ECOLOGICAL EVALUATION OF HYDROPOWER PULSED RELEASES ON CALIFORNIA STREAM SYSTEMS

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Preface

The California Energy Commission’s Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

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For more information on the PIER Program, please visit the Energy Commission’s website at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.
# Table of Contents

Abstract........................................................................................................................................vii  

Executive Summary.........................................................................................................................1  

1.0 Introduction: The Pulsed Flow Program ...............................................................................11  

1.1. Background..........................................................................................................................11  

1.2. Purpose of the Program ........................................................................................................11  

2.0 Research Program Management.........................................................................................13  

2.1. Summary of White Paper and Research Project Reports ...............................................14  

2.1.1. Hydropower-related pulsed flow impacts on stream fishes, amphibians and macroinvertebrates (Young et al. 2007) ................................................................. 14  

2.1.2. Evaluating the impacts of manufactured recreation streamflows on the macroinvertebrate community of a regulated river (GANDA 2006a) .................. 18  

2.1.3. Reproductive timing of freshwater mussel and potential impacts of pulsed flows on reproductive success (Spring River 2007) ........................................... 20  

2.1.4. Identifying climatic and water flow triggers associated with breeding activities of a foothill yellow-legged frog (Rana boylii) population on the North Fork Feather River, California (GANDA 2006b) ...................................................... 23  

2.1.5. Pulse flow guidelines: Managing the annual snowmelt hydrograph and winter floods in regulated boulder-bedrock Sierra Nevada rivers (McBain and Trush, Inc. 2007) .................................................................................................................. 26  

2.1.6. Establishing baseline information for assessment of flow management alternatives for mitigating effects of myxozoan pathogens in the Klamath River (Bartholomew and Bjork 2006) ................................................................. 29  

2.1.7. Research needs assessment for hydropower relicensing processes in California: Developing tools for more efficient and effective resource management (Cox 2007) .................................................................................................................. 32  

2.1.8. California native fishes and streamflows: A literature review (Yoshiyama and Moyle 2006) ..................................................................................................................... 33  

2.1.9. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River (Year One; Klimley et al. 2005) ........................................................................................................... 38  

2.1.10. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River... 44  

3.0 Benefits to California ..............................................................................................................58  

4.0 References ..............................................................................................................................60
Abstract

In order to assess short- and long-term ecological impacts of pulsed flow releases on California stream systems regulated for hydropower production, the Public Interest Energy Research Program of the California Energy Commission and the Division of Water Rights of the State Water Resources Control Board established the Pulsed Flow Program through the Center for Aquatic Biology and Aquaculture of the University of California, Davis. The Program objective was to specifically look at the ecological effects of manufactured or augmented flows from hydropower facilities on aquatic habitats and biotic communities within California streams and rivers. A whitepaper and nine research projects resulted from this Program.

Results from this program provided background information, potential concerns, and priority research needs for California research studies to address the ecological impacts of hydropower pulsed flow on fishes, amphibians and macroinvertebrates in California streams and rivers. Research projects also provided results and recommendations that will assist California’s managers of hydroelectric facilities, industry regulators and policy makers. Improvements in managing regulated rivers will ideally result in perpetuating and enhancing the quality of California’s natural resources and heritage while also improving opportunities for the people of California to enjoy and benefit from them.

Keywords: pulsed flow releases, stream fishes, amphibians, benthic macroinvertebrates, flow manipulation, mussels, myxozoan pathogens, snowmelt hydrographs
Executive Summary

Introduction

Hydroelectricity is a critical element of the California generation system because it provides peaking reserve capacity, spinning reserve capacity, load following capacity, transmission support, and low production costs as well as providing 15 percent of electricity needs over the last 20 years. However, there is substantial evidence that both hydroelectric and water storage and flood control dams have negatively impacted fish, amphibians, macroinvertebrates, and other aquatic biota. Apart from the well-documented long-term effects of dams and reservoirs on downstream environments and their role in fragmentation of riverine networks, concerns about direct impacts of pulsed flow releases have been raised.

In order to assess short- and long-term ecological impacts of pulsed flow releases on California stream systems regulated by hydropower production, the Public Interest Energy Research Program of the California Energy Commission established the Pulsed Flow Program through the Center for Aquatic Biology and Aquaculture of the University of California, Davis. The Program objective was to specifically look at the ecological effects of manufactured flows from hydropower facilities on aquatic habitats and biotic communities within California streams and rivers. Manufactured flows refer to discharges from hydropower facilities to meet load following, sediment and vegetation management and recreational requirements.

