J. Drennan, and M. E. Power. 2012a. Effects of Flow Regimes Altered by Dams on Survival, Population Declines, and Range-Wide Losses of California River-Breeding Frogs. *Conservation Biology* 26: 513-524.
- Kupferberg, S., Catenazzi, A., and Power, M. E. 2012b. Foothill yellow-legged frog conservation in relation to physical habitat and temperature. DRAFT Final Report to the California Energy Commission, PIER. Publication number TBD.
- Larned, S., D. Arscott, N. Blair, B. Jarvie, D. Jellyman, K. Lister, M. Schallenberg, S. Sutherland, K. Vopel, and B. Wilcock. 2007. Ecological studies of *Didymosphenia geminata* in New Zealand, 2006-2007. NIWA Client Report: CHC2007-070. NIWA Project: MAF07507. CHC2006-086, Christchurch, New Zealand.
- Lancaster J and A.G. Hildrew. 1993. Flow refugia and the microdistribution of lotic macroinvertebrates. *Journal of the North American Benthological Society* 12: 385–393.
- Lind, A., H. Welsh, and R. Wilson. 1996. The effects of a dam on breeding habitat and egg survival of the foothill yellow-legged frog (*Rana boylei*) in Northwestern California. *Herpetological Review* 27: 62-67.
- Lind, A.J. and S.M. Yarnell, Eds. 2008. Habitat suitability criteria for the foothill yellow-legged frog (*Rana boylei*) in the northern Sierra Nevada and coast ranges of California. Final report compiled for Pacific Gas and Electric Company's Desaba-Centerville Project (FERC #803).
- Lytle, D. A. and N. L. Poff. 2004. Adaptation to natural flow regimes. *Trends in Ecology and Evolution* 19: 94-100.
- Merritt, R. W. and K. W. Cummins. 2008. An introduction to the Aquatic insects of North America. 4th edition. Kendall/ Hunt Pub. Co., Dubuque, Iowa.
- Michel, M. J. 2012. Phenotypic plasticity in complex environments: effects of structural complexity on predator- and competitor-induced phenotypes of tadpoles of the wood frog, *Rana sylvatica*. *Biological Journal of the Linnean Society* 105: 853-863.
- Miller, M. P., D. M. McKnight, J. D. Cullis, A. Greene, K. Vietti, and D. Liptzin. 2009. Factors controlling streambed coverage of *Didymosphenia geminata* in two regulated streams in the Colorado Front Range. *Hydrobiologia* 630: 207-218.
- Miller, S.W., P. Budy, J.C. Schmidt. 2010. Quantifying macroinvertebrate responses to in-stream habitat restoration: Applications of meta-analysis to river restoration. *Restoration Ecology* 18(1): 8-19.
- Moyle, P. B. 2002. Inland fishes of California. Rev. and expanded. edition. University of California Press, Berkeley.
- Naiman, R. J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications* 3(2): 209-212.
- Naiman, R.J., J.J. Latterell, N.E. Pettit, and J.D. Olden. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience* 340(9-10): 629-643.
- NID and PG&E. 2011. Yuba-Bear & Drum-Spaulding Project Relicensing, Final License Application, Volume II: Exhibit E.

<http://www.eurekasw.com/NID/Final%20License%20Application/Yuba-Bear%20FLA%20Volume%20I%20-%20Part%20I.pdf>

- Null, S. E., J. H. Viers, M. L. Deas, S. K. Tanaka, and J. F. Mount. 2013. Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Climatic Change* 116: 149-170.
- Oksanen, J. 2011. Multivariate Analysis of Ecological Communities in R: vegan tutorial.
- Palmer, M.A., C.M. Swan, K. Nelson, P. Silver, R. Alvestad. 2000. Streambed landscapes: evidence that stream invertebrates respond to the type and spatial arrangement of patches. *Landscape Ecology* 15(6): 563-576.
- Pastuchova Z., M. Lehotsky, A. Greskova. 2008. Influence of morphohydraulic habitat structure on invertebrate communities (Ephemeroptera, Plecoptera and Trichoptera). *Biologia* 63: 720-729.
- PCWA. 2010. Middle Fork Project Relicensing, Aquatic Pre-Application Technical Study Report, Instream Flow. <http://relicensing.pcwa.net/html/science/padreportaquatic.php>
- Petts, G.E. 2000. A perspective on the abiotic processes sustaining the ecological integrity of running waters. *Hydrobiologia* 422: 15-27.
- Petts, G.E. and A.M. Gurnell. 2005. Dams and geomorphology: research progress and future directions. *Geomorphology* 71: 27-47.
- Poole, G.C., and C.H. Berman. 2000. Pathways of Human Influence on Water Temperature Dynamics in Stream Channels. U.S. Environmental Protection Agency, Region 10. Seattle, WA. 20 p.
- R-Development-Core-Team. 2012. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Reese, D. A. and H. H. Welsh. 1998. Comparative demography of *Clemmys marmorata* populations in the trinity river of California in the context of dam-induced alterations. *Journal of Herpetology* 32: 505-515.
- Rehn, A. C. 2009. Benthic macroinvertebrates as indicators of biological condition below hydropower dams on west slope Sierra Nevada streams, California, USA. *River Research and Applications* 25: 208-228.
- Rost, A. L., C. H. Fritsen, and C. J. Davis. 2011. Distribution of freshwater diatom *Didymosphenia geminata* in streams in the Sierra Nevada, USA, in relation to water chemistry and bedrock geology. *Hydrobiologia* 665: 157-167.
- Scheiner, S. M. 1993. Genetics and Evolution of Phenotypic Plasticity. *Annual Review of Ecology and Systematics* 24: 35-68.
- Smith, D. G. 2001. Pennak's freshwater invertebrates of the United States. John Wiley and Sons, New York, New York.
- Spaulding, S. A. and L. Elwell. 2007. Increase in nuisance blooms and geographic expansion of the freshwater diatom *Didymosphenia geminata*. Recommendations for response. EPA.
- Thorp, J. H. and A. P. Covich. 2001. Ecology and classification of North American freshwater invertebrates. 2nd edition. Academic Press, San Diego.
- Upton, G.J.G., and B. Fingleton. 1985. Spatial data analysis by example, volume I: point pattern and quantitative data. Wiley, Oxford, United Kingdom. 410 p.
- Van Buskirk, J. 2002. A comparative test of the adaptive plasticity hypothesis: Relationships between habitat and phenotype in anuran larvae. *American Naturalist* 160: 87-102.
- Ward, J. V. and J. A. Stanford. 1982. Thermal Responses in the Evolutionary Ecology of Aquatic Insects. *Annual Review of Entomology* 27: 97-117.

- Welsh, H. H. and G. R. Hodgson. 2008. Amphibians as metrics of critical biological thresholds in forested headwater streams of the Pacific Northwest, USA. *Freshwater Biology* 53: 1470-1488.
- Wheeler, C. A. and H. H. Welsh. 2008. Mating Strategy and Breeding Patterns of the Foothill Yellow-Legged Frog (*Rana Boylii*). *Herpetological Conservation and Biology* 3: 128-142.
- Wiggins, G. B. 1996. Larvae of the North American caddisfly genera (Trichoptera). 2nd edition. University of Toronto Press, Toronto ; Buffalo.
- Yarnell, S.M. 2005. Spatial Heterogeneity of *Rana boylii* Habitat: Physical Processes, Quantification and Ecological Meaningfulness. University of California, Davis. Hydrologic Sciences. PhD Dissertation.
- Yarnell, S. M., J. H. Viers, and J. F. Mount. 2010. Ecology and Management of the Spring Snowmelt Recession. *BioScience* 60: 114-127.
- Yarnell, S. M., A. J. Lind, and J. F. Mount. 2012. Dynamic flow modelling of riverine amphibian habitat with application to regulated flow management. *River Research and Applications* 28: 177-191.

CHAPTER 2: Management of the Spring Snowmelt Recession in Regulated Systems

2.1 Introduction

In unregulated rivers in the Sierra Nevada mountains of California, the spring snowmelt recession links high winter flows to low summer baseflows and is a consistent and predictable portion of the annual hydrograph. Consequently, it is an important resource to both riverine ecosystems and California's water supply (Yarnell et al. 2010). In regulated river systems where the spring snowmelt recession is often captured behind dams or diverted for hydropower, restoration of a more natural spring flow regime can provide distinct ecological benefits, such as breeding and migration cues, increased habitat availability, and greater hydraulic habitat diversity. However, knowledge of how to create and manage an ecologically beneficial spring snowmelt recession in a regulated river system is lacking.

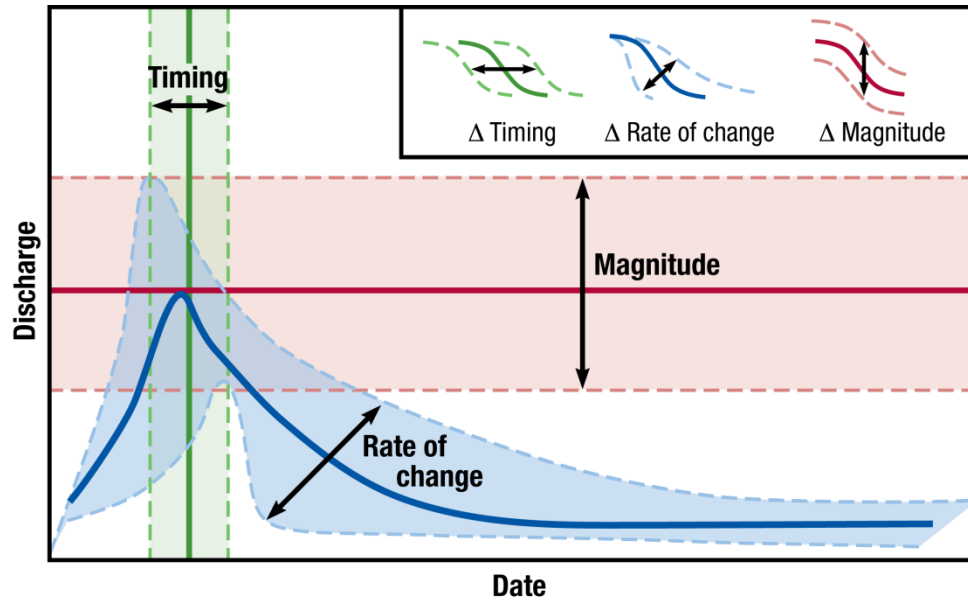
Of the 15 major watersheds that span the Sierra Nevada, only one basin, the Cosumnes, remains fully unregulated. There are an additional seven unregulated rivers with Strahler stream orders greater than 4 that span the mountain range from north to south and occur at a variety of elevations. A comparison of their spring flow regime characteristics, particularly the quantitative aspects such as magnitude, timing and rate of change, provides insights to the natural predictability and variability across watersheds. With a better understanding of the nature of unregulated systems and their quantifiable aspects, flow regimes in regulated systems can be modeled to mimic those predictable characteristics most important to ecological function.

This study sought to define a methodology by which spring flow regimes can be modeled in regulated systems from the quantifiable characteristics of spring snowmelt recessions in unregulated rivers. A quantitative analysis of the flow history within these eight largest unregulated basins across the Sierra Nevada mountain range was completed, and those characteristics found to be most predictable across basins were modeled. A variety of modeled spring flow recessions were then input to a two-dimensional hydrodynamic model at a study site on the regulated Rubicon River to determine the effects of the flows on aquatic habitat for species of interest, such as the Foothill yellow-legged frog. Additionally, the flow scenarios were assessed with regard to the diversity and distribution of hydraulic habitat conditions through time, and then compared with the hydraulic habitat requirements of native species guilds to determine potential impacts on aquatic biodiversity.

2.2 Characteristics of Unregulated Spring Snowmelt Recessions

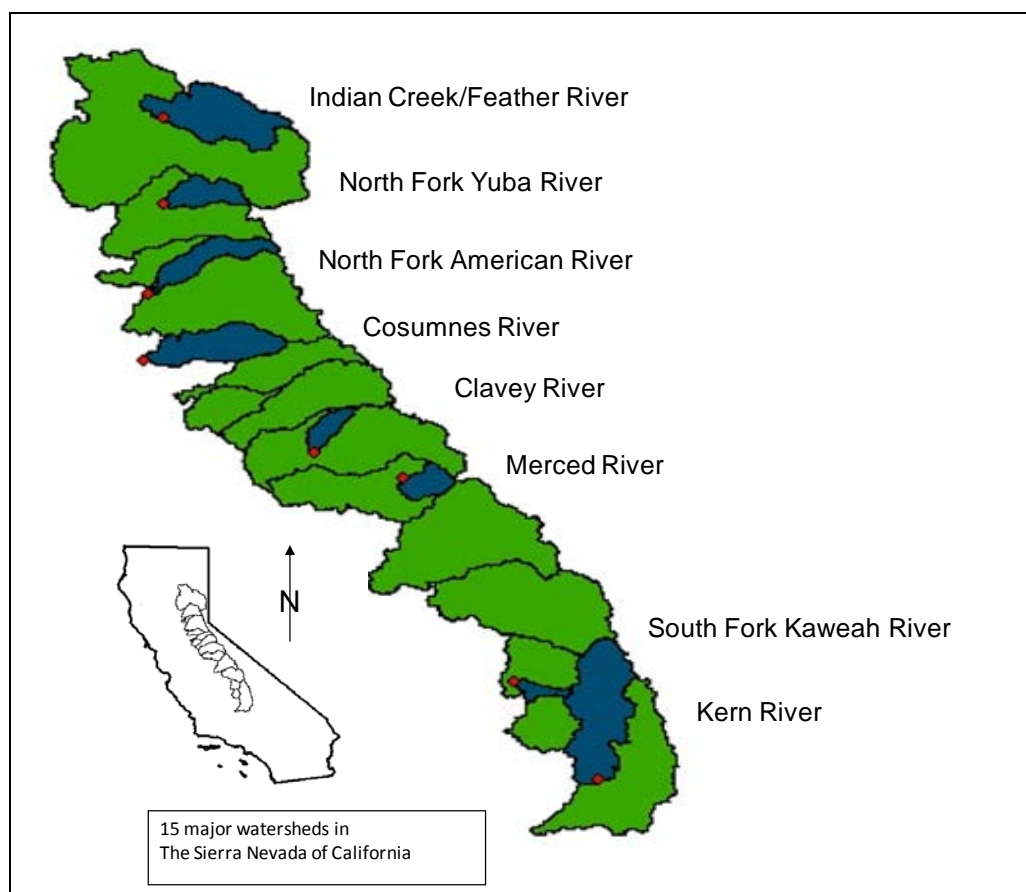
The spring snowmelt recession, like any flow event, can be quantified using several of the primary flow components described by Poff et al. (1997): magnitude, timing and rate of change (Figure 2.1). However, little research has been conducted to date regarding quantification of these characteristics for western mountain rivers. To address this knowledge gap in the Sierra Nevada mountains of California, the form and variability of the spring snowmelt recession was described across the eight largest watersheds without dams or significant hydrologic alterations. A detailed analysis and description provided by Epke (2011) is attached (Attachment A) and summarized here.

Figure 2.1: Quantifiable components of the spring snowmelt recession (Yarnell et al. 2010).



Eight unregulated watersheds located north to south across the Sierra Nevada and ranging in size and elevation from 223 km² to 2191 km² and 933 m to 2746 m, respectively, were chosen for assessment (Figure 2.2). Using historic discharge data, the spring recession period was determined and calculations were made of the magnitude, timing, rate of change (curvature), and duration. Calculations for the magnitude, timing, duration, and start and end dates of the recession were determined from the mean daily flows of record for each gaged basin, while the rate of change was calculated from daily discharge data for each year.

Figure 2.2: Unregulated Sierra Nevada study basins selected for spring recession analysis



The rate of change was modeled with an exponential decay curve in two forms: a regression across the recession period of the hydrograph that distills the seasonal shape into a single coefficient, and a daily percent change in flow that describes the shape on a daily time-step. Both approaches utilize varying forms of the exponential decay equation, which has been applied for decades to recessions of individual precipitation events, diel signals, and seasonal snowmelt (see background in Epke 2011). The regression approach is useful for generalized characterization in that the shape is described across the season by the exponential decay coefficient (k),

$$Q = Q_0 \times e^{kt}$$

The daily percent change calculation provides insight into the recession pattern throughout the season and is synonymous with the decay coefficient:

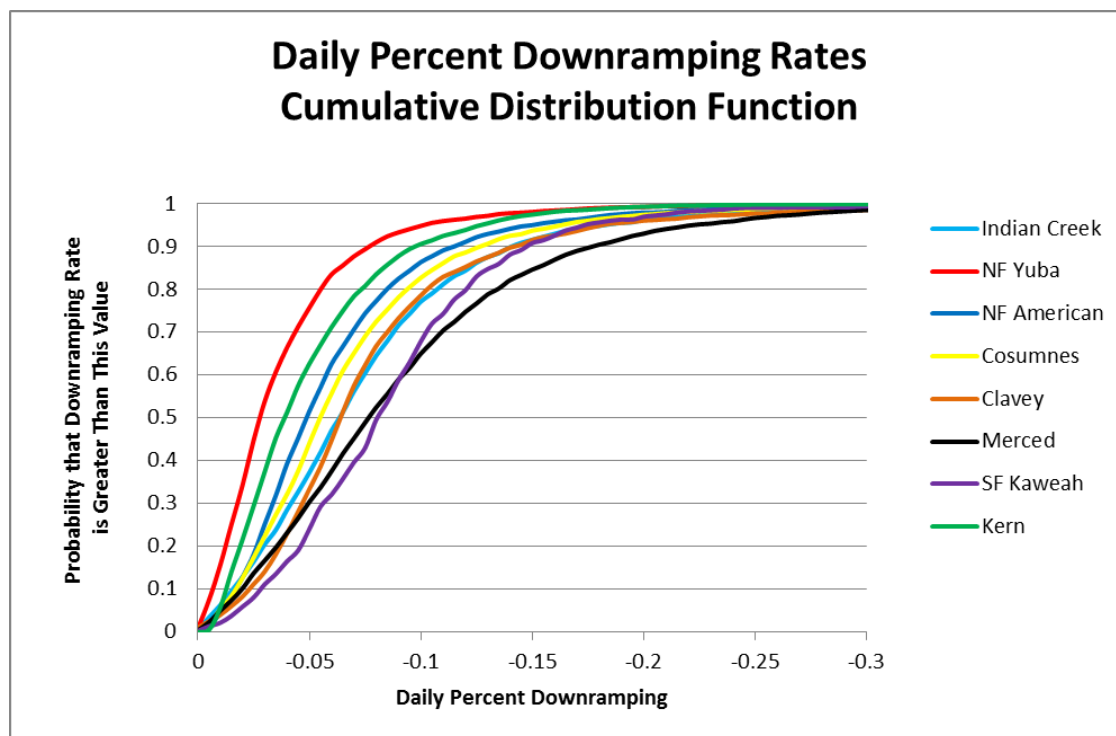
$$-k = \frac{dQ/dt}{Q}$$

While the exponential coefficient is useful for comparing seasonal recessions across basins and between years, the daily percent change method can show when in the season hydrologic factors may be changing, such as when the snowmelt is gone and the baseflow becomes the dominant streamflow source. Furthermore, unlike the exponential method, the daily percent change method does not depend on the start and end dates of the spring recession, which in some years can be difficult to discern in unregulated basins.