A program management team consisting of representatives from the Energy Commission, the State Water Resources Control Board and the Center for Aquatic Biology and Aquaculture was established for efficient and effective management of the Pulsed Flow Program. A technical advisory committee, consisting of representatives from academia, state and federal agencies, utilities, non-governmental organizations and consultants, was established to assist in identifying research priorities for the Program. The Technical Advisory Committee identified as research priorities the assessment of the potential effects of the magnitude and timing (season and time of day) of the above described pulsed flows on fishes, amphibians, and macroinvertebrates. The advisory committee identified geomorphic and habitat impacts as another important area for study in relation to magnitude and timing of pulsed flow discharges. Requests for proposals were announced and after proposal evaluations and selections, a total of nine projects were funded through the Program.

A white paper was prepared to provide background material for the technical advisory committee. The white paper included a review of peer reviewed literature and identified potential research gaps and needs regarding the effects of hydropower pulsed flow releases on stream fishes, amphibians and macroinvertebrates.

Summaries of white paper and research projects
1. **Hydropower-related pulsed flow impacts on stream fishes, amphibians and macroinvertebrates**

Although pulsed flows are intended to produce various benefits, the effects of the resulting fluctuations in water flows on aquatic habitats and biotic communities are not fully understood. The general objective of this paper is to provide background information on the potential and actual effects of pulsed flows on fishes, amphibians and macroinvertebrates. Additionally, this paper is intended to lay out issues and potential concerns related to pulsed flows on these key organisms and to identify priority research needs that would add to the existing body of knowledge.

Under certain circumstances, depending on timing, frequency, duration, and magnitude, pulsed flows can have adverse and/or beneficial short and long-term effects on resident or migratory stream fishes, amphibians, and macroinvertebrates. Although numerous studies have been conducted on specific types of pulsed flows, there remain critical research gaps in the knowledge needed to better understand the impacts of pulsed flows on California stream fishes, amphibians, and macroinvertebrates. Major gaps include effects of different magnitude, ramping rates, and timing (season and time of day) of pulsed flows on the abundance and distribution of stream fishes, amphibians and macroinvertebrates at different life stages. It is critical to investigate the relative cumulative effect of recreational pulsed flows and operational pulsed flows on these key organisms. This report enumerates several approaches applicable to all aspects of research on pulsed flow effects.

2. **Evaluating the impacts of manufactured recreation streamflows on the macroinvertebrate community of a regulated river**

Benthic macroinvertebrate data from reaches of the North Fork Feather River, affected and unaffected by monthly pulsed recreation streamflow releases during 2004, were compared using a before-after control-impact design. Macroinvertebrate populations in the treated and control reaches were sampled using representative artificial substrates (rock basket samplers) and standard kick-sampling techniques. Macroinvertebrate data were described using the recently developed hydropower multi-metric index (Hydro-MMI), which was designed to be sensitive to the effects of hydropower operations. Analysis of variance was used to test for a pulsed-flow effect. The control-to-treated difference in Hydro-MMI was significantly different from pre-flow to post-flow. Among basket-sample data, seasonal trends between these two reaches were generally similar; however, kick-sample data suggest a seasonal pattern of increasing richness and abundance in the control reach that was not observed in the treated reach.
Comparisons of the basket- and kick-sampling techniques demonstrated that basket samplers selected for a subset of the benthic community dominated by filter-feeding organisms such as net-spinning caddisflies. These organisms appeared able to quickly colonize and capitalize on free interstitial spaces provided in basket samplers. Kick samples provided a better representation of the overall benthic community. Differences in the composition of the two sample types suggest that seasonal trends among basket-sample data primarily followed natural seasonal patterns for the filter-feeder-dominated community that developed in basket samplers, which may be less sensitive to flow-related changes than the larger benthic community.

3. Reproductive timing of freshwater mussel and potential impacts of pulsed flows on reproductive success

Reproductive timing of native freshwater mussel species in the Pit River drainage in northeastern California was investigated from April 2004 through early May 2006 to assess potential impacts of pulsed flow releases from hydroelectric facilities on mussel reproduction. Because these species are sedentary, sensitive to environmental changes, and long-lived, they can be an excellent biological indicator of water quality. The California floater (Anodonta californiensis), winged floater, A. nutalliana (wahlamatensis), western ridged muscle (Gonidea angulata), and western pearlshell (Margaritifera falcata) were studied, although Anodonta were not identified to species because the taxonomy is unresolved.

Anodonta were observed to be gravid, which means distended with eggs, throughout most of the field seasons except from late July to mid October, and their glochidia, their larval stage, were observed on fish during all months except September and October. Gonidea angulata were gravid from late March to mid July, and their glochidia were observed on fish from late March to late July/early August. Reproductive timing in these species was similar (within 2 weeks) in unregulated and regulated river reaches with different flow regimes. Gravid western pearlshell (Margaritifera falcate) were found in one Pit River reach in April and June 2004 and April 2005, in another reach in June and July 2005, and in a spring-fed tributary in July 2005.

In the Pit River, seasonal pulsed flows for channel maintenance/recreation should be scheduled during or after September to minimize interference with mussel reproduction and settlement of newly excysted juvenile mussels.