The results from the analyses showed that basin size and amount of precipitation scaled the recession duration and magnitude, and basin elevation dictated the timing, but the shape of the recession, particularly during the latter half, was extremely consistent from year to year. On average, the spring recession in the Sierra Nevada lasted 75 days and began in mid-May, with small differences in timing due to elevation (lower elevation recessions begin earlier). Higher elevation basins had a larger volume of their annual runoff occurring within the spring recession, and larger basins tended to have longer durations. The magnitude of the discharge changed annually with different water year types, but the curvature was consistent across different water year types. Seasonally, the exponential coefficient k was between -0.03 and -0.05 (std. deviation 0.007, N S ME 0.64) across basins and water year types.

In five of the eight basins, the daily percent change in flow during the recession generally decreased linearly from 10% at the start to 5% near the end. In the remaining three basins, precipitation factors (e.g. rain shadow effects and limited snow) may influence runoff such that the daily percent decrease in flow was more constant between 5 and 10% throughout the recession, mimicking a true exponential decay form. In all years and all basins, 90% of the daily percent decrease in flow during the recession was less than 18%, and no daily percent decrease in flow was greater than 30% (Figure 2.3).

Figure 2.3: Cumulative distribution of daily percent decrease rates during the recession period of each year.



The results indicate streamflows of the Sierra Nevada are strongly auto-correlated, where the variation in the snowmelt recession is consistent across water year types, elevations and latitudes. The consistency of the spring recession curvature in particular, supports the conclusion that the spring snowmelt recession is, with the possible exception of the late summer baseflow, the most predictable element of the annual Sierran flow regime. These results also show the ease with which this consistency can be quantified and modeled, and thus provide a method for modeling springtime environmental flows in regulated systems.

2.3 Calculating a Spring Recession Flow Regime

The results from the analysis of spring snowmelt recessions in unregulated basins across the Sierra Nevada revealed a compellingly simple method for mimicking a 'natural' spring recession in regulated basins. From any starting discharge, flows can be ramped down at a constant or linearly decreasing daily percent rate to create a steadily decreasing flow regime that transitions between high and low flows similar to how flows transition in natural flow regimes. Rates of daily decrease can be chosen to reflect those observed in unregulated systems (e.g. 6% per day or decreasing from 10% to 4% per day over the recession), and the starting and ending discharges can be determined based on the system infrastructure and minimum instream flow requirements. When assessed in conjunction with the channel morphology, the stage changes associated with the modeled recession can be compared to stage changes observed in unregulated systems and evaluated as to whether aquatic species of interest may be adversely affected. The simplicity of this approach allows for implementation in a variety of river systems with differing infrastructure, instream flow needs and water availability.

Modeling a spring recession flow regime requires knowledge of a) the hydrology of the regulated river, b) the hydrology of an analogous unregulated river or assumptions pertaining to the unimpaired flows of the regulated river, c) limitations of the regulated system infrastructure, d) hydraulic-related thresholds for aquatic species of interest (e.g. maximum allowable ramping rates), and e) representative channel morphology of the regulated river.

Flow regimes in regulated rivers are typically controlled by the infrastructure and operational needs of the system. Most infrastructure is designed to fully control the flows below certain discharges (e.g. from a low flow release value in a dam or from a powerhouse outlet) and to release high flows or 'spill' above certain reservoir holding capacities. In these instances, high winter flows typically spill over the dam until the inflows naturally decrease and 'control' of the system is regained. In most instances, once flows stop spilling, the flow below the dam is abruptly decreased to a minimum instream flow, resulting in very large stage changes downstream in short periods of time (e.g. 1 m stage decrease in 12 hours has been observed on the South Fork Yuba River). Depending on the infrastructure at the dam, the spill flows could be ramped down at a more natural rate using the low level outlets, gate structures on the spillway or even via generation of power and subsequent flow releases from the powerhouse. An example is provided below to illustrate the process of determining an appropriate prescribed spring recession flow following winter spill over a dam in a regulated stream.

2.3.1 Rubicon River Example

The Rubicon River below Hell Hole Reservoir is regulated whereby flows are diverted from the reservoir, sent via tunnels to powerhouses downstream, and minimum instream flows are released to the river downstream of the reservoir via a low-flow outlet in the dam. High flows are spilled over the dam in spring and once inflows to the reservoir have decreased below the spillway, spill flows cease abruptly and minimum flows to the river continue through the outlet valve in the dam. For the purposes of this example, the outlet has the capability of releasing flows ranging from 15 cfs to 700 cfs, the outlet flows can only be changed every three days, and minimum instream flows are typically 30 cfs. The operators would like to create recession flows that more naturally transition from the high spill flows to the minimum instream flow.

The closest unregulated river is the North Fork American River (NF American), which has similar geology, topography, elevational range and hydrologic characteristics. The spring recession on the NF American decreases on average from about 2000 cfs to 50 cfs over 75 days. The daily percent change in flow during the recession decreases linearly from approximately 8% per day at the start of the recession to 5% per day in early summer.

Using the unregulated NF American flow regime as a model for more natural spring flows on the Rubicon River, the operators could choose to start their recession from spill at 700 cfs when

they gain control of the system, decrease flows at rates similar to the natural rates (8-5%), and reach the minimum instream flow within 45 days. Using a 'flow calculator' created in Microsoft Excel (included as an electronic addendum to the report), a flow recession was calculated. Starting with 700 cfs, the subsequent day's flow was calculated as 8% less or 644 cfs. The third day in the flow recession was 7.9% less or 593 cfs, the fourth day was 7.8% less or 547 cfs, and so on, until the 45th day when flows were 35 cfs or 5% less than the previous day. From this recession, the operators could create a flow schedule by manually selecting the flow magnitudes for each three day period that approximated the values in the recession (Table 2.1). For example, the flow steps from 700 cfs to 600 cfs on day 2 and holds for 3 days, before decreasing again to 500 cfs. Averaged over 3 days, this flow decrease is about 8% per day, but in reality, is a 14% decrease on the day the flows change. While 14% is higher than the natural rate of 8%, it is still within the range of daily decreases observed on unregulated systems (Figure 2.3). Daily rates in excess of 20% are rare in unregulated systems and can produce stage changes in the river with adverse effects for aquatic biota.

Table 2.1: Calculated flow recession and proposed flow schedule for Rubicon River example.

Calculated Recession Flows			Flow Schedule	
Day	Flow	Step % change	Flow	Step % change
1	700	--	700	--
2	644	0.080	600	0.143
3	594	0.079	600	0.000
4	547	0.078	600	0.000
5	466	0.077	500	0.167
...
42	40	0.052	40	0.000
43	38	0.051	35	0.125
44	36	0.051	35	0.000
45	35	0.050	35	0.000

The changes in flow proposed in the flow schedule can be evaluated in relation to changes in stage if rating curves exist at representative sites in the river reach. On the Rubicon River, channel cross-section data at representative sites shows that under the proposed flow schedule, stage will decrease approximately 0.7 m over the course of the recession. At the largest daily percent change in flow (22% when flows decrease from 250 cfs to 200 cfs), the corresponding change in stage is 0.05 m. This stage drop is small enough to be protective of certain lifestages of sensitive species such as egg masses of the Foothill yellow-legged frog (see further discussion below in section 2.4.2.1).

2.4 Spring Recession Flow Scenarios

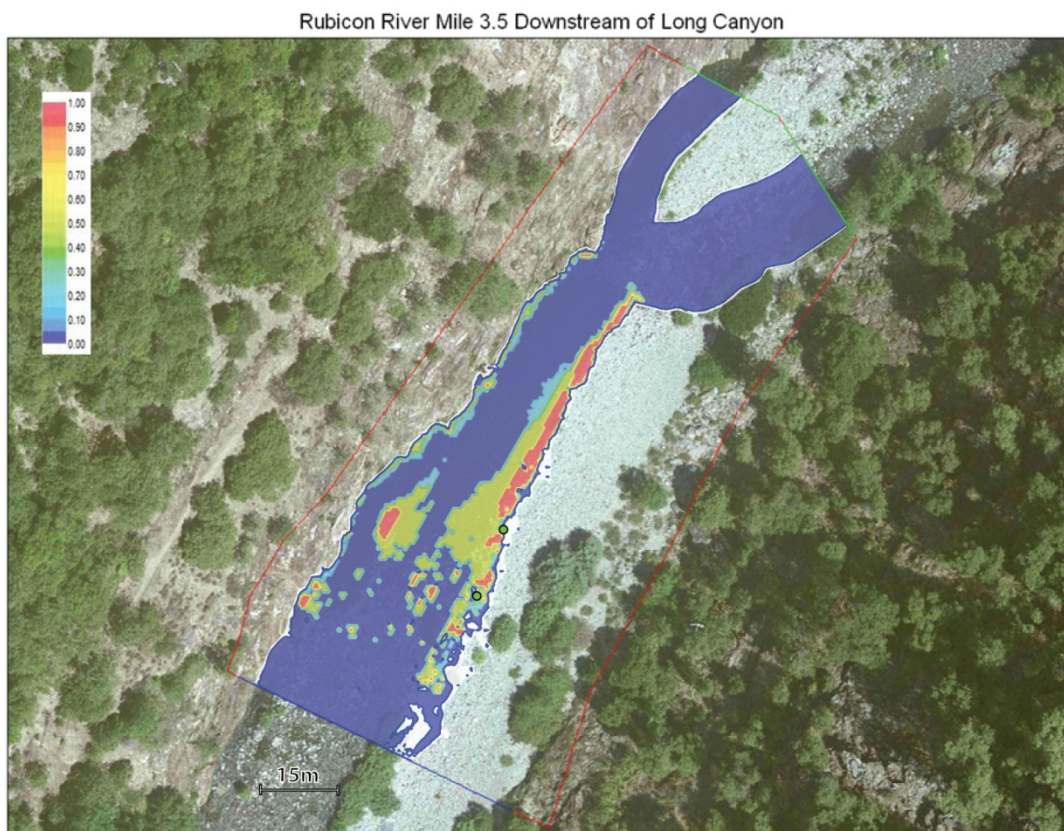
As a case study of how spring recession flows could be modeled in a regulated river to create increased instream habitat availability for native aquatic species, a series of flow scenarios were run through an existing modeled study site on the Rubicon River known to support native populations of multiple sensitive aquatic species (i.e., frogs, fish, benthic macroinvertebrates). Four flow scenarios were completed ranging from slow recession rates common to unregulated

Sierran rivers to rapid recession rates typical of many regulated rivers during cessation of winter spills below dams. The availability of instream habitats for native aquatic species was evaluated under each flow scenario to determine whether suitable habitat requirements were met for various species.

2.4.1 Study Site

The Rubicon River study site has been the focus of multiple aquatic studies since 2007, including studies for the Placer County Water Agency (PCWA) Middle Fork Project relicensing in 2008 (PCWA 2010), a UC Davis research study on Foothill yellow-legged frog habitat suitability in 2009 (Bondi et al. 2013), and for the field-based research in this CEC-funded project (see Chapter 1). Although two sub-reaches of the study site have been modeled using a two-dimensional hydrodynamic model in the past, the lower sub-reach below the confluence of Long Canyon Creek was selected for this analysis as more representative of typical Sierran river habitat (Figure 2.4).

Figure 2.4: Rubicon River Modeling Site.



2.4.1.1 Hydrodynamic Model

A two-dimensional (2D) hydrodynamic model (River2D) was used to predict instream depths and mid-column velocities over a variety of modeled flows at the Rubicon River study site. River2D is a depth-averaged finite element model freely available and used by the California Department of Fish and Game, U.S. Fish and Wildlife Service and others in fish habitat evaluation studies (Steffler and Blackburn 2002, Tiffan et al. 2002, Gard 2006). The 2D model for the Rubicon study site was developed within the instream flow study for the PCWA Middle Fork American hydropower relicensing project (FERC #2079) for use in evaluating potential project effects on instream flow conditions. Details on the calibration of the model, including

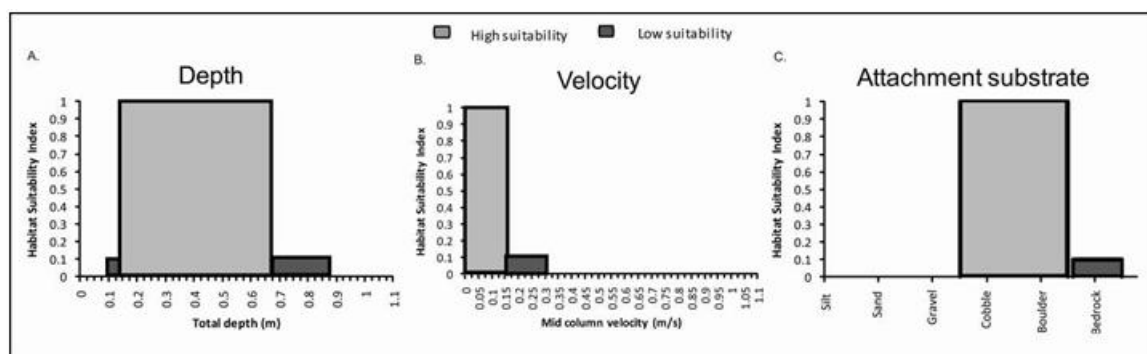
information on the input topography, mesh density and model error, can be found online (PCWA 2010). The calibrated model was provided for use in this study by PCWA.

2.4.1.2 Habitat Models

Two approaches were used to examine how instream habitat changed under each flow scenario. The first approach focused on changes in stage and duration of suitable habitat for Foothill yellow-legged frogs (FYLF), a sensitive species of interest in California. The output from the model was used to determine the location and amount of suitable habitat at each flow, whether the habitat remained suitable as flows decreased and how water surface elevations decreased through time.

To determine the availability of FYLF habitat under various flow scenarios, habitat suitability criteria (HSC) were input into the 2D model of the Rubicon study site. HSC were regionally derived percentile-based univariate suitability indices for depth, mid-column velocity and attachment substrate for egg masses—the most vulnerable life stage during the spring—as defined by Bondi et al. (2013) (Figure 2.5). The HSC were input into the 2D model, combined using a geometric mean approach, and categorical habitat suitability ranging from 0-1 was mapped across the modeled reach at each of the modeled flows.

Figure 2.5: Percentile-based univariate egg mass suitability indices for each hydraulic variable: (A) total depth, (B) mid-column velocity and (C) attachment substrate type (Bondi et al., 2013).