4. Identifying climatic and water flow triggers associated with breeding activities of a foothill yellow-legged frog (Rana boylii) population on the North Fork Feather River, California

The movements and breeding activities of a population of foothill yellow-legged frogs (Rana boylii) were monitored to determine their relationship to climatic variables in six tributaries and their associated breeding sites on the Poe and Cresta reaches of the North Fork Feather River (NFFR) during spring in 2004 and
2005 by visual surveys and radio telemetry. The foothill yellow-legged frog is one of a few California amphibians whose complete life cycle is associated with fluvial environments. Over the last half century, the foothill yellow-legged frog (R. boylii) has declined dramatically, especially in Southern California and the southern Sierra Nevada mountains. Dams and reservoirs have been cited as likely factors in this decline because they drastically alter the disturbance regime and sediment budget of rivers in which native species have evolved, resulting in permanent alteration to in-stream habitats. Continued declines of this species may lead to the frog being listed as endangered or threatened. The ensuing impact on R. boylii survival has been a focus of study over the last decade, but many knowledge gaps remain. Perhaps one of the largest gaps is in understanding the factors influencing frog breeding activities.

Male frogs left tributaries earlier than females and stayed longer at breeding sites. Breeding areas were located along the mainstem river adjacent to the tributaries, and tributaries acted as refugia for most of the year. While there was much variation in actual timing, day length (i.e., time of year) was the only parameter statistically correlated with initial movements in females. Females moved initially in late April/early May, and mean daily tributary temperatures were greater than or equal to 10°C when females left home ranges on tributaries to eventually breed on the North Fork Feather River. Oviposition (egg laying) dates were clustered in periods when mean mainstem temperatures were between 10°C and 16°C and mainstem flow was between base flow and less than 55 percent above base flow. A small percentage of frogs laid eggs at somewhat higher flows, but only during a declining hydrograph, (chart). Length of stay by females at river breeding sites was extended by high flows and, on the Cresta Reach, relatively low numbers of males. Late season rains and associated high flows delayed breeding in 2005 when compared to 2004, especially in the Poe Reach, the warmer of the two reaches where breeding typically occurred first. Based on the model of environmental parameters affecting breeding activity, hydroelectric power managers are provided with information to enhance foothill yellow-legged frog breeding success (e.g., movement dates, temperature and flow preferences) by preventing sharp fluctuations in flow during the breeding season from April through June.

5. Pulse flow guidelines: Managing the annual snowmelt hydrograph and winter floods in regulated boulder-bedrock Sierra Nevada rivers

This Project investigates the ecological role of the annual snowmelt hydrograph in the Clavey River, a tributary to the Tuolumne River, and proposes a methodology for identifying the timing and magnitude of pulse flows in Sierra Nevada boulder-bedrock rivers. The methodology is largely field-based, relying on expert habitat mapping for quantifying streamflow – habitat relationships, and on photographic comparisons for assessing channelbed mobility thresholds.
Three examples of quantitative pulse flow guidelines were formulated to demonstrate the method’s feasibility. The Project found that: (1) Sierra Nevada boulder-bedrock rivers have at least three nested levels of depositional features that each serve important ecological functions, (2) Annual snowmelt peak flows in the Clavey River were significantly less important than winter floods in performing most geomorphic work, (3) Inter-annual variation of winter peak floods is required to maintain nested depositional features, (4) Flows represented by variable annual snowmelt hydrographs, particularly their fast and slow recession limbs, are necessary to sustain dynamic woody riparian vegetation and to provide good fish, amphibian, and benthic macroinvertebrate habitats, and (5) Inter-annual shifts in the location of thermal biological thresholds during and following the slow snowmelt recession limb (the trombone effect) might be an important mechanism for sustaining aquatic species diversity.

6. Establishing baseline information for assessment of flow management alternatives for mitigating effects of myxozoan pathogens in the Klamath River

Ceratomyxa shasta is a myxozoan parasite identified as a significant contributor to salmon mortality in the Klamath River and elsewhere. This parasite, which infects all salmon species, including Chinook salmon (Oncorhynchus tshawytscha) and Steelhead trout (Oncorhynchus mykiss), has a complex life cycle with life stages developing in both a fish and a freshwater polychaete (segmented worm) host, Manayunkia speciosa. The ecological requirements of this polychaete influence the severity of infection in fish. An understanding of what contributes to high densities and infection of the polychaete host may provide management opportunities for hydropower operators through water releases to reduce the parasite effects. This study investigated the effects of temperature and de-watering on the survival of the polychaete in its two primary substrates, Cladophora sp. and a mixture of sand and silt. An inverse relationship between temperature and polychaete survival was observed. A small percentage of polychaetes survived 24 h de-watering in both substrates. A laboratory based flow experiment showed that a higher water velocity (0.05 m/s) supported greater polychaete densities. However, experimentally induced polychaete infection prevalence was greater at the slower water velocity (0.01 m/s). Rainbow trout held in the slower flow treatments had a shorter mean day to death as a result of their infections than those held at the high flow. This difference indicates a higher infection severity, possibly a result of a higher parasite dose. Thus, at least under slow flow conditions, increased water velocities associated with pulsed flows may decrease C. shasta infection severity in the fish and infection prevalence in the polychaete host. Extrapolation of these results to explain what would occur under natural flow conditions will require collection of data from field locations.