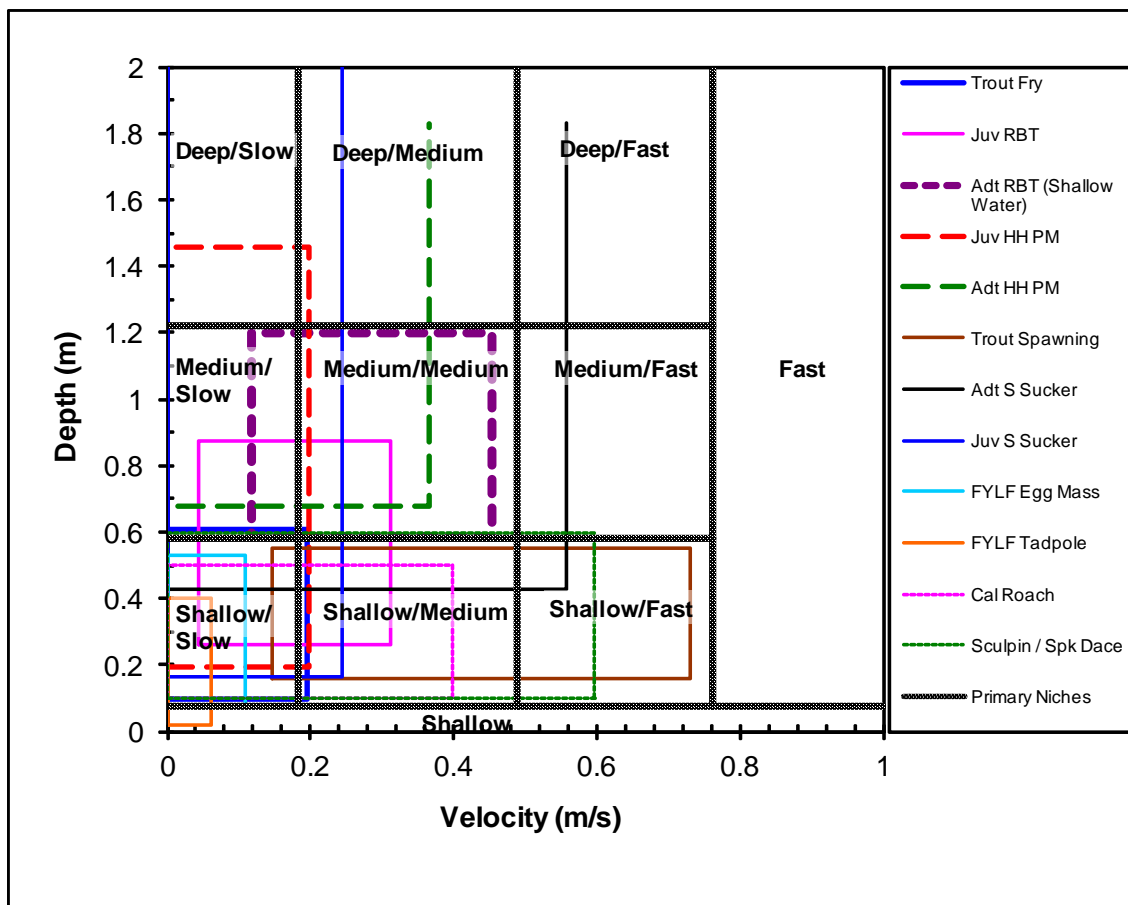
FYLF habitat suitability at the start of each flow scenario was calculated and tracked as flows decreased to determine which locations remained suitable at the end of the flow recession scenario. The change in depth at these initially suitable locations was tracked at each incremental flow decrease to ascertain the change in stage and the discharge at which these locations became dry. Egg masses develop and hatch on average two weeks after they are laid, while tadpoles require approximately one week to become mobile and follow a receding shoreline (Lind and Yarnell 2011). Therefore successful breeding requires suitable habitats to remain wetted for at least three weeks during the spring. The rate of change in depth of suitable habitat under each flow scenario was therefore calculated to determine whether instream flow conditions remained suitable for an appropriate duration of time to allow for successful tadpole emergence. These point-based calculations of the rate of decreasing depth were compared to the site-wide rate of change in water surface elevation to provide a reliable quantification of rate of change in stage under each flow scenario.

The second approach for examining instream habitat under each flow scenario focused on changes in availability, duration and diversity of suitable habitat for native species guilds, where a guild is defined as a set of species occupying a similar spatial niche. A spatial niche approach was used to model hydraulic habitat for all aquatic species of interest in the 2008 Middle Fork Project relicensing study (PCWA 2010). Primary priority species for management

modeled included rainbow trout (juvenile rearing, adult rearing, and spawning), hardhead (juvenile and adult rearing), and Foothill yellow-legged frog (FYLF) (breeding and tadpoles). Additional species and life stages of interest included juvenile and adult Sacramento pikeminnow, Sacramento sucker, California roach, sculpin species, speckled dace, fry of all the fish species, and macroinvertebrates. Each species/ life stage was assigned to one or more of eleven primary depth and velocity guilds (Figure 2.6). Each guild and the corresponding life stage of its species members is listed in Table 2.2.

At a series of representative flows within the flow scenarios, the distribution of hydraulic habitat across all spatial niches (depths < 1.5m and velocities < 1.5 m/ s) was determined, and the proportion of habitat within each of the 11 spatial niches was calculated. Simpson's Diversity Index was calculated from the relative proportion of spatial niches at each of the representative flows to provide a quantification of overall instream habitat diversity at varying flows.

Figure 2.6: Depth and velocity guilds for the aquatic species of interest in the PCWA Middle Fork Project for use in the spatial niche analysis (PCWA 2010).



Fry = Rainbow Trout, RBT = Rainbow Trout, HH = Hardhead, PM = Sacramento Pikeminnow, Spaw n = Trout Spaw ning, S = Sacramento, FYLF = Foothill Yellow -Legged Froq, Cal = California, Spk = Speckled, Juv = Juvenile, Adt = Adult

Table 2.2: Depth and velocity guilds for the aquatic species in the PCWA Middle Fork Project for use in the spatial niche analysis.

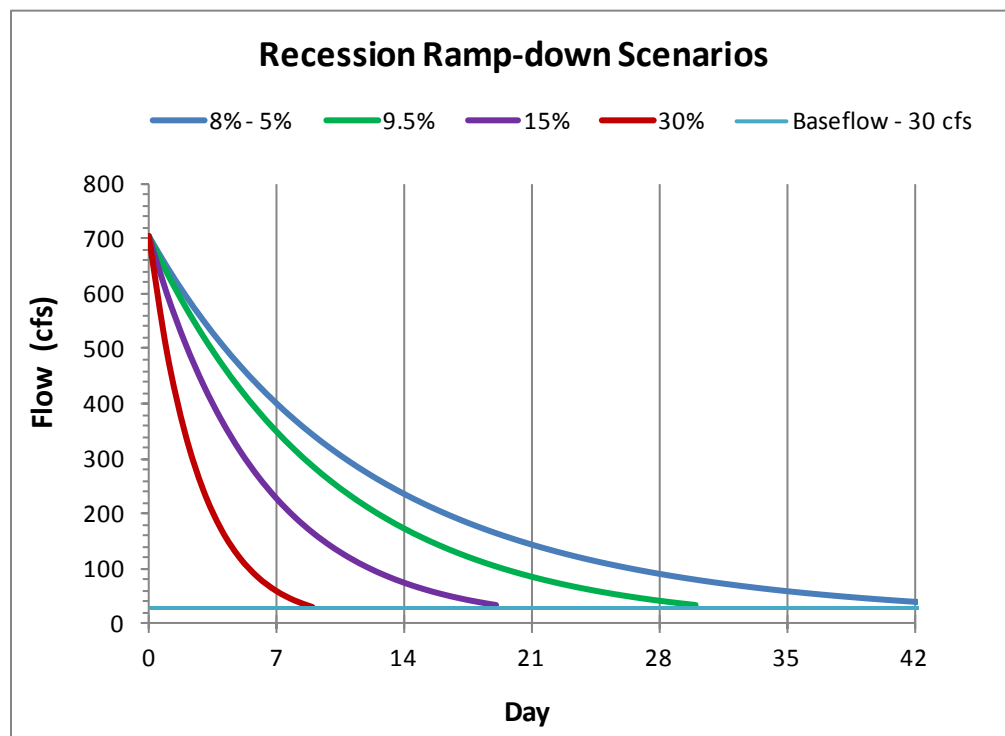
Guild Name (by water depth / velocity type)	Life Stage	Species Members	Velocity Range (m/s)	Depth Range (m)
Very Shallow	All:	Limited use by all species	All	<0.08
Shallow / Slow	Fry:	All Species	0 - 0.18	0.08 - 0.58
	Juvenile:	Hardhead, Sac Sucker, Sac Pikeminnow, Trout		
		California Roach, Sculpin, Speckled Dace		
	Breeding/Tadpole:	Foothill Yellow-Legged Frog		
Shallow / Medium	Aquatic:	Macroinvertebrates	>0.18 - 0.49	0.08 - 0.58
	Spawning:	Trout		
		Sculpin, Speckled Dace, California Roach		
	Juvenile:	Trout, Sac Sucker ¹		
Shallow / Fast	Aquatic:	Macroinvertebrates	>0.49 - 0.76	0.08 - 0.58
	Spawning:	Trout		
		Sculpin, Speckled Dace		
	Adult:	Sac Sucker ¹		
Medium / Slow	Aquatic:	Macroinvertebrates	0 - 0.18	>0.58 - 1.22
	Adult:	Hardhead, Sac Pikeminnow, Sac Sucker, Trout		
	Juvenile:	Hardhead, Sac Pikeminnow, Sac Sucker, Trout		
Medium / Medium	Aquatic:	Macroinvertebrates	>0.18 - 0.49	>0.58 - 1.22
	Adult:	Trout, Hardhead, Sac Pikeminnow, Sac Sucker		
	Juvenile:	Trout, Sac Sucker ¹		
Medium / Fast	Aquatic:	Macroinvertebrates	>0.49 - 0.76	>0.58 - 1.22
	Adult:	Sac Sucker ¹ , Trout ¹		
Deep / Slow	Adult:	Hardhead, Sac Pikeminnow, Sac Sucker, Trout ¹	0 - 0.18	>1.22
	Juvenile:	Hardhead, Sac Pikeminnow		
	Aquatic:	Macroinvertebrates ¹		
Deep / Medium	Adult:	Hardhead, Sac Pikeminnow, Sac Sucker, Trout	>0.18 - 0.49	>1.22
	Aquatic:	Macroinvertebrates ¹		
Deep / Fast	Adult:	Sac Sucker ¹ , Trout ¹	>0.49 - 0.76	>1.22
	Aquatic:	Macroinvertebrates ¹		
Very Fast	All:	Limited use by species except for macroinvertebrates in shallow to medium depth water (0.08-1.22 m) and velocity less than 1.25 m/s	>0.76	All

¹Limited use in this niche.

2.4.2 Modeled Flow Scenarios

Four modeling scenarios were chosen spanning a range of ramping rates from low to high. The lowest rate decreased gradually from 8% per day to 5% per day as is common in unregulated systems (Epke 2011), while the highest rate decreased uniformly at 30% per day as is sometimes observed in regulated systems and is the most extreme rate observed in an unregulated system (Figure 2.7). While regulated systems often exhibit ramping rates following winter spill as high as 80-90% per day (see chapter 1), the scenarios chosen here were intended to provide information on a variety of more gradual ramp-down scenarios that might be considered in flow negotiations within FERC hydroelectric relicensing. Each flow scenario ramped from a moderately high flow of 725 cfs when flows flooded onto the large left-bank coble bar in the study site to 30 cfs at baseflow when flows were present only in the main channel. The duration of each recession increased with decreasing recession rate from 9 days at 30%, 19 days at 15%, 30 days at 9.5% to 45 days at 8-5%.

Figure 2.7: Hydrographs of each flow recession scenario. Flows were decreased at different rates (in terms of percent decrease/day) from a high flow of 725 cfs to a baseflow of 30 cfs.



2.4.2.1 Habitat Suitability - FYLF

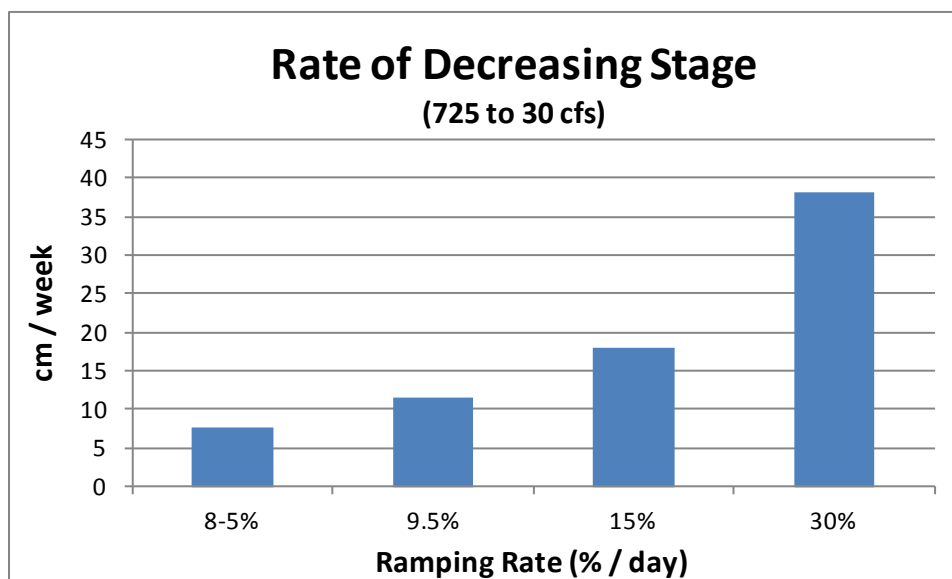
Due to the time required for FYLF egg masses to hatch and for tadpoles to develop the ability to swim and follow the receding shoreline, high rates of change in stage during the recession can limit habitat suitability and reproductive success. Rapid increases in flow can scour egg masses, while rapid decreases in flow can result in stranding and desiccation (Kupferberg et al. 2009). On average, the number of days for egg masses to hatch ranges from 7 days at mean daily temperatures of 20°C to 21 days at mean daily temperatures of 12°C (Lind and Yarnell 2011). Temperatures of 10–15°C are common to Sierran rivers in early spring (April–May) and typically increase to 16–20°C by June and July (see Chapter 1). Development of egg masses during the spring recession therefore may range from one to three weeks, averaging roughly two weeks across the season. After hatching, newly emerged tadpoles are not fully mobile with an ability to swim for approximately one week, increasing the length of time breeding habitat must remain wetted to an average of three weeks during the spring season. Data from previous studies in Sierran rivers shows that the majority of egg masses (74–94%) are deposited in water depths of less than 0.6 m and at least 40% are deposited in water depths less than 0.3 m (Bondi et al. in press). Furthermore, Kupferberg et al. (2012) showed that stranding of egg masses has population level effects, where if more than 40% of egg masses are stranded each year, the probability of extinction of the local population increases to as much as 4 times that of a population with no stranding. Thus, to protect at least half of all egg masses from stranding, the rate of flow recession should be less than 0.3 m over three weeks or less than 10 cm per week (Lind and Yarnell 2011).

For the flow scenarios, suitable habitat for FYLF calculated at the starting flow of 725 cfs was tracked as flows incrementally decreased to a baseflow of 30 cfs. On average, suitable habitat at modeled nodes decreased 49 cm in depth between 725 cfs and 30 cfs. More than half the originally suitable habitat was dry at 220 cfs, and only 8% of the suitable habitat remained wetted with depths greater than zero at baseflow. Under each flow scenario, the average

decrease in stage at suitable locations resulted in varying rates of change in depth during the recession, with higher ramping rates having higher rates of decreasing stage (Figure 2.8). The average rates of stage change at suitable locations were comparable to stage changes calculated more broadly across the study site from changing water surface elevations, but were about 5% lower on average. Suitable habitat for FYLF is typically located in low velocity backwaters and edge margins where stage changes may be slightly more buffered than mid-channel locations, particularly at higher flows that inundate the channel bar.

The two lowest recession rate scenarios (8–5% and 9.5%) provided habitat conditions throughout the recession that were conducive to successful FYLF tadpole emergence with rates of decreasing stage equivalent to 10 cm or less per week. The 15% ramp rate scenario created stage decreases of 18 cm per week, which based on egg mass depths observed across the Sierras, could result in desiccation of up to 85% of egg masses laid during the recession (Bondi et al., in press). Under the 30% ramp rate scenario, stage decreased at a rate of 38 cm per week, which could result in desiccation of all egg masses laid during the recession.

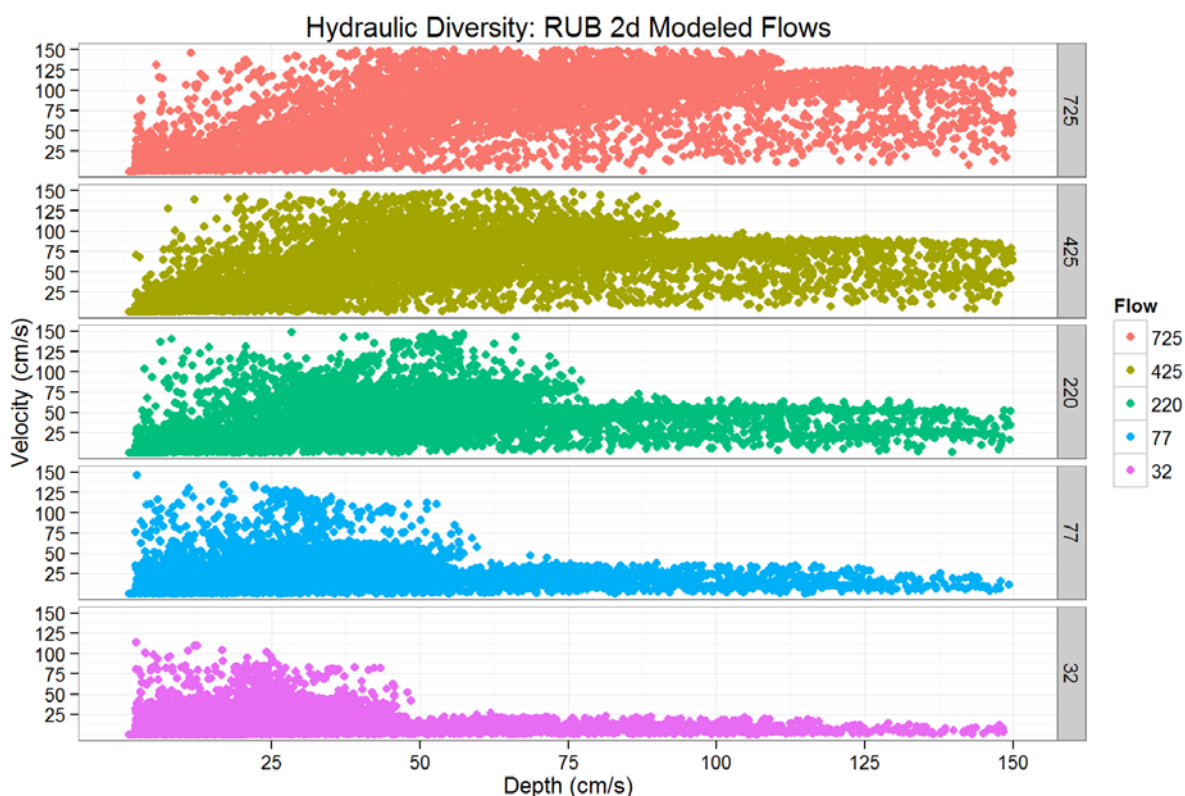
Figure 2.8: Rate of decreasing stage in centimeters (cm) per week for each flow recession scenario.



2.4.2.2 Habitat Suitability

The spatial niche analysis provided a general overview of how hydraulic habitat was distributed across the study site in space and time under each flow scenario. In general, depths and velocities decreased throughout the study site as flows decreased with a distinct contraction into the shallower, slower spatial niches (Figure 2.9). At high flow (725 cfs), depths and velocities were fairly uniformly distributed across the spatial niche range, with the highest density of points occurring at velocities > 75 cm/ s. While at baseflow (30 cfs), depths up to 150 cm remained present in the pools, but velocities above 125 cm/ s were absent, and velocities greater than 25 cm/ s were present only in the shallow riffles and runs (depths < 50 cm).

Figure 2.9: Distribution of depth and velocity points at five representative modeled discharges. Data was aggregated and analyzed using R (R Core Development Team 2012).



The distribution of points within each spatial niche as flows decreased likewise shifted from deeper faster niches to slower, shallower niches (Figure 2.10). A calculation of Simpson's Diversity Index for the distribution of points across spatial niches at each modeled flow showed that the mid-magnitude flows (near 220 cfs) provided the highest diversity of hydraulic habitat (Figure 2.11). While the spatial diversity of hydraulic habitat remained the same for each flow scenario, as all scenarios began at 725 cfs and decreased stepwise to 30 cfs, the duration of time at each flow step differed with the varying ramp-down rates (Figure 2.12). At a rate of 8–5% per day, flows were within 25% of 425 cfs (530 cfs to 320 cfs) for 7 days, within 25% of 220 cfs (275 cfs to 165 cfs) for 8 days and within 25% of 77 cfs (96 cfs to 58 cfs) for 10 days. Thus the total number of days at the most diverse intermediate flows (from approximately 530 cfs to 60 cfs) was 25 days. Conversely, at a ramp-down rate of 15% per day, flows were within 25% of 425 cfs, 220 cfs, and 77 cfs for only 4 days each, respectively, for a total of 12 days. At a ramp rate of 30% per day, diverse intermediate flows between 530 cfs and 60 cfs occurred for only 7 days total, with 1 day of flows within 25% of 425 cfs, 3 days of flows within 25% of 220 cfs and 3 days of flows within 25% of 77 cfs.

Figure 2.10: Percent of modeled nodes with depths and velocities less than 1.5 m and 1.5 m/s, respectively, within each spatial niche at each of five modeled discharges (725 cfs – 32 cfs).

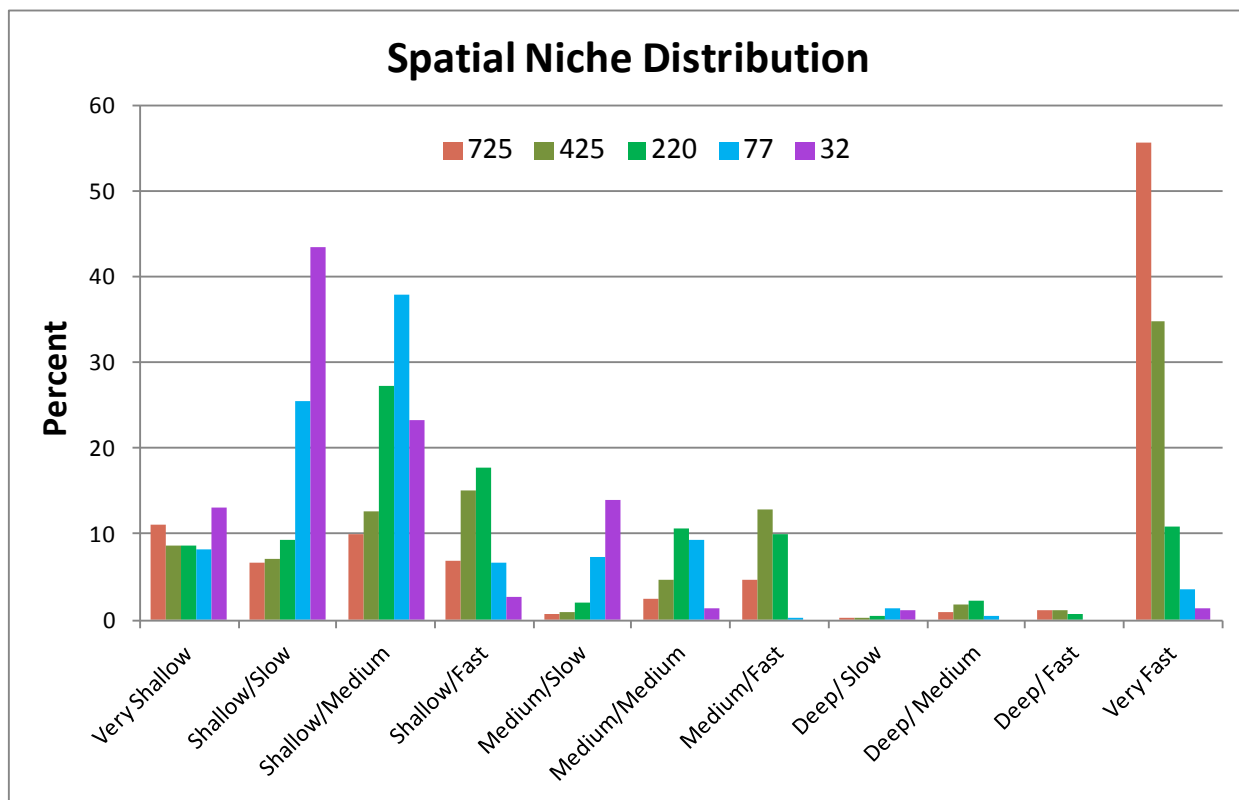


Figure 2.11: Simpson's Diversity Index calculated from the distribution of spatial niches at each of five modeled discharges.

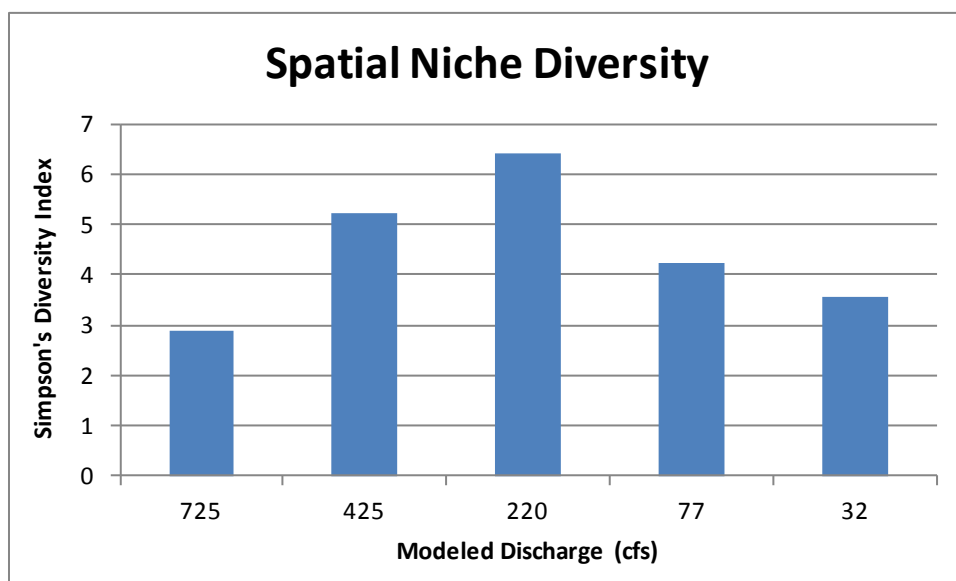
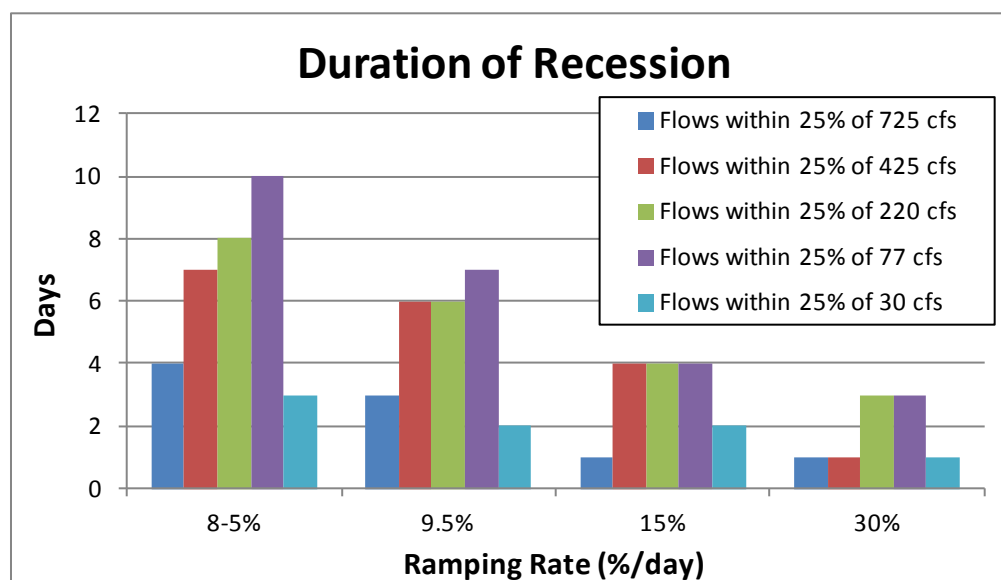


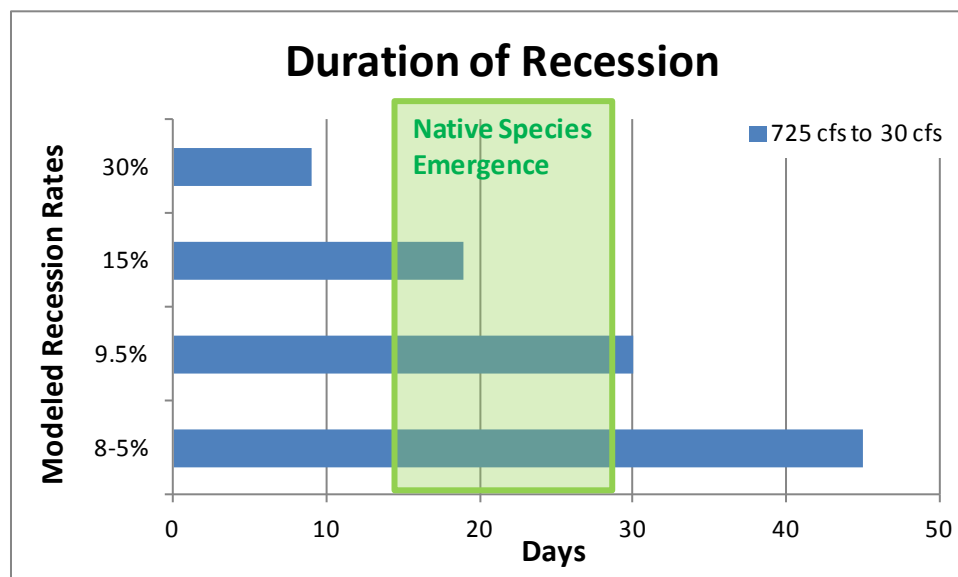
Figure 2.12: Duration of flows within 25% of five modeled discharges for each of the flow recession scenarios. For example, duration of “flows within 25% of 425 cfs” represents the number of days for flows to decrease from 530 cfs to 320 cfs.



The duration of time required by native species guilds for their associated spatial niche to persist typically varies from two to four weeks. Many native spring spawners lay eggs in medium to deep habitats with slow to medium velocity conditions. Similar to FYLF, Sacramento pikeminnow require 7 days for eggs to incubate and hatch at 18°C, and an additional 7 days until larvae develop enough to swim (Moyle 2002). California roach develop more quickly, with eggs hatching after 2–3 days and fry becoming viable swimmers after an additional week. In contrast, riffle sculpin are particularly vulnerable to flow reductions and increased temperatures as their eggs incubate for 11 to 24 days (at 15°C and 10°C, respectively) and the fry remain benthic for several additional weeks (Moyle 2002). Sacramento suckers and rainbow trout typically spawn earlier in spring when temperatures are lower, and subsequently require 2–5 weeks for eggs to incubate and hatch. As a result, most native spring spawners require suitable habitat conditions for 3 weeks on average during the spring.

Under the assumption that native fish generally spawn in shallow depth locations, only the two lowest recession rate scenarios (8-5% and 9.5%) provide an adequate duration greater than 3 weeks for native species emergence (Figure 2.13). The 15% recession rate scenario provides a total of 19 days to ramp from high to baseflow, but if the spawning habitat was located at depths of less than 30 cm, the habitat would be dry after 2 weeks, resulting in unsuccessful emergence for most native species.

Figure 2.13: Total duration in days of flow recession scenarios. Green box indicates average duration required (2-4 weeks) for native spring spawning species of fish fry, frog tadpoles and benthic macroinvertebrates to hatch and emerge.



2.5 Examples in Managed Systems

Flow regimes are a primary focus during relicensing of hydropower projects through the Federal Energy Regulatory Commission (FERC). Over the last decade, stakeholders involved in relicensing projects (e.g., state and federal resource and regulatory agencies, non-governmental organizations, and other interested parties) have used the 'natural flow regime' paradigm (Poff et al. 1997) as a guide for developing license conditions/ measures for minimum instream flows and channel maintenance flows, especially winter pulse flows. For projects in the Sierra Nevada of California, recognition that the spring snow melt period is critical for a variety of biological and physical river attributes (Yarnell et al. 2010) has led to the incorporation of this element in recent relicensing efforts.

Snowmelt recession flows may be incorporated into licenses in several different ways, under different names, depending on the mode of control and the designated purpose. Ramping rate requirements, specific step down flow measures (down ramp schedules or spill cessation), and/ or reservoir operation measures (reservoir management) have all been used to address the flow transition period from spill at a dam to minimum flows. Ramping rates are typically described as the volume of water over time that flow releases are allowed to change, when a licensee has control of project flows and is either increasing or decreasing those flows. Most licenses (even older ones) incorporate some type of ramping rate for these transitions to minimize effects on aquatic species, most commonly to avoid stranding of fish. Ramping rates may be required during facility outages, pulse flows, and during any other transition period from one flow to another, and are often expressed as a flow volume per hour. Spill related measures such as daily down ramping, cessation, and reservoir management measures have been included in more recent relicensing efforts in order to provide a longer transition to baseflow and better mimic unregulated spring flows (Table 2.3).

Table 2.3: Inclusion of snowmelt recession flows during relicensing of FERC-licensed hydroelectric projects (example projects are ordered oldest to most recent).

FERC Project Name and Number	River(s)	Licensee	Relicensing Status*	Ramping Rate and Spill Management License Conditions	Range of Estimated Daily Percent Change
Rock Creek-Cresta Project, no. 1962	North Fork Feather – Cresta Reach only	Pacific Gas and Electric Company	Settlement agreement and license issued in 2001; included three five-year test flow periods; an Ecological Resources committee is currently negotiating the 3 rd five year period flows (June 2013)	<p><i>1st five-year flow schedule</i> included <u>ramping rates</u> to follow an unregulated tributary (March-May) and faster rates the rest of the year. It did not include specific spill management measures.</p> <p><i>2nd five-year flow schedule</i> included similar <u>ramping rates</u> as the 1st five years. Also incorporated a whitewater boating flow that had high flows in early May reduced down in two long duration steps to minimum flows in June or July, depending on WY type.</p> <p><i>3rd five-year flow schedule</i> is currently being negotiated, but the current agreement includes <u>spill management</u> using block loading of powerhouses from 3000 cfs to 1000 cfs to create flows similar to the unregulated tributary. From 1000 cfs to minimum flows, a 21 day duration flow reduction schedule will be implemented. Within the 21 day schedule, flows are held at 600cfs for 15 days for whitewater boating.</p>	8-20% (10-11% for most steps).
Pit 3,4, and 5 Project, no. 233	Pit River	Pacific Gas and Electric Company	New license issued in 2007.	<u>Reservoir Management</u> (Year-round): The stated goal in the FS Final Revised 4e Conditions is: "...to allow spills from Project reservoirs to increase and decrease at a rate resembling the natural unimpaired condition..." To achieve that goal, the license includes a series of operational measures that integrate inflow to project reservoirs, powerhouse loading, and opening and closing of gates and low-level outlets.	Difficult to assess.
McCloud-Pit, no. 2106	McCloud River	Pacific Gas and Electric Company	FS filed final 4e conditions in 2010; Final EIS complete; SWB water quality certification in process; then new license.	<u>Ramping Rates</u> (Year-round): For spills of 1000 cfs down to minimum flows (usually 175cfs) reduce flow by 150 cfs every 48 hours. Constant cfs approach results in daily change that gets higher when approaching minimum flows.	7.5% - 30%.