7. Research needs assessment for hydropower relicensing processes in California: Developing tools for more efficient and effective resource management
Hydropower has a long history in California and hydroelectric production continues as a key element in meeting the State’s electrical demand. However, hydropower projects can result in significant environmental impacts through the modification of natural instream flow regimes. The objective of this paper is to identify gaps in scientific understanding of instream flows and identify research needs related to developing economically efficient and ecologically effective management tools for use in Federal Energy Regulatory Commission (FERC) hydropower relicensing processes in California. Because of the economic and environmental significance of California’s stream resources, and the 30-to-50 year time horizon involved in Federal Energy Regulatory Commission hydropower licensing process, there is a continuing need to refine and improve available scientific tools for allocating water among competing demands, including hydroelectric generation, recreation and aquatic species.

Through an Assessment of California hydropower relicensing processes and interviews with knowledgeable individuals representing hydropower industry, government, recreational and environmental stakeholder groups, key resource issues and research needs were identified. The most commonly identified resource issue was the difficulty of balancing competing demands for a limited water resource. In regard to research, stakeholders saw a need for studies that would a) encourage increased consistency of hydropower licensing study protocols, and b) compare and contrast standard environmental flow assessment methods with a number of less well known, but promising, new approaches. Overall, our assessment indicates that additional instream flow research would benefit California by improving the economic and ecological effectiveness of Federal Energy regulatory Commission hydropower licensing processes.

8. California native fishes and streamflows: A literature review
California’s native freshwater fish populations are in steep decline due to habitat changes. Better information on how to manage hydropower operations can help protect many species. This research project was a literature review on selected river systems in the Central Valley drainage with the initial goal of consolidating information on native fish species and associated streamflow conditions. The intent was to examine and summarize the results of surveys from several unpublished reports into a form that is more accessible to other researchers. The authors also drew from more recent journal publications when studies were available.

The reviewed information varied widely in extent and quality among the different rivers. The most extensive studies were surveys for the lower Pit and North Fork Mokelumne rivers. Those two studies contained data on fish abundance and distribution and streamflows for an array of locations in the
watersheds, hence providing potential data for more detailed future examinations of fish-streamflow relationships.

The authors did not discern any consistent, quantitative relationships pervading the range of studies we examined within the project time-frame. However, the search for a general pattern was subordinated by our primary goal of broadly summarizing results of the studies in terms of fish and streamflow data. Possibly, further evaluations focused on one or two data-rich studies may yet identify patterns between streamflow regimes and fish population robustness. In this project, the authors achieved the broad goal of providing descriptive summaries of streamflows and fish population information for the selected rivers but we were unable to form a detailed analytical understanding based on that information.

A secondary aspect emerging from this project was a simplified conceptual framework addressing the question of how streamflow regimes affect fish assemblages. The authors suggested examples of parameters to utilize and questions to ask in regard to streamflow changes and their effects on fish species. They also provided examples of working hypotheses that may aid our understanding--on broad temporal and spatial scales--how streamflow regimes and fish assemblages are related.

9. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River (Year One)

There are many anthropogenic causes of increased water flow (pulses) in California rivers, including electricity generation, flood control, and facilitating river rafting, that may impact the distribution of native stream species because the increased frequency of these flows and their late, warm-season timing represent significant deviations from the natural hydrograph. For that reason, both experimental and field studies were conducted to assess the impact of these flows on four species of fishes that inhabit Californian rivers. Rainbow and brown trout, carrying implanted radio beacons, were tracked during a single pulsed flow in the Silver Creek reach of the American River. No significant differences were found between the distances moved after capture, later prior to the pulsed release, during the release, and after the release. Fish numbers were recorded in pools along this reach during snorkel surveys before and after the pulsed flow, and the total fish density in each pool did not appear to differ markedly before and after the pulse. The responses were recorded of rainbow trout, hardhead minnows, and Sacramento suckers to artificially pulsed flows within a longitudinal flume, in which were placed rocks to simulate the bottom of the mainstem of the American River. Although fish moved either upstream or downstream, the mean position of the individuals was close to the center of the flume during increasing and decreasing flows. The movements of individuals of
these species were also determined in a lateral displacement flume, consisting of a rectangular tank separated into a main channel that never drained and a raised wide channel that alternately flooded and became exposed. Water circulated through the apparatus, flowing downward over a slope into a series of channels and potential holding areas for this fish. Four pools existed on the raised wide channel with different shapes, holding, and draining capacities. Fish could become stranded in one of these pools as the water level subsided within the apparatus. Only three of the 38 fish placed within the apparatus became stranded within one of the artificial pools. The field and laboratory studies, described in this report, provide an evaluation of the impacts of pulsed releases of water for recreational and commercial purposes on the behavior and movements of subadults and adults of these species of fishes.

10. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River (Year Two)

The overall objective of this research was to identify the effects of pulsed flows on fishes. Experimental and field investigations were conducted on two species: rainbow trout (Oncorhynchus mykiss) and hardhead (Mylopharodon conocephalus). These fish species were chosen either because of their recreational value or sensitivity to hydropower operations. There were three phases to Year 2 of this study: 1) tracking the movement of adult trout (greater than 25 cm TL) tagged with radio transmitters in a river to ascertain whether individuals are displaced longitudinally in response to pulsed flows, 2) implanting electromyogram (EMG) tags in adult rainbow trout to assess and estimate the energetic costs of experiencing pulsed flows, and 3) ascertaining the temperature preferences of adult rainbow trout and hardhead utilizing a large laboratory annular apparatus. We tracked the movements of ten small (SL 25.5 - 31.0 cm) and ten large (SL 32.0 - 38.5 cm) radio-tagged trout in response to frequent pulsed flow releases in the South Fork American River (California) from July to October, 2005. During this period the river had base flows of 5 m$^3$s$^{-1}$ with 4-hour midday releases of 40 m$^3$s$^{-1}$ on most days for whitewater rafting, plus increased releases on many days with peaks up to 110 m$^3$s$^{-1}$. Repeated measures ANOVA analyses showed no significant relationships between fish movement and water flow variables, release site, location within river, fish size, or fish condition ($p > 0.05$ for all variables). Utilizing radio telemetry with electromyogram sensors the potential factors related to median swimming speeds, such as river discharge, time, sex, location, and pulse stage, were analyzed using a mixed linear model. Pulse stage was found to be statistically significant; increasing pulse stage was correlated with increasing swimming speeds. Hardhead (mean TL: 36.2 cm) and rainbow trout (mean TL: 35.4 cm) were acclimated to 12, 15, and 18 °C and tested, individually, in a 12 – 24 °C annular gradient. The hardhead preferred a range of 19.6 - 20.0 °C, while the trout preferred a significantly cooler range: 16.0 - 18.4 °C. All of the hardhead avoided water less than 17 °C, whereas the 12 and 15 °C trout
acclimation groups avoided water greater than 19 °C, and the 18 °C trout avoided water less than 16 °C and greater than 20 °C.

11. Pulsed flow effects on the foothill yellow-legged frog (*Rana boylii*): Integration of empirical, experimental and hydrodynamic modeling approaches

Four analytical approaches support the hypothesis that altered flow regimes, particularly spring and summer pulsed discharges, contribute to the decline of foothill yellow-legged frogs *Rana boylii* in regulated rivers. (1) A review of literature and Federal Energy Regulatory Commission re-licensing reports indicates that egg masses are negatively affected by pulsed flows via scouring, or desiccation, if spawning occurs during spills that abruptly cease. Tadpole stranding was documented in several studies. Effects on young of the year and older life stages were equivocal. (2) Long-term population monitoring in three watersheds shows that frequency and magnitude of pulsed flows that harm embryos and tadpoles are factors in determining adult population status. These effects are offset by 2-3 years, representing the time to reproductive maturity in central and northern California. (3) Experiments illustrate that tadpoles seek refuge in the substrate as velocity increases, are not adapted for sustained swimming, and are swept downstream. Tadpoles confined to refugia face predation and energetic costs in terms of growth and development. (4) Simulations using River2D, a 2-dimensional hydrodynamic model, show that velocity and depth conditions exceed tolerances of *R. boylii* egg masses and tadpoles during a range of pulsed flows. While mesoscale suitability of near shore habitat was accurately predicted, error in modeled point velocities at egg locations arose from limitations in fine scale surveying of the large, poorly sorted, rock substrate. Management that avoids aseasonal flow fluctuations would benefit *R. boylii*, and other taxa, whose lifecycles are synchronous with the natural timing of runoff in California’s river.

**Benefits to California**

This program has provided background information, potential concerns, and priority research needs for California research studies to address the ecological impacts of hydropower pulsed flow on fishes, amphibians and macroinvertebrates in California streams and rivers. This program also administered funds from the California Energy Commissions on research projects that provided results and recommendations that will assist California’s managers of hydroelectric facilities, industry regulators and policy makers. Improvements in managing regulated rivers will ideally result in perpetuating and enhancing the quality of California’s natural resources and heritage while also improving opportunities for the people of California to enjoy and benefit from them.
1.0 Introduction: The Pulsed Flow Program

1.1. Background
Over 380 hydroelectric power projects distributed throughout California are located on almost all of the state’s major rivers and streams. Hydroelectricity is a critical element of the California generation system because it provides peaking reserve capacity, spinning reserve capacity, load following capacity, transmission support, and low production costs as well as providing 15% of electricity needs over the last 20 years. Many facilities of California’s hydropower system are part of a broader multi-use water system providing water supply, flood control, recreation, and other beneficial uses (McKinney 2003). However, these societal benefits have not come without a cost to the native biota of the state. There is substantial evidence that both hydroelectric and water storage/flood control dams have negatively impacted fish, amphibians, macroinvertebrates, and other aquatic biota. Apart from the well-documented long-term effects of dams and reservoirs on downstream environments and their role in fragmentation of riverine networks, concerns about direct impacts of pulsed flow releases have been raised.

1.2. Purpose of the Program
In order to assess short- and long-term ecological impacts of pulsed flow releases on California stream systems regulated for hydropower production, the Public Interest Energy Research Program (PIER) of the California Energy Commission (CEC) and the Division of Water Rights of the State Water Resources Control Board (SWRCB) established the Pulsed Flow Program (PFP) through the Center for Aquatic Biology and Aquaculture of the University of California, Davis (UC Davis). The Program objective was to specifically look at the ecological effects of manufactured or augmented flows from hydropower facilities on aquatic habitats and biotic communities within California streams and rivers. It was not intended to address issues such as the ecological benefits or effects of dam removal, or the economic consequences of providing recreation flows. The goals of this program were to:

- Identify and fund research that would document the ecological effects of pulsed flows, especially peaking, load-following and recreation flows;
- Identify the relationship between pulsed flows and base flow conditions;
- Improve existing or develop new protocols and models for resource assessment and impact identification;
- Identify potential thresholds that could be considered in environmental analysis of flow release projects; and
• Recommend possible mitigation measures that would reduce or help avoid negative impacts.

Research and development projects funded under this program should further our understanding of these processes and provide better tools to resolve the more significant negative impacts while avoiding unnecessary curtailment of hydropower operation and/or recreation flows because of a lack of knowledge. As such, it was also necessary that funded research provide information and/or tools that would be applicable to all types of hydropower generated pulsed flows.
2.0 Research Program Management

The Ad Hoc Committee consisting of the Program Director Prof. Douglas E. Conklin (UC Davis), CEC Project Manager Joseph O’Hagan, Prof. Joseph J. Cech, Jr. (UC Davis), Andy Sih (UC Davis), and Lisa Thompson (UC Davis) was established for the initial organization of the Program. The Ad Hoc Committee also assisted the Program Administrative Officer Pacienza S. Young in starting the white paper intended to present a literature review and identify research gaps and needs on “Hydropower pulsed flow impacts on aquatic habitats and biotic communities”.

The Program Management Team (PMT) consisted of the Program Director Prof. Douglas E. Conklin (UC Davis), Program Administrative Officer Dr. Pacienza S. Young (UC Davis), CEC Project Manager Joseph O’Hagan, representative from SWRCB James Canaday, and representative from Sustainable Conservation Carson Cox. The PMT was necessary for efficient and effective management of the Program and convened regularly to discuss the directions and progress of the Program. The PMT also developed the proposal evaluation and selection criteria, evaluated the white paper and proposals, selected proposals for funding, reviewed annual and final reports, and assisted in the organization of the Program workshop (held July 2005) and conference (held September 18, 2007). The PMT also made comments and suggestions to improve the Pulsed Flow Program website http://animalscience.ucdavis.edu/PulsedFlow.

A Technical Advisory Committee (TAC) was established to assist the PMT in identifying research priorities for the Program. During the meeting on the November 12th, 2003, the TAC discussed the first draft of the white paper, and also identified as research priorities the assessment of the potential effects of the magnitude and timing (season and time of day) of the above described pulsed flows on fishes, amphibians, and macroinvertebrates. The request for proposals was announced December 2, 2003. It was the intention of the Program to fund research projects addressing these priorities. The white paper draft was revised based on the comments and suggestions of the TAC members and narrowed the topic into “Hydropower-related pulsed flow impacts on stream fishes, amphibians and macroinvertebrates”.

During the May 27th, 2004 meeting, the TAC identified Geomorphic and habitat impacts as another important area for study in relation to magnitude and timing of pulsed flow discharges. A second request for proposals was announced July 2, 2004 that included these priorities.

A total of 9 projects were funded through the Program with a total amount of $1,478,255. The next section presents the executive summary of the white paper and each research project report.
2.1. Summary of White Paper and Research Project Reports

2.1.1. Hydropower-related pulsed flow impacts on stream fishes, amphibians and macroinvertebrates (Young et al. 2007)


Introduction
Many California hydroelectric power plants produce manufactured pulsed flows as a byproduct of electrical power generation or for the beneficial purpose of vegetation control, habitat enhancement, and/or recreational demands. These rapidly increasing and decreasing pulsed flows, ramped over varying durations that may or may not match naturally occurring rates, are characterized by significantly higher flow volume and rate for short periods of time over the operational base flows and may have significant impacts on native and non-native biota and their habitats. Pulsed flows can be categorized as electrical peaking flows, load following flows, flushing flows (channel maintenance and remedial), spill flows, recreational flows, and discretionary operational flows.