FERC Project Name and Number	River(s)	Licensee	Relicensing Status*	Ramping Rate and Spill Management License Conditions	Range of Estimated Daily Percent Change
Middle Fork American Project, no. 2079	Middle Fork American, Rubicon	Placer County Water Agency	FS filed final 4e conditions in 2012; Final EIS complete; SWB water quality certification in process; then new license.	<p><u>Down Ramp Schedule</u> (May through July): MF American has a 7 day daily spill ramp down schedule with $\pm 10\%$ of target flows; Rubicon has a 14-17 day spill ramp down schedule with flow settings for varying durations (2-4 days) due to facility limitations.</p> <p><u>Pulse flows</u> are also required in all project-affected streams. These flows include ramp downs to minimum flows; however, if a spill occurs during a pulse, the ramp down from spill schedule supersedes the pulse flow ramping rates.</p>	<p>MF American: 30.8-43.5%.</p> <p>Rubicon: 8.3-14.5%.</p>
Yuba-Bear, no. 2266; Drum-Spaulding, no. 2310	Middle Yuba, South Yuba, Canyon Creek, Bear River and many associated tributaries	<p>Nevada Irrigation District (Yuba-Bear);</p> <p>Pacific Gas and Electric Company (Drum-Spaulding)</p>	FS filed preliminary 4e conditions in August 2012. Draft EIS complete; FS final 4e conditions and Final EIS due in late 2013/early 2014; then SWB water quality certification and new license.	<p><u>Spill cessation</u> measures were developed for MYuba, SYuba, and Canyon Creek for any spills occurring in the April/May through September time period. The flow schedules in the MYuba and SYuba start at flows suitable for whitewater boating, which are held from 2 to 6 days depending on water year type. Then flows step down over a 21 day period to minimums. In Canyon Creek, flows immediately step down over a 21 day period to minimums. Duration of each flow step (2-4 days) varied depending on facility limitations.</p> <p>For the Bear River, <u>spill and reservoir management</u> were incorporated to provide flows that were more similar to unregulated recession regimes.</p>	<p>MYuba: 6.7-12.5 %</p> <p>SYuba: 4-20%</p> <p>Canyon Creek: 5-20%</p>

* FS = USDA Forest Service (Federal Power Act 4e conditioning authority); SWB = State Water Board

Recession flows that have been negotiated in recent relicensing efforts have been developed using information on unregulated river recession rates (Epke 2011), ecological requirements of amphibian species of concern (Lind and Yarnell 2011), riparian vegetation requirements (Yarnell et al. 2010), recreational whitewater boating flow interests, consideration of physical facilities and operations (e.g., types of spill gates and gate controls, outlet sizes), and potential negative effects on water supplies and power generation. Recession flow requirements associated with spills may apply year-round or only in the spring months, depending on the project and the rationale for including spill management measures.

The spill cessation measures for the Yuba-Bear (Nevada Irrigation District) and Drum-Spaulding (Pacific Gas and Electric Company) projects (Table 2.3) are good recent examples of how these elements can be balanced to meet ecological and recreation interests as well as address licensee concerns about operational feasibility and affects on water supply and power generation. For three major stream reaches in these projects (Middle Yuba River, South Yuba River, and Canyon Creek) relicensing participants worked together to develop spill cessation

flow schedules that were initiated and held for several days at preferred whitewater boating flow levels and then stepped down over a three week period (typical foothill yellow-legged frog egg hatching period) to minimum flows, at rates that mimicked unregulated Sierra Nevada river snow-melt recessions. The duration (number of days) and volume of individual flow steps were adjusted to accommodate licensee concerns about operational limitations and water and power generation losses. Other recent relicensing efforts have included flow measures that meet these elements to a lesser degree (e.g., Middle Fork American Project and Rock Creek-Cresta Project).

In recent hydroelectric project relicensing efforts, a variety of approaches have been developed to achieve flow recession rates that mimic unregulated rivers. On-going and future relicensing efforts will likely build on and refine these approaches, which will further benefit the native aquatic species that are adapted to the spring snowmelt recession.

2.6 Conclusions and Recommendations

In an effort to help mitigate the well-known negative impacts of flow regulation (Ligon et al. 1995, Power et al. 1996, Marchetti and Moyle 2001) by restoring predictable ecologically-relevant spring flow patterns (Yarnell et al. 2010), this study sought to define a methodology by which spring flow regimes can be modeled in regulated systems from the quantifiable characteristics of spring snowmelt recessions in unregulated rivers. An analysis of eight unregulated rivers across the Sierra Nevada mountain range found that unregulated Sierran systems behaved similarly with respect to seasonal patterns and flow recession shape (recession limb curvature), and thus spring snowmelt recession flows could be modeled in a manner that mimics those predictable characteristics. Using a methodology that quantifies spring snowmelt recession flows in terms of a daily percent decrease in flow, a series of flow recession scenarios were created for application in an existing study site on the regulated Rubicon River. The modeling results show that flow recessions with slow ramping rates similar to those observed in unregulated systems (less than 10% per day) were protective of Foothill yellow-legged frog egg masses, while flows that receded at rates greater than 10% per day resulted in desiccation of egg masses and potential stranding of newly hatched tadpoles. Furthermore, recession rates of less than 10% per day provided the most diverse hydraulic habitat for an appropriate duration in spring to support all native species guilds and maximize aquatic biodiversity.

The spatial niche modeling results also supported the general notion that hydraulic diversity in both space and time is necessary to support the full complement of native aquatic species (Ward and Stanford 1995, Lytle and Poff 2004, Pastuchova et al. 2008). As flows gradually transition from high flows inundating cobble bars, floodplains, and riparian habitats to lower flows inundating the main channel, hydraulic conditions shift and move across a varied channel morphology. At any given point in *time*, the diversity in space allows for an abundance of spatial niches to exist (see Figure 1.22-1.23, previous chapter). While at any given point in *space*, the duration of inundation over varying discharges further creates an abundance of spatial niches (Figure 2.12). The key to this shifting hydraulic mosaic however, is that these shifts in time happen relatively slowly (Figure 2.13), allowing for complete development of aquatic eggs and larvae within a single spatial niche before the niche disappears. The large diversity of spatial niches that occurs through time thus allows for more species with varying habitat requirements to exist and reproduce successfully.

The methodology described in this study can be easily applied to regulated systems throughout the Sierra Nevada, as well as to other snowmelt regions with knowledge of regional unregulated flow characteristics. Within the federal relicensing process for hydropower dams, there is a unique opportunity to re-operate flows below dams to mitigate negative effects on sensitive native aquatic taxa. While a variety of hydroelectric projects require some form of hourly ramping rates when transitioning from high to low flow and vice versa, only a handful of recent projects require longer duration spring flow recessions when transitioning from spill flow to baseflow. The 'flow calculator' created for use in this study has recently been utilized within the relicensing process on the Yuba-Bear Drum-Spaulding project (FERC #2266) to create flow recessions that more naturally transition from high spill flows to minimum instream flows.

Other Sierran hydroelectric projects currently in the process of relicensing are considering implementing spring spill recession flows in order to minimize adverse impacts from sudden changes in flow in spring as well as to provide the spring ecological cues that many native species depend on for successful reproduction.

2.6 References

- Bondi, C.A., S.M. Yarnell, and A.J. Lind. 2013. Transferability of habitat suitability criteria for a stream breeding frog (*Rana boylei*) in the Sierra Nevada, California. *Herpetological Conservation and Biology*. *In press*.
- Epke, G.A. 2011. Spring snowmelt recession in rivers of the western Sierra Nevada mountains. Master's Thesis. Hydrologic Sciences. University of California, Davis.
- Gard, M. 2006. Changes in salmon spawning and rearing habitat associated with river channel restoration. *International Journal of River Basin Management* 4:201-211.
- Kupferberg, S.J., A.J. Lind, and W.J. Palen. 2009. Pulsed flow effects on the Foothill Yellow-legged Frog (*Rana boylei*): population modeling. Final Report. California Energy Commission, PIER. Publication number 500-2009-002a. 80 p. Available from: <http://animalscience.ucdavis.edu/pulsedflow/Kupferberg%20Sept2010.pdf>
- Kupferberg, S.J., W.J. Palen, A. J. Lind, S. Bobzien, A. Catenazzi, J. Drennan, and M.E. Power. 2012. Effects of flow regimes altered by dams on survival, population declines, and range-wide losses of California river-breeding frogs. *Conservation Biology* 26:513–524.
- Ligon F.K., W.E. Dietrich, W.J. Trush. 1995. Downstream ecological effects of dams. *BioScience* 45: 183–192.
- Lind, A.J. and S.M. Yarnell. 2011. Assessment of risks to Sierra Nevada populations of Foothill yellow-legged frogs (*Rana boylei*) under varying snowmelt hydrograph recession rates in rivers. Short technical report prepared for US Forest Service. March 2011. 6 pgs.
- Lind, A.J. and S.M. Yarnell. 2011. Frogs That Go With the Flow. *River Management Society Journal*. 24(4):10/ 26 (Winter).
- Lytle D.A. and N.L. Poff. 2004. Adaptation to natural flow regimes. *Trends in Ecology and Evolution* 19: 94–100.
- Marchetti M.P. and P.B. Moyle. Effects of flow regime on fish assemblages in a regulated California stream. *Ecological Applications* 11: 530-539.
- Moyle, P.B. 2002. *Inland fishes of California*. University of California Press. Berkeley, CA.
- Pastuchova Z., M. Lehotsky, A. Greskova. 2008. Influence of morphohydraulic habitat structure on invertebrate communities (Ephemeroptera, Plecoptera and Trichoptera). *Biologia* 63: 720–729.
- Placer County Water Agency (PCWA). 2010. Middle Fork Project Relicensing, Aquatic Pre-Application Technical Study Report, Instream Flow. <http://relicensing.pcwa.net/html/science/padreportaquatic.php>
- Poff N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. *BioScience* 47: 769–784.
- Power M.E., W.E. Dietrich, and J.C. Finlay. 1996. Dams and downstream aquatic biodiversity: Potential food web consequences of hydrologic and geomorphic change. *Environmental Management* 20: 887-895.

- R Core Development Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, <http://www.R-project.org/>.
- Steffler, P., and J. Blackburn. 2002. River2D: Introduction to Depth Averaged Modeling and User's Manual. University of Alberta. Release September, 2002. Available from <http://www.river2d.ualberta.ca> [Accessed 15 August 2012].
- Tiffan, K.F., D.G. Rodney, and D.W. Rondorf. 2002. Quantifying flow-dependent changes in subyearling fall Chinook Salmon rearing habitat using two-dimensional spatially explicit modeling. *North American Journal of Fisheries Management* 22:713–726.
- Ward J.V. and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers-Research and Management* 11: 105–119.
- Yarnell, S.M., J.H. Viers, and J.F. Mount. 2010. Ecology and management of the spring snow melt recession. *BioScience* 60(2):114–127.
- Yarnell, S.M., A.J. Lind, and J.F. Mount. 2012. Dynamic flow modeling of riverine amphibian habitat with application to regulated flow management. *River Research and Applications* 28:177–191.

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

3.0 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.

3.1 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 as 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 an external climate-sensitive rainfall-runoff model.

3.1.1 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).

3.1.2 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 hydropеaking, causing Englebright Reservoir to act as a re-regulating facility. These general concepts can be applied to help restore spring snow melt 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.

3.1.3 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 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:

$$Z = \sum_{t=1}^T B_t(s_{t-1}, r_t) + B'_T(s_T) \quad (0.1)$$

subject to:

$$s_t = s_{t-1} + q_t - r_t - l_t + Cr_t \quad t = 1, \dots, T \quad (0.2)$$

$$s_t^{\min} \leq s_t \leq s_t^{\max} \quad t = 1, \dots, T \quad (0.3)$$

$$r_t^{\min} \leq r_t \leq r_t^{\max} \quad t = 1, \dots, T \quad (0.4)$$

where B is the benefit associated with the storage vector \mathbf{s} (i.e., the storage vector of all reservoirs in the system) at the beginning of each period ($t-1$) and the release vector \mathbf{r} during each period t . B'_T is a function measuring the benefit of leaving 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; \mathbf{l} includes any non-beneficial losses (spill, evaporation, seepage) \mathbf{C} is the connectivity matrix that identifies the upstream/ downstream relationships between reservoirs. s_t^{\min} and s_t^{\max} are upper and lower bounds on the storage available for hydropower generation and r_t^{\min} and 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 \mathbf{B} and \mathbf{B}' for each period (the functions will likely differ for each reservoir); 2) define the minimum and maximum releases (r^{\min} and 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.

3.2 Study Area

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 km², 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 production¹ and about 8% (1.7 MAF) of total annual inflow² 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 1983-2001³, about 3% of California’s annual hydropower energy production.

Approximately 160x10⁶ m³/ year (130x10³ 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 3.1). 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

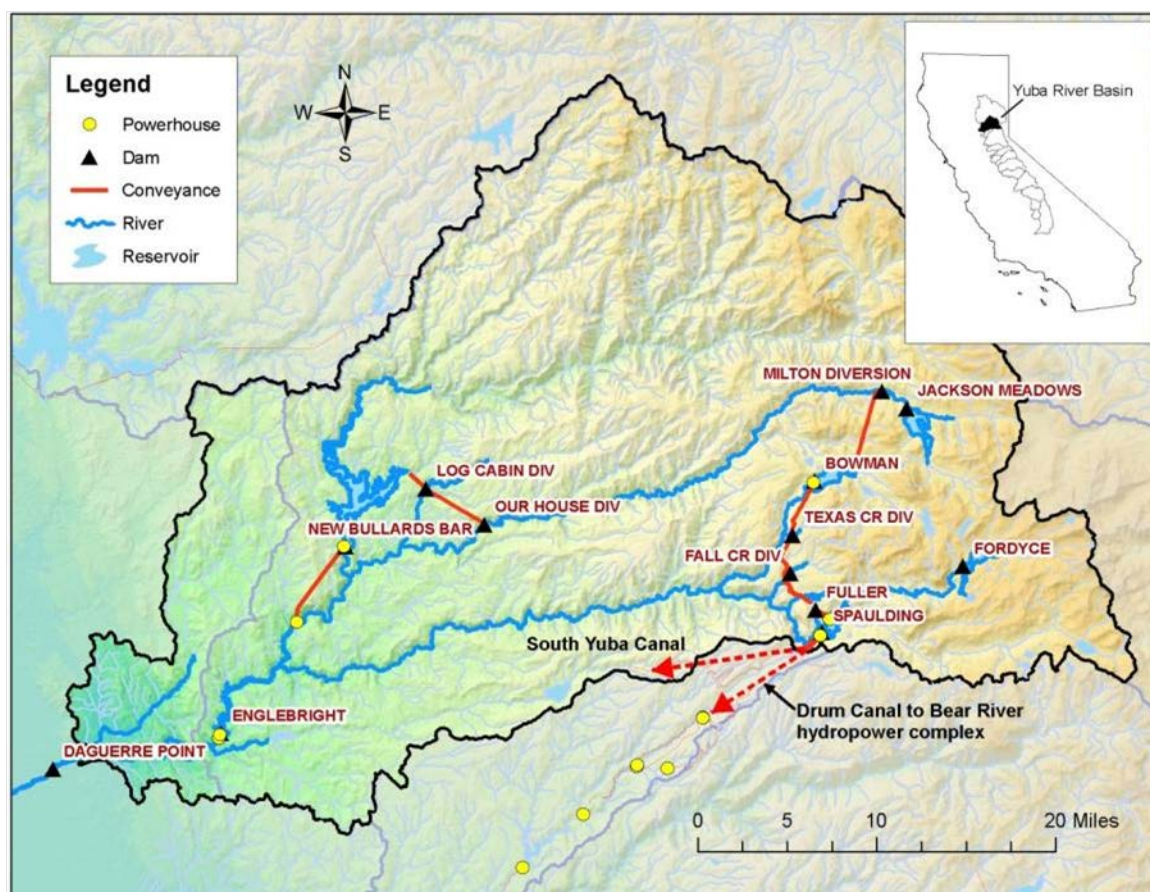
runoff into the reservoirs. Of this stored water, 900 cfs, or 27 TAF/ year, can be diverted to South Yuba Canal and Drum Canal. Of this 900 cfs, 850 cfs can be diverted to the Bear River via Drum Canal while 200 cfs can be sent to the South Yuba Canal.

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.



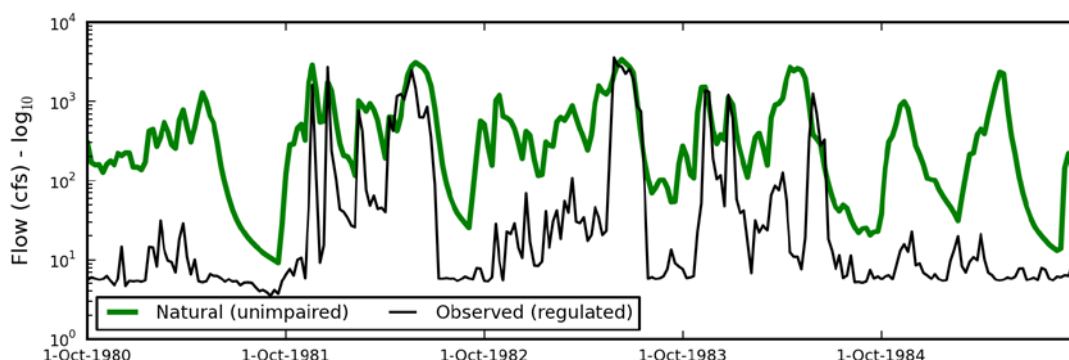
3.2.1 Flow Regulation Effects in the Yuba River Watershed

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 hydropowering. 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.



3.2.2 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.



3.2.3 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.

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.

3.3 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.

3.3.1 Modeling Assumptions

Assumptions described here directly affect the formulation of the model method. Other relevant assumptions, such as 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.