The Pulsed Flow Program
Although pulsed flows are intended to produce various benefits as described above, the effects of the resulting fluctuations in water flows on aquatic habitat and biotic communities are not fully understood. To assess short- and long-term ecological impacts of pulsed flows on California stream systems regulated for hydropower production, the Public Interest Energy Research Program (PIER) of the California Energy Commission and the Division of Water Rights of the State Water Resources Control Board established the Pulsed Flow Program (PFP) through the Center for Aquatic Biology and Aquaculture of the University of California, Davis (UC Davis).

A Technical Advisory Committee (TAC) established by the PIER-UC Davis PFP identified assessments of the potential effects of the magnitude and timing (season and photophase) of the above described pulsed flows on fishes, amphibians, and macroinvertebrates as research priorities. Geomorphic/habitat impacts were later identified by the TAC as another important area for study in relation to magnitude and timing of pulsed flow discharges. It is the intention of UC Davis and the PIER Program to fund research projects addressing these priorities.

Purpose of this White Paper
The general objective of this paper is to provide background information on these key areas of research. Additionally, this paper is intended to:

- lay out issues and potential concerns related to pulsed flows; and
- identify priority research needs to add to the existing body of knowledge.
It should be noted that this paper does not deal with geomorphic effects of pulsed flows. However, it is important to point out that pulsed flows can have beneficiary effects by preventing smothering of cobble and gravel substrates. This is beneficial in the long term maintenance of the riverine ecosystem and habitat diversity that, in turn, may result in species diversity of macroinvertebrates and fishes.

Key Concern: Fishes

Under certain circumstances, depending on timing, frequency, duration, and magnitude, pulsed flows can have adverse and/or beneficial short and long-term effects on resident or migratory stream fishes. Among the possible adverse effects are direct losses and impacts to fish energetics due to: 1. lateral displacement (including stranding) of fishes along the changing channel margins, 2. longitudinal displacement (washing out) of fishes down the stream channel, and 3. reduced spawning and rearing success, which may also be due to redd dewatering and untimely or obstructed migration. Some of the possible beneficial effects are: 1. maintenance and replenishment or spawning gravels, 2. biological cues to trigger spawning, and 3. maintenance of summering and rearing habitats.

Key Concern: Amphibians

Under certain circumstances, depending on timing, frequency, duration, and magnitude, pulsed flows can have adverse and/or beneficial short and long-term effects on resident amphibians. Among the possible adverse effects are losses due to: 1. scouring of amphibian eggs from substrate, 2. displacement or stranding of larvae, and 3. changes in water temperatures that, depending on the timing, frequency and duration of the pulses, may affect the development of both eggs and larvae. Ecological triggers achieved by pulsed flows to initiate breeding and other activities in amphibians are some of the possible benefits of pulsed flows. One species that is the focus of amphibian studies in California streams is the foothill yellow-legged frog, which is currently listed as a “Species of Special Concern” in California and Federal status as U.S. Forest Service, Region 5 “Sensitive Species”.

Key Concerns: Macroinvertebrates

Under certain circumstances, depending on timing, frequency, duration, and magnitudes, pulsed flows can have adverse and/or beneficial both short and long-term effects on macroinvertebrate communities. In the short-term, some pulses can cause “catastrophic drift” that may result in increased mortality, particularly of organisms that normally exhibit little drift and are, thus, not well adapted to flow pulses. In the long-term, pulses can have persistent effects on the spatial distribution of macroinvertebrate habitat, including the macroinvertebrates themselves and the expected distribution and
abundance of stream organisms, including fishes that prey upon these macroinvertebrates.

Research needs

The relative cumulative effect of recreational pulsed flows and operational pulsed flows, as well as the changes in fish, amphibians, and macroinvertebrates caused by hydroelectric projects, needs to be investigated. Although numerous studies have been conducted on specific types of pulsed flows, there remain critical research gaps in the knowledge needed to better understand the impacts of pulsed flows on California stream fishes, amphibians, and macroinvertebrates. Major gaps include effects of different magnitude, ramping rates, and timing (season and time of day) of pulsed flows on the abundance and distribution of stream fishes, amphibians, and macroinvertebrates at different life stages.