3.3.2 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:

$$z = \sum_t^T \sum_{ph}^N \pi_{t,ph} \quad (0.5)$$

Revenue is a function of energy price times energy generation:

$$\pi_{t,ph} = \bar{p}_t \cdot E_{t,ph} \quad (0.6)$$

where \bar{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:

$$E_{t,ph} = \eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot Q_{t,ph} \quad (0.7)$$

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 \bar{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 \bar{p}_t is therefore:

$$\bar{p}_t = \bar{p}(\theta_t) \quad (0.8)$$

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

$$\pi = \bar{p}(\theta) \cdot \eta \cdot h \cdot \gamma \cdot Q \quad (0.9)$$

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

$$\pi = R(\eta, h, \gamma, Q, Q^{max}) \quad (0.10)$$

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

$$\pi = \eta, h, \gamma \cdot Q^{max} \cdot R\left(\theta = \frac{Q}{Q^{max}}\right) \quad (0.11)$$

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:

$$Z = \sum_t \sum_{ph} \eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot R_{t,ph}(Q_{t,ph}) \quad (0.12)$$

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

$$Z = \sum_t \sum_{ph} \left(\eta_{ph} \cdot h_{ph} \cdot \gamma_{ph} \cdot \sum_n m_{t,n} Q_{t,ph,n} \right) \quad (0.13)$$

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:

$$Z = \sum_t \sum_{ph} \pi_{t,ph} + \sum_t \sum_d B_{t,d}^{supply} Q_{t,d} + \sum_{res} B_{res}^{V_f} V_{f,res} + \sum_t \sum_r \sum_v M_{t,r}^v Q_{t,r}^v \quad (0.14)$$

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.

3.3.3 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 ($loss$):

$$V_t = V_{t-1} + \sum_{in} \mathbf{C} Q_{t,in} + \sum_{gain} Q_{t,gain} - \sum_{rel} \mathbf{C} Q_{t,rel} - \sum_{loss} Q_{t,loss} \quad (0.15)$$

where \mathbf{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 :

$$Q_{t,inflow} = I_t \quad (0.16)$$

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

$$V_{t,res} \leq V_{t,res}^{max} \quad (0.17)$$

$$V_{t,res} \geq V_{res}^{min} \quad (0.18)$$

When $t = 1$:

$$V_{t-1,res} = V_{0,res} = V_{res}^{init} \quad (0.19)$$

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:

$$Q_{t,ph} \leq Q_{ph}^{max} \quad (0.20)$$

$$Q_{t,ch} \leq Q_{ch}^{max} \quad (0.21)$$

$$Q_{t,rel} \leq Q_{rel}^{max} \quad (0.22)$$

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

3.3.4 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:

$$Q_{t,hab} + Q_{t,hab}^{deficit} \geq Q_{t,hab}^{min} \quad (0.23)$$

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

$$Q_{t,hab} + Q_{t,hab}^{down} \geq (1 + \Delta_{t,hab}^{down}) Q_{t-1,hab}; \forall t > 1 \quad (0.24)$$

where $\Delta_{t,hab}^{down}$ is the maximum down ramp rate expressed as a percent change in total weekly flow and $Q_{t,hab}^{down}$ 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_t^{down}) is included:

$$\Delta V_t = V_{t-1} - V_t \leq V_t^{down} \quad (0.25)$$

Water supply demand is specified as a maximum constraint:

$$Q_{t,dem} \leq D_t \quad (0.26)$$

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.

3.3.5 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:

$$\text{maximize: } z_T = R_T = \sum_{t=1}^T B_t(Q_t) \quad (0.27)$$

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:

$$B_t(Q_t) = \eta \cdot \gamma \cdot h \cdot Q_t \cdot P_t \quad (0.28)$$

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:

$$z = \sum_{t=1}^T B_t(Q_t) = \eta \cdot \gamma \cdot h \cdot \sum_{t=1}^T Q_t P_t \quad (0.29)$$

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:

$$z = \sum_{t=1}^T Q_t P_t \quad (0.30)$$

subject to:

$$Q_t \leq C \quad (0.31)$$

$$\sum_t Q_t \leq V_{total} \quad (0.32)$$

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.

3.4 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 ($1 \text{ m}^3/\text{s} = 35.3 \text{ ft}^3/\text{s} (\text{cfs})$).

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 ³ T ⁻¹]	(3.13)
Unmet flow requirement penalties	$M_{t,r}^v = M_{t,r}^{Q^{deficit}}$	\$/[L ³ T ⁻¹]	(3.14)
Spill penalties	$M_{t,r}^v = M_{t,r}^{Q^{spill}}$	\$/[L ³ T ⁻¹]	(3.14)
Water supply demand	D_t	L ³ T ⁻¹	(3.26)
Water supply benefit	$B_{t,d}^{supply}$	\$/[L ³ T ⁻¹]	(3.14)
Powerhouse turbine flow capacity	Q_{ph}^{max}	L ³ T ⁻¹	(3.20)
Channel capacity	Q_{ch}^{max}	L ³ T ⁻¹	(3.21)
Reservoir release capacity	Q_{rel}^{max}	L ³ T ⁻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 snow melt are both predictable and last for several months, the weekly time step is well suited for use in a model that considers the natural snow melt recession flows. Therefore, this study uses a weekly time step.

3.4.1 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.

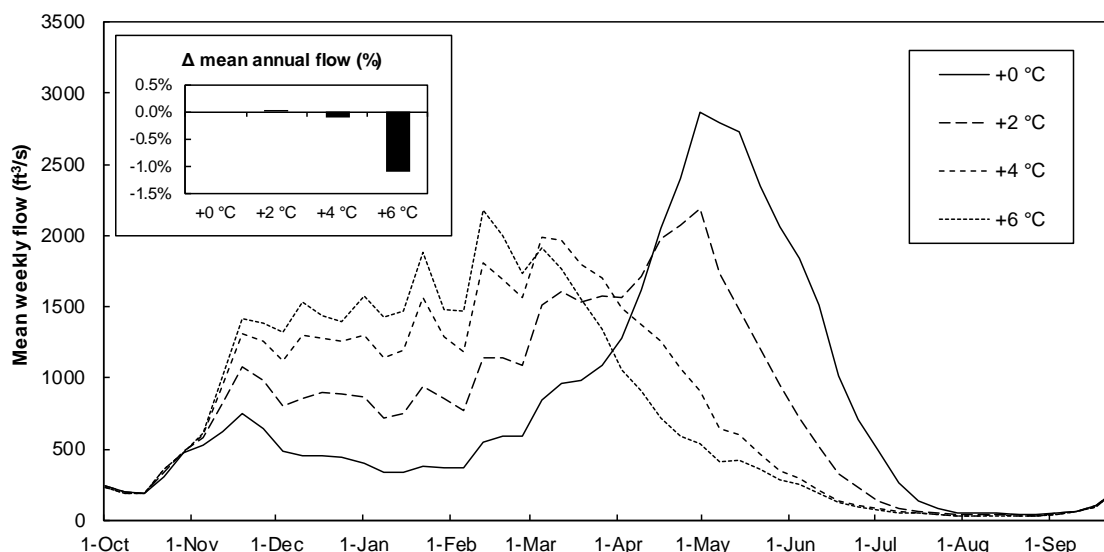
This study uses weekly inflow hydrology changes anticipated with uniform air temperature increases of +0, 2, 4, and 6 °C, as considered by Young et al. (2009). Young et al. (2009) developed a weekly time step rainfall-runoff model of the western Sierra Nevada, calibrated to the major basin outlets, using 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 snow melt. 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.



3.4.2 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.

3.4.2.1 Base Case (BC) instream flow requirements

Existing IFRs consist of minimum instream flow requirements at the three locations identified above (Figure 3.3). 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.

3.4.2.2 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

3.4.2.3 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).

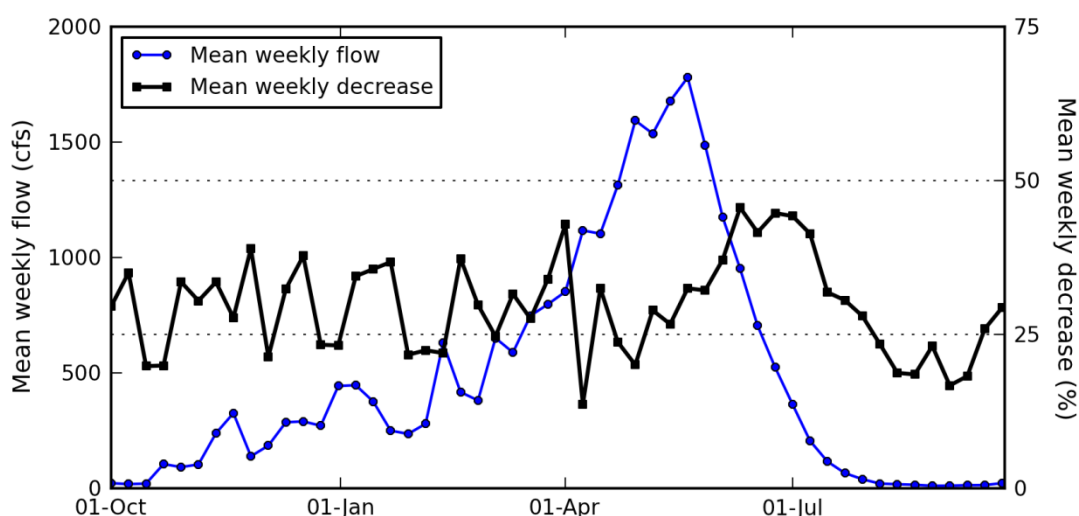


Table 3.5: Maximum Down Ramp Rate (DRR) scenarios.

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

3.4.3 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.

3.4.3.1 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/ m³ 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

3.4.3.2 Bear River hydropower complex

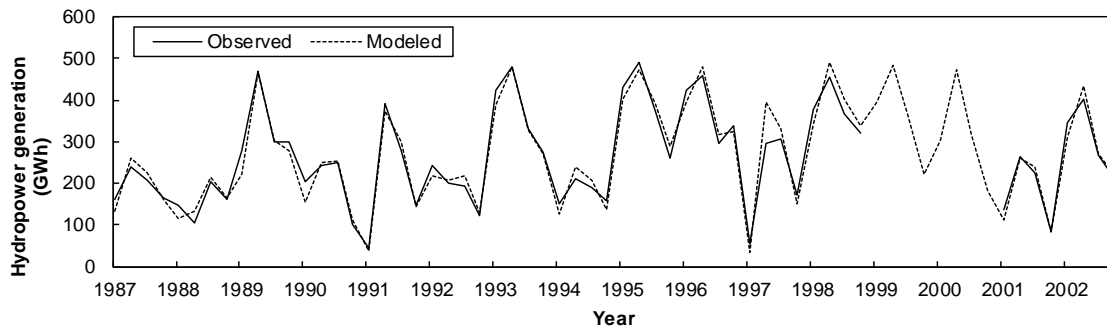
Representation of the Bear River hydropower complex posed a unique challenge, since modeling every hydropower plant in the Bear River watershed was beyond the scope of this work. The Bear River system was modeled as a single composite powerplant with a characteristic head and generating efficiency, supplied 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 generation⁵ 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.).

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).



3.4.3.3 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.

3.4.3.4 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.

3.4.3.5 Spill penalties

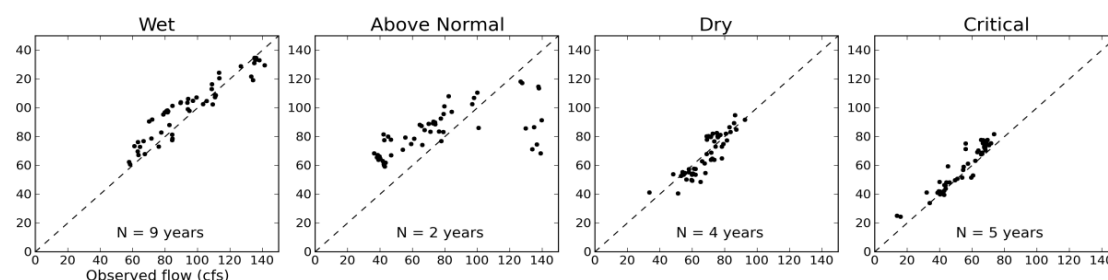
Spill is excess water released directly into the river below a reservoir, unable to be captured for use. Reservoir optimization models generally avoid spill to maximize benefit from hydropower revenue and other beneficial uses. Releases to meet IFRs are not considered spill. Though the model generally 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.

3.4.3.6 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 Rheinheimer (2011). The Sacramento Valley WYI is a supra-regional 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, Rheinheimer [2011]), 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.

3.4.3.7 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.

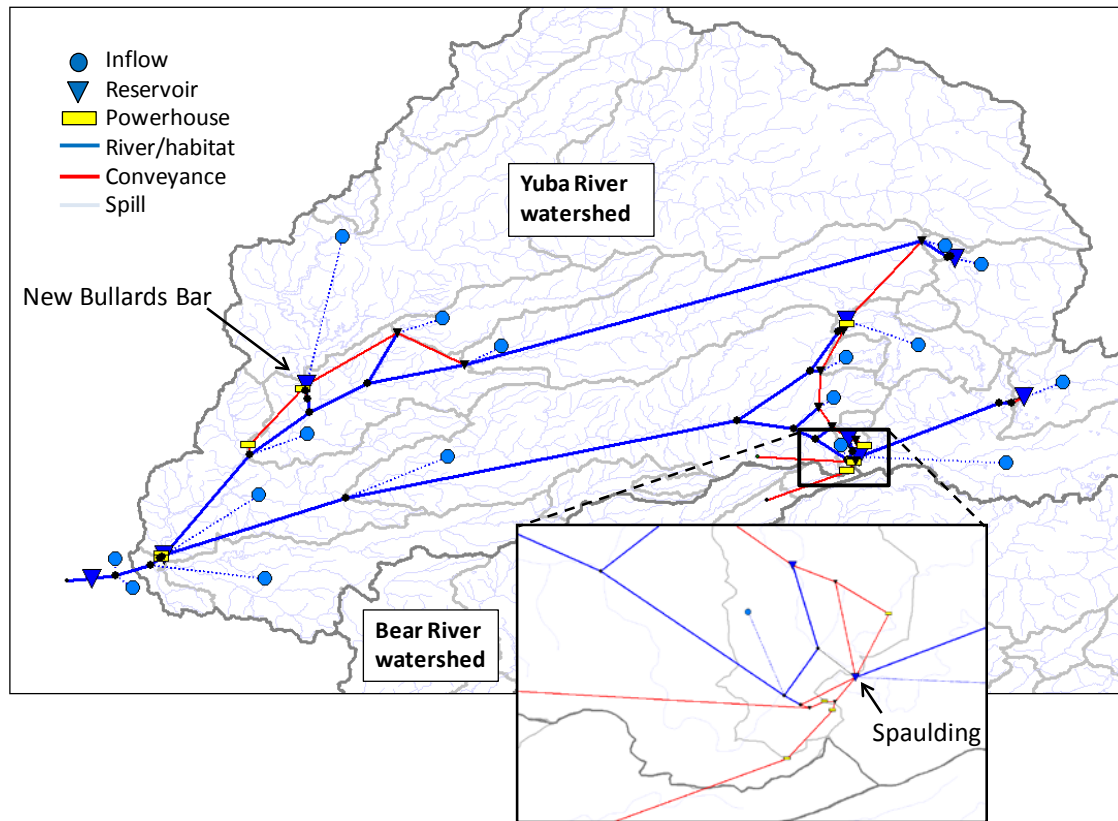
Table 3.7: Upper Yuba River reservoir characteristics.

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

3.4.4 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.



3.5 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.

3.5.1 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.

3.5.1.1 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.

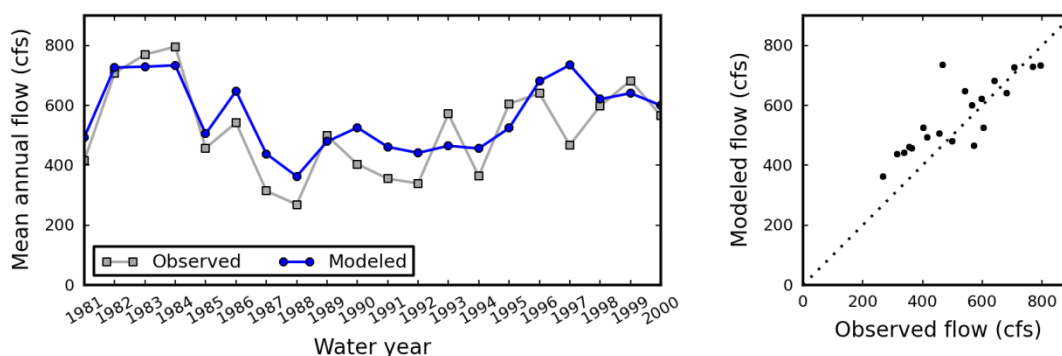
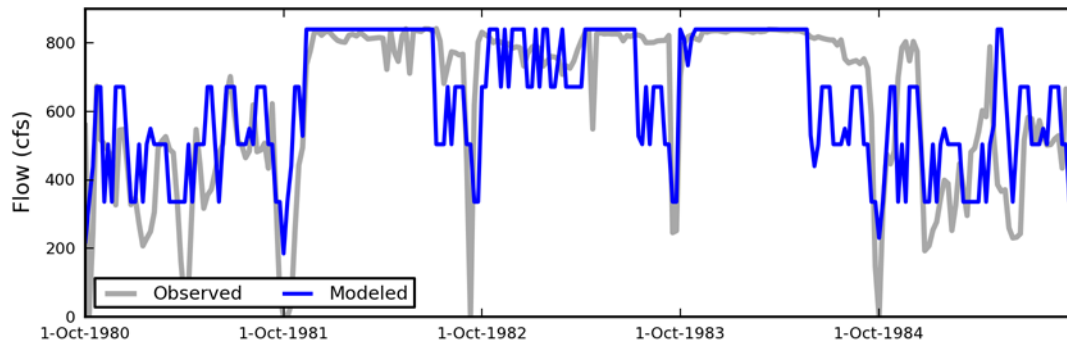


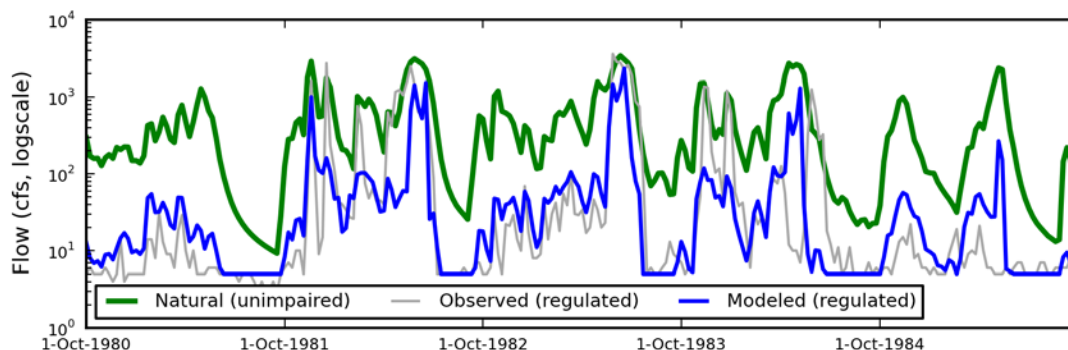
Figure 3.10: Observed and modeled weekly flows in Drum Canal for WY 1981-1985.



3.5.1.2 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.

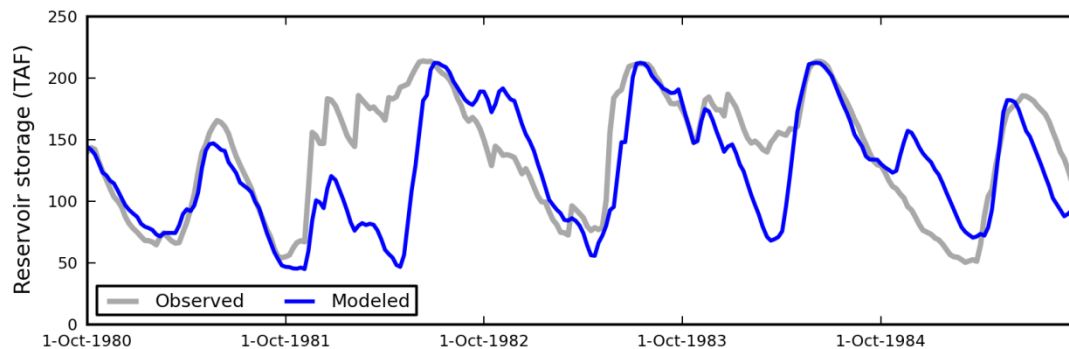
Figure 3.11: Unimpaired and regulated flows in the South Fork Yuba River.



3.5.1.3 Reservoir storage

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.

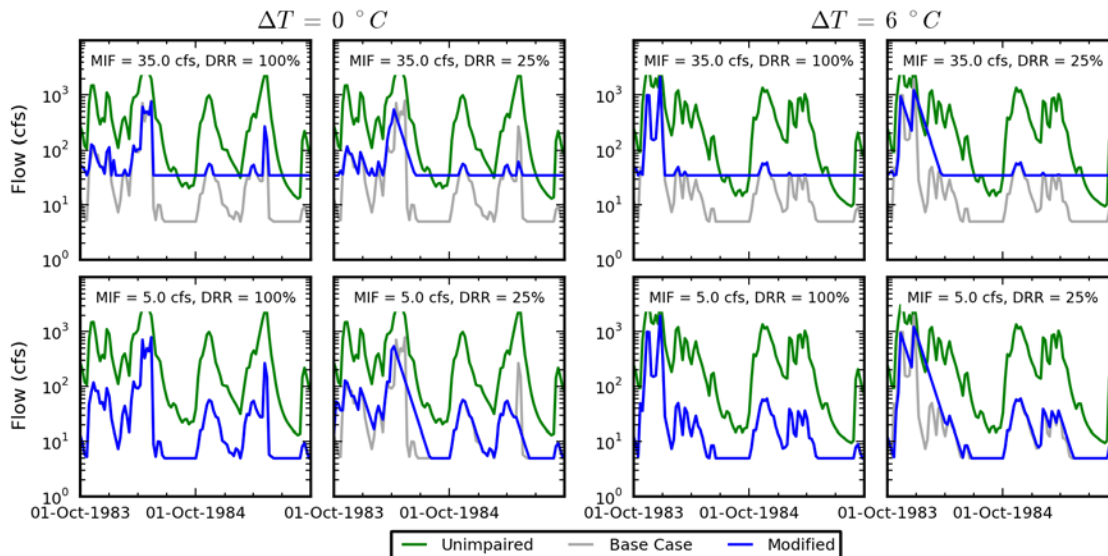


3.5.2 Warming and IFR Effects on Regulated Streamflow

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 3.15). 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 $6^\circ C$ warming, most spill occurs during high, precipitation-driven events during the winter. However, even though winter runoff is greater with $6^\circ C$ 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 $2^\circ C$ warming, yet a slight increase in spill with $6^\circ C$ 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.

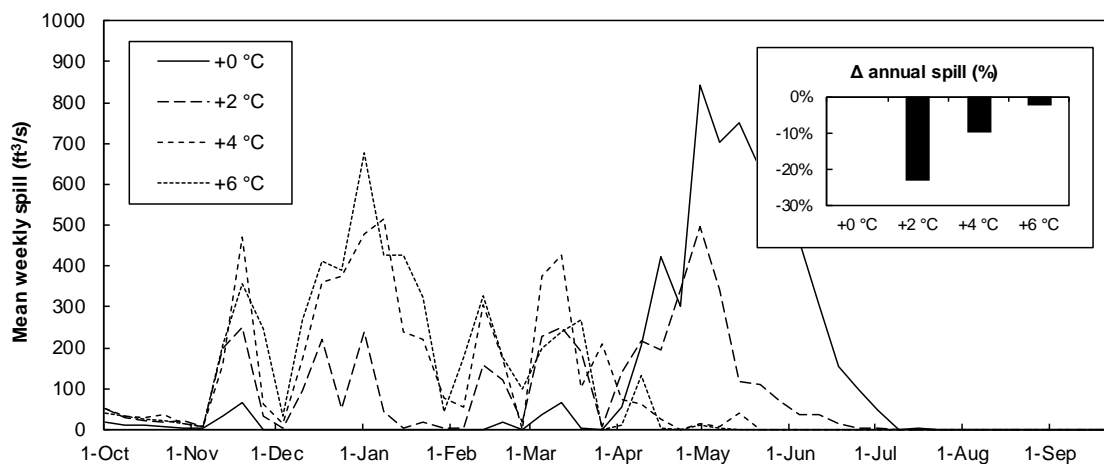
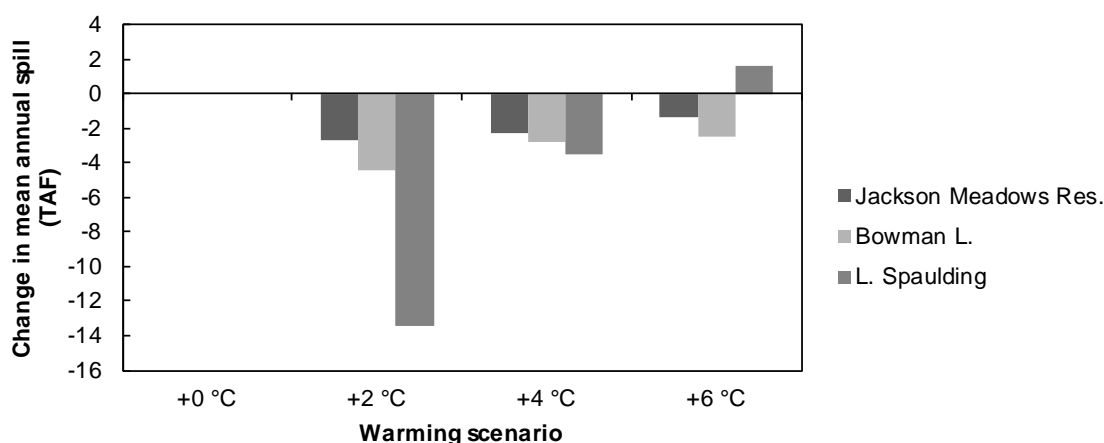


Figure 3.15: Change in mean annual spill from the three main Upper Yuba River reservoirs with warming compared to a historical climate.



3.5.3 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.

3.5.3.1 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 Ch 2., Rheinheimer 2011) 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.

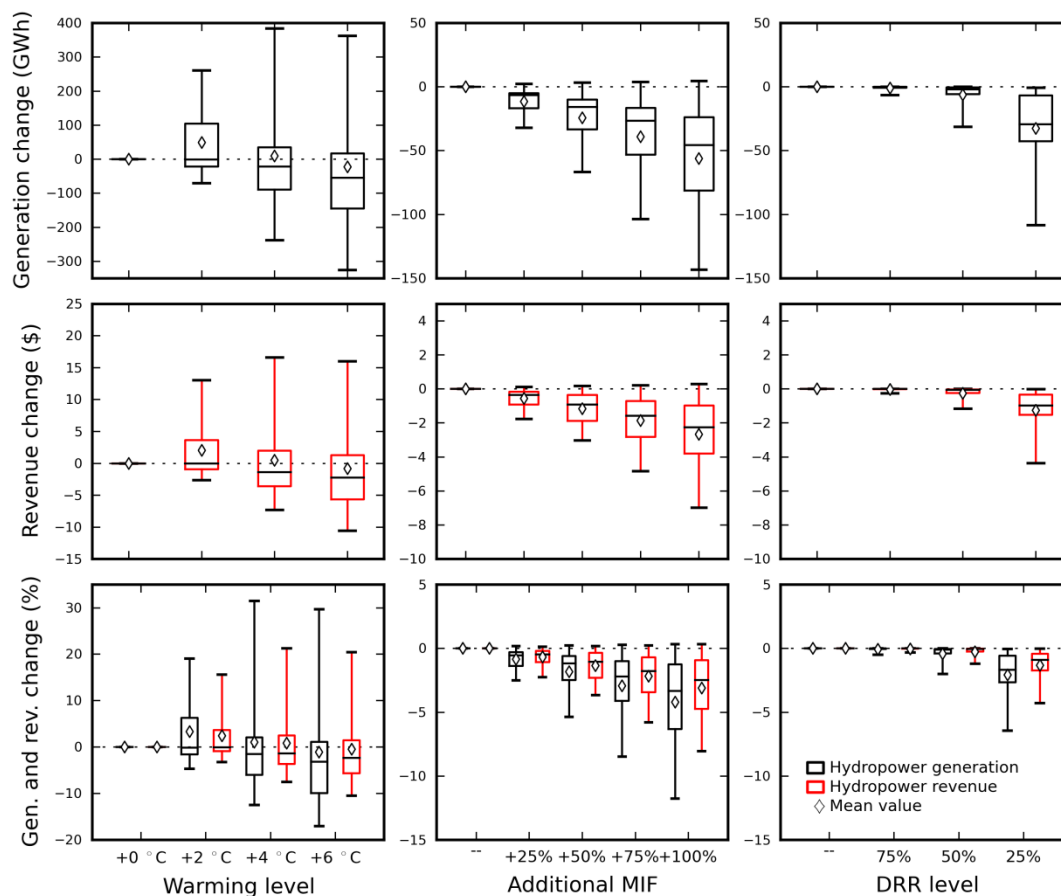
With an increase in additional MIF of 100% (i.e., MIFs at each location are increased to the most ecologically beneficial levels, as identified in Table 3.4), mean annual hydropower generation and revenue decrease by 3.8% (56 GWh/ year) and 3.0% (\$2.7M/ year), respectively. Imposing a maximum DRR to restore the spring snow melt 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.

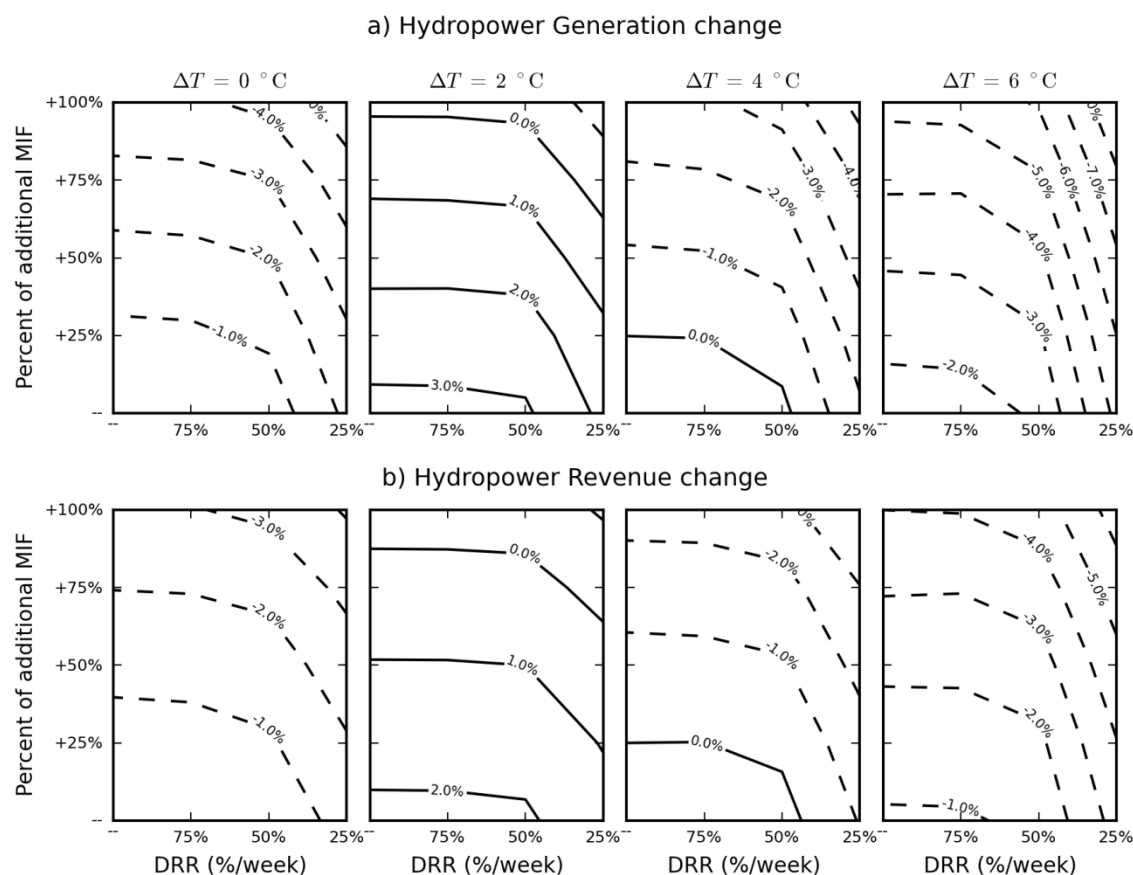
Figure 3.16: Absolute hydropower generation (top) and revenue (middle) and relative changes in generation and revenue from Base Case (bottom) with univariate changes in mean temperature (left), minimum instream flow requirement (center), and maximum down ramp rate requirement (right). Boxplots show annual level quartiles; diamonds show mean annual levels. DRR units are %/week.



3.5.3.2 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.

Figure 3.17: Combined effects of warming, MIF, and DRR on mean annual hydropower generation and revenue.

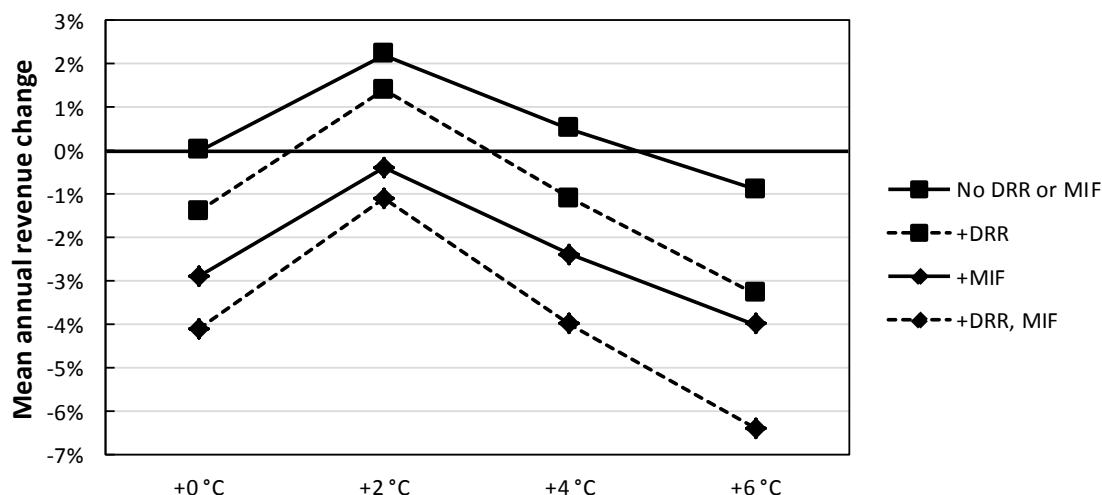


It is useful to explore the extreme points in Figure 3.17, which show changes in generation and revenue with combinations of no or full MIF and DRR levels, with warming. The values of these points are listed in Table 3.8 for generation and revenue and plotted in Figure 3.18 for revenue only. With no 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.

Warming Scenario	Generation change (%)				Revenue change (%)			
	+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.

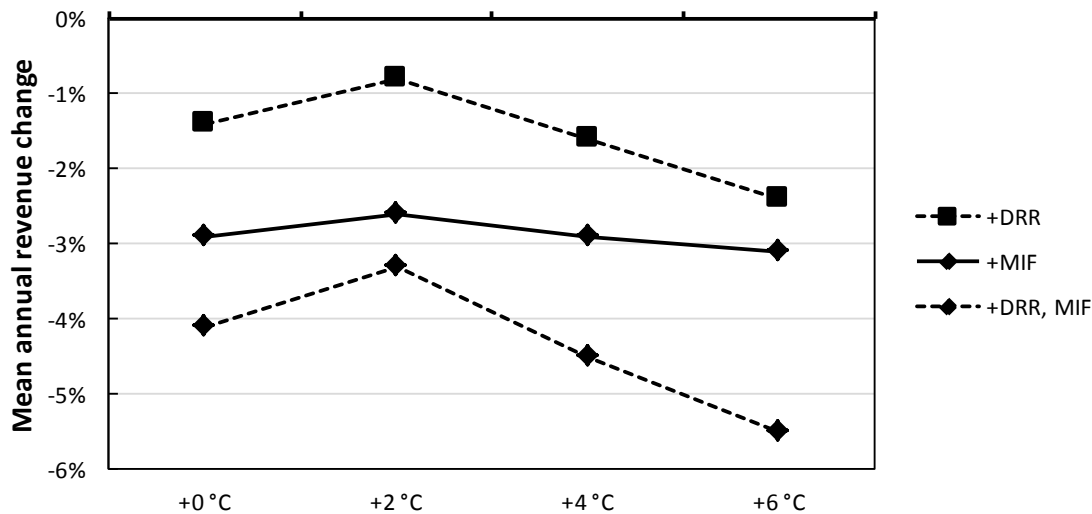


If warming is uncontrollable, from a management perspective, it might also be useful to know how much of the cost—in generation or revenue—can be attributed specifically to the new IFRs. These isolated costs, derived directly from Table 3.8, are listed in Table 3.9 (generation and revenue) and plotted 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.

Warming Scenario	Generation change (%)				Revenue change (%)			
	+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.

Warming Metric	Generation change (GWh/year)				Generation change (%)			
	+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.

Metric \ Warming	Revenue change (\$M/year)				Revenue change (%)			
	+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

3.6 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.

3.7 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.

3.7 References

- Acreman, M., and Dunbar, M. J. (2004). "Defining environmental river flow requirements – a review." *Hydrology and Earth Systems Sciences*, 8(5), 861-876.
- Arthington, A. H., and Zalucki, J. M. (1998). "Comparative evaluation of environmental flow assessment techniques: Review of methods." Land and Water Resources Research and Development Corporation, Canberra, Australia.
- Baron, J. S., Poff, N. L., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston, N. G., Jackson, R. B., Johnston, C. A., Richter, B. D., and Steinman, A. D. (2002). "Meeting ecological and societal needs for freshwater." *Ecological Applications*, 12(5), 1247-1260.
- Boulton, A. J., Sheldon, F., Thoms, M. C., and Stanley, E. H. (2000). "Problems and constraints in managing rivers with variable flow regimes." Global perspectives on river conservation: Science, policy and practice, P. J. Boon, B. R. Davies, and G. E. Petts, eds., Wiley, New York, 415-430.
- Bovee, K. D. (1982). "A guide to stream habitat analysis using the IFIM." *FWS/OBS-82/26*, US Fish and Wildlife Service, Fort Collins, Colorado.
- Bovee, K. D., Lamb, B. L., Bartholow, J. M., Stainaker, C. B., Taylor, J., and Henriksen, J. (1998). "Stream habitat analysis using the instream flow incremental methodology." U.S. Geological Survey-BRD, Fort Collins, CO.
- Brown, C. A., and King, J. M. (2003). "Environmental flows: Concepts and methods [technical note C.1]." 26320, The World Bank, Washington, DC.
- Bunn, S. E. "Recent approaches to assessing and providing environmental flows: Concluding comments." *Water for the Environment: Recent Approaches to Assessing and Providing Environmental Flows*, Brisbane, Australia.
- Bunn, S. E., and Arthington, A. H. (2002). "Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity." *Environmental Management*, 30(4), 492-507.
- Buzinde, C. N., Manuel-Navarrete, D., Kerstetter, D., and Redclift, M. (2010). "Representations and adaptation to climate change." *Annals of Tourism Research*, 37(3), 581-603.
- California ISO. (2010). "Open access same-time information system (oasis) energy price data."
- Cardwell, H., Jager, H. I., and Sale, M. J. (1996). "Designing instream flows to satisfy fish and human water needs." *Journal of Water Resources Planning and Management*, 122, 356-363.
- Carron, J. C. (2000). "Simulation and optimization of unsteady flow and water temperature in reservoir regulated rivers," University of Colorado, Boulder, Colorado.
- Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., and van den Belt, M. (1997). "The value of the world's ecosystem services and natural capital." *Nature*, 387(6630), 253-260.
- Creager, W. P., and Justin, J. D. (1927). *Hydroelectric handbook*, Wiley, New York.
- Daubert, J. T., and Young, R. A. (1981). "Recreational demands for maintaining instream flows: A contingent valuation approach." *American Journal of Agricultural Economics*, 63(4), 666-676.
- Dettinger, M. D. (2005). "From climate-change spaghetti to climate-change distributions for 21st century California." *San Francisco Estuary & Watershed Science*, 3(1), Article 4.
- Dettinger, M. D., Cayan, D. R., Meyer, M., and Jeton, A. E. (2004). "Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099." *Climatic Change*, 62(1-3), 283-317.
- Dynesius, M., and Nilsson, C. (1994). "Fragmentation and flow regulation of river systems in the northern third of the world." *Science*, 266, 753-762.
- Epke, G. (2011). "Characterizing the spring snowmelt recession limb in rivers of California's west slope Sierra Nevada," M.S. Thesis, University of California, Davis.
- Foxton, T. J., Butler, D., Dawes, J. K., Hutchinson, D., Leach, M. A., Pearson, P. J. G., and Rose, D. (2000). "An assessment of water demand management options from a systems approach." *Water and Environment Journal*, 14(3), 171-178.
- Graf, W. L. (1999). "Dam nation: A geographic census of American dams and their large-scale hydrologic impacts." *Water Resources Research*, 35(4), 1305-1311.
- Graf, W. L. (2006). "Downstream hydrologic and geomorphic effects of large dams on American rivers." *Geomorphology*, 79(3-4), 336-360.

- Grygier, J. C., and Stedinger, J. R. (1985). "Algorithms for optimizing hydropower system operation." *Water Resources Research*, 21(1), 1-10.
- Harou, J. J., Pinte, D., Tilmant, A., Rosenberg, D. E., Rheinheimer, D. E., Hansen, K., Reed, P. M., Reynaud, A., Medellín-Azuara, J., Pulido-Velazquez, M., Matrosov, E., Padula, S., and Zhu, T. (2010). "An open-source model platform for water management that links models to a generic user-interface and data-manager." International Environmental Modelling and Software Society (iEMSS) 2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting, D. A. Swayne, W. Yang, A. A. Voinov, A. Rizzoli, and T. Filatova, eds., Ottawa.
- Harpman, D. A. (1999). "Assessing the short-run economic cost of environmental constraints on hydropower operations at Glen Canyon Dam." *Land Economics*, 75(3), 390-401.
- Hayhoe, K., Cayan, D., Field, C. B., Frumhoff, P. C., Maurer, E. P., Miller, N. L., Moser, S. C., Schneider, S. H., Cahill, K. N., Cleland, E. E., Dale, L., Drapek, R., Hanemann, R. M., Kalkstein, L. S., Lenihan, J., Lunch, C. K., Neilson, R. P., Sheridan, S. C., and Verville, J. H. (2004). "Emissions pathways, climate change, and impacts on California." *Proceedings of the National Academy of Sciences of the United States of America*, 101(34), 12422-12427.
- Homa, E. S., Vogel, R. M., Smith, M. P., Apse, C. D., Huber-Lee, A., and Sieber, J. (2005). "An optimization approach for balancing human and ecological flow needs." EWRI 2005 World Water and Environmental Resources Congress, American Society of Civil Engineers, Anchorage, Alaska.
- Jager, H. I., and Smith, B. T. (2008). "Sustainable reservoir operation: Can we generate hydropower and preserve ecosystem values?" *River Research and Applications*, 24(3), 340-352.
- Jewitt, G. (2001). "Can integrated water resources management sustain the provision of ecosystem goods and services?" 2nd WARFSA/ WaterNet Symposium: Integrated Water Resources Management: Theory, Practice, Cases, Cape Town.
- Jowett, I. G. (1997). "Instream flow methods: A comparison of approaches." *Regulated Rivers: Research & Management*, 13(2), 115-127.
- King, J., Brown, C., and Sabat, H. (2003). "A scenario-based holistic approach to environmental flow assessments for rivers." *River Research and Applications*, 19(5-6), 619-639.
- King, J. M., Tharme, R. E., and Villiers, M. S. D. (2000). "Environmental flow assessments for rivers: Manual for the building block methodology." *WRC Report No: TT 131/00*, Water Research Commission, Pretoria, South Africa.
- Kosnik, L. (2008). "The potential of water power in the fight against global warming in the US." *Energy Policy*, 36(9), 3252-3265.
- Kotchen, M. J., Moore, M. R., Lupi, F., and Rutherford, E. S. (2006). "Environmental constraints on hydropower: An *ex post* benefit-cost analysis of dam relicensing in michigan." *Land Economics*, 83(3), 384-403.
- Labadie, J. W. (2004). "Optimal operation of multireservoir systems: State-of-the-art review." *Journal of Water Resources Planning and Management*, 130(2), 93-111.
- Lankford, B. A. (2003). "Environmental water requirements: A demand management perspective." *Water and Environment Journal*, 17(1), 19-22.
- Ligare, S. T., Viers, J. H., Null, S. E., Rheinheimer, D. E., and Mount, J. F. (2011). "Non-uniform changes to whitewater recreation in California's Sierra Nevada from regional climate warming." *River Research and Applications*.
- Loucks, D. P., and Gladwell, J. S., eds. (1999). "Sustainability criteria for water resource systems." International Hydrology Series, Cambridge University Press, 139pp.
- Lund, J. R. (2000). "Derived power production and energy drawdown rules for reservoirs." *Journal of Water Resources Planning and Management*, 126(2).
- Lytle, D. A., and Poff, N. L. (2004). "Adaptation to natural flow regimes." *Trends in Ecology & Evolution*, 19(2), 94-100.
- MacDonnell, L. J. (2009). "Return to the river: Environmental flow policy in the United States and Canada." *Journal of the American Water Resources Association*, 45(5), 1087-1099.
- Madani, K., and Lund, J. R. (2009). "Modeling California's high-elevation hydropower systems in energy units." *Water Resources Research*, 45, W09413.

- Madani, K., and Lund, J. R. (2010). "Estimated impacts of climate warming on California's high-elevation hydropower." *Climatic Change*, 102(3-4), 521-538.
- Mehta, V. K., Rheinheimer, D. E., Yates, D., Purkey, D. R., Viers, J. H., Young, C. A., and Mount, J. F. (2011). "Potential impacts on hydrology and hydropower under climate warming of the Sierra Nevada." *Journal of Water and Climate Change*, 2(1), 29-43.
- Olivares, M. A. (2008). "Optimal hydropower reservoir operation with environmental requirements," Dissertation, University of California, Davis.
- Pérez-Díaz, J. I., and Wilhelmi, J. R. (2010). "Assessment of the economic impact of environmental constraints on short-term hydropower plant operation." *Energy Policy*, 38(12), 7960-7970.
- Poff, N. L. (2009). "Managing for variability to sustain freshwater ecosystems." *Journal of Water Resources Planning and Management*, 135(1), 1-4.
- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E., and Stromberg, J. C. (1997). "The natural flow regime." *BioScience*, 47(11), 769-784.
- Poff, N. L., Bledsoe, B. P., and Cuhaciyan, C. O. (2006). "Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems." *Geomorphology*, 79(3-4), 264-285.
- Poff, N. L., and Hart, D. D. (2002). "How dams vary and why it matters for the emerging science of dam removal." *BioScience*, 52(8), 659-668.
- Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E., and Warner, A. (2010). "The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards." *Freshwater Biology*, 55, 147-170.
- Postel, S., and Carpenter, S. (1997). "Freshwater ecosystem services." *Nature's services: Societal dependence on natural ecosystems*, G. C. Daily, ed., Island Press, Washington, D.C.
- REN21. (2011). "Renewables 2011 global status report." REN21 Secretariat, Paris.
- Renöfält, B. M., Jansson, R., and Nilsson, C. (2010). "Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems." *Freshwater Biology*, 55(1), 49-67.
- Rheinheimer, D. E. (2011). "Modeling multi-reservoir hydropower systems in the Sierra Nevada with environmental requirements and climate warming." Dissertation for Department of Civil and Environmental Engineering, University of California at Davis (United States), 143 pp.
- Richter, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P. (1996). "A method for assessing hydrological alteration within ecosystems." *Conservation Biology*, 10(4), 1163-1174.
- Richter, B. D., Baumgartner, J. V., Wigington, R., and Braun, D. P. (1997). "How much water does a river need?" *Freshwater Biology*, 37(1), 231-249.
- Richter, B. D., Mathews, R., Harrison, D. L., and Wigington, R. (2003). "Ecologically sustainable water management: Managing river flows for ecological integrity." *Ecological Applications*, 13(1), 206-224.
- Richter, B. D., and Thomas, G. A. (2007). "Restoring environmental flows by modifying dam operations." *Ecology and Society*, 12(1).
- Rosenberg, D. M., Berkes, F., Bodaly, R. A., Hecky, R. E., Kelly, C. A., and Rudd, J. W. M. (1997). "Large-scale impacts of hydroelectric development." *Environmental Reviews*, 5(1), 27-54.
- Rosenberg, D. M., McCully, P., and Pringle, C. M. (2000). "Global-scale environmental effects of hydrological alterations: Introduction." *BioScience*, 50(9), 746-751.
- Sale, M. J., Brill Jr., E. D., and Herricks, E. E. (1982). "An approach to optimizing reservoir operation for downstream aquatic resources." *Water Resources Research*, 18(4), 705-712.
- Shiau, J.-T., and Wu, F.-C. (2004). "Feasible diversion and instream flow release using range of variability approach." *Journal of Water Resources Planning and Management*, 130(5), 395-404.
- Stalnaker, C. B., Lamb, B. L., Henriksen, J., Bovee, K., and Bartholow, J. (1995). "The Instream Flow Incremental Methodology: A primer for IFIM." U.S. Geological Survey, Washington, DC.
- Stewart, I. T., Cayan, D. R., and Dettinger, M. D. (2005). "Changes toward earlier streamflow timing across western North America." *Journal of Climate*, 18(8), 1136-1155.

- Tanaka, S. K., Zhu, T. J., Lund, J. R., Howitt, R. E., Jenkins, M. W., Pulido, M. A., Tauber, M., Ritzema, R. S., and Ferreira, I. C. (2006). "Climate warming and water management adaptation for California." *Climate Change*, 76(3-4), 361-387.
- Tennant, D. L. (1976). "Instream flow regimens for fish, wildlife, recreation and related environmental resources." *Fisheries*, 1, 6-10.
- Tharme, R. E. (2003). "A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers." *River Research and Applications*, 19(5-6), 397-441.
- UC Berkeley. (2010). "Electricity market data." URL: <http://www.ucei.berkeley.edu/datamine/datamine.htm>, accessed Oct. 3, 2010.
- Vicuna, S., Dracup, J. A., and Dale, L. (2009). "Climate change impacts on the operation of two high-elevation hydropower systems in California." California Climate Change Center.
- Vicuna, S., Dracup, J. A., Lund, J. R., Dale, L. L., and Maurer, E. P. (2010). "Basin-scale water system operations with uncertain future climate conditions: Methodology and case studies." *Water Resources Research*, 46(W04505).
- Vicuna, S., Leonardson, R., Hanemann, M. W., Dale, L. L., and Dracup, J. A. (2008). "Climate change impacts on high elevation hydropower generation in California's Sierra Nevada: A case study in the upper american river." *Climatic Change*, 87, 123-137.
- Vicuna, S., Maurer, E. P., Joyce, B., Dracup, J. A., and Purkey, D. (2007). "The sensitivity of California water resources to climate change scenarios." *Journal of the American Water Resources Association*, 43(2).
- Viers, J. H. (2011). "Hydropower relicensing and climate change." *Journal of the American Water Resources Association*.
- Viers, J. H., and Rheinheimer, D. E. (2011). "Freshwater conservation options for a changing climate in California's Sierra Nevada." *Marine & Freshwater Research*, 62, 266-278.
- Watts, R. J., Richter, B. D., Opperman, J. J., and Bowmer, K. H. (2011). "Dam reoperation in an era of climate change." *Marine & Freshwater Research*, 62(3), 321-327.
- Yarnell, S. M., Viers, J. H., and Mount, J. F. (2010). "Ecology and management of the spring snowmelt recession limb." *BioScience*.
- Yates, D., Sieber, J., Purkey, D., and Huber-Lee, A. (2005). "WEAP21 – a demand-, priority-, and preference-driven water planning model: Part 1, model characteristics." *Water International*, 30(4), 487-500.
- Yeh, W. W. G. (1985). "Reservoir management and operations models: A state-of-the-art review." *Water Resources Research*, 21(12), 1797-1818.
- Young, C. A., Escobar-Arias, M. I., Fernandes, M., Joyce, B., Kiparsky, M., Mount, J. F., Mehta, V. K., Purkey, D., Viers, J. H., and Yates, D. (2009). "Modeling the hydrology of climate change in California's Sierra Nevada for subwatershed scale adaptation." *Journal of the American Water Resources Association*, 45(6), 1409-1423.
- Zhu, T., Jenkins, M. W., and Lund, J. R. (2005). "Estimated impacts of climate warming on California water availability under twelve future climate scenarios." *Journal of the American Water Resources Association*, 41(5), 1027-1038.