Several approaches applicable to all aspects of research on pulsed flow effects are as follows:

a) Monitoring and documentation of downstream changes in biotic communities before, during and after pulsed flows;

b) Identifying thresholds (rate of change, magnitude, duration, frequency, and timing of pulsed flows) beyond which a specific impact (adverse or beneficial) on the biotic communities is expected;

c) Synthesizing and integrating results into conceptual models that will describe the physical and biological processes occurring with pulsed flows and that can be used to predict outcomes in other regulated streams experiencing pulsed flows;

d) Addressing and predicting long-term effects of pulsed flows on the biotic communities; and

e) Evaluating existing mitigation measures for effectiveness, and developing potential new mitigation measures that will reduce or avoid negative impacts.

Benefits to California

This paper provides background information, potential concerns and priority research needs for California studies necessary to fill the gaps in our understanding of the impacts of pulsed flows on the three main organisms of concern: stream fishes, amphibians and macroinvertebrates. Research and development are needed to provide better tools for resource managers to address the more significant impacts while avoiding unnecessary curtailment of hydropower operation in California because of a lack of knowledge.
2.1.2. Evaluating the impacts of manufactured recreation streamflows on the macroinvertebrate community of a regulated river (GANDA 2006a)

Authors: Ian Chan and Robert Aramayo (Garcia and Associates)

Introduction
This report provides information regarding the effects of pulsed recreation streamflow releases on benthic macroinvertebrate communities. Macroinvertebrate data from a “treated” reach and an unaffected “control” reach of the North Fork Feather River (NFFR), Plumas County, California, were compared using a limited before-after control-impact (BACI) experimental design. In the treated reach, one-day pulsed flows that were between four and seven times the magnitude of the baseflow were provided once per month for recreational whitewater boating. These pulsed-flow events occurred from late June through late October 2004, during the typical low-flow season.

Project Approach
The treated and control reach were sampled concurrently, before and after each pulsed-flow event. Both reaches were sampled using the same representative artificial substrate sampling method that was employed in a previous study of the treated reach (rock basket samplers), as well as standard kick-sampling techniques. The primary objectives of this study were to (1) quantify and compare any short-term differences between the benthic community of the treated and control reaches immediately before and after pulsed recreation streamflow events; (2) determine if longer-term seasonal trends in the benthic community of the treated reach differed from trends in the control reach following repeated pulsed-flow events; and (3) compare the efficacy of representative artificial substrate sampling vs. standard kick-sampling methods for detecting pulsed-flow-related changes.

Macroinvertebrate data from pre- and post-flow sampling events in each reach were described using the recently developed hydropower multi-metric index (Hydro-MMI), which was designed to be sensitive to the cumulative effects of hydropower operations. Analysis of variance (ANOVA) was used to test for a pulsed-flow effect using this multi-metric index as the response variable. Similar ANOVAs were also used to test for differences between seasonal trends in the treated and control reaches, and to test for differences between the basket- and kick-sampling methods.

Project Outcomes
The control-to-treated difference in Hydro-MMI was significantly different from pre-flow to post-flow (p < 0.10). Seasonal trends between these reaches were generally similar among basket-sample data, although the control reach generally scored higher than the treated reach. Seasonal trends in Hydro-MMI were not significantly different (p > 0.10); however, some divergence in Hydro-MMI scores as well as in individual metrics was apparent between the treated and control reaches at the
end of the sampling season (which may be biologically significant). Moreover, kick-sample data suggest a seasonal pattern of increasing richness and abundance in the control reach that was not observed in the treated reach.

Kick samples provided a better representation of the overall benthic community than basket samples in our study. Basket samplers tended to select for a subset of the benthic community that was heavily dominated by filter-feeding organisms such as net-spinning caddisflies (primarily of the family Hydropsychidae). These organisms were able to quickly colonize basket samplers and capitalize on free interstitial spaces throughout the volume of these samplers (i.e., including spaces between rocks near the bottom of the sampler, not just the exposed rock surfaces at the top). On average for basket samples, the abundance of net-spinning caddisflies was overrepresented by approximately 60% relative to kick samples. Several other key species were also either overestimated or underestimated to some degree in basket samples. Statistically significant differences between kick- and basket-sampling methods were detectable (ANOVA, \( p < 0.10 \)) implying that the two sampling methods yield different results.

Overall, short-term control-to-treated differences were not consistent or large enough to necessarily be considered biologically significant, even though statistical significance was detected in the context of BACI comparisons. Conversely, longer-term seasonal differences, especially among kick-sample data, suggest biologically significant control-to-treated differences, despite the fact that no statistical significance was detected. Differences in the composition of basket vs. kick samples suggest that seasonal trends among basket-sample data primarily follow the natural seasonal patterns for the filter-feeder-dominated community that developed in our basket samplers; and furthermore, that these filter-feeding taxa may be more robust to flow-related changes by virtue of their specific microhabitat preferences and adaptations.

**Recommendations**

It is recommended that future evaluations of pulsed recreation streamflows in the NFFR be based on direct bottom sampling methods such as kick sampling, instead of artificial substrate sampling. Kick samples appeared to detect pulsed-flow-related disturbances better than basket samples, particularly potential cumulative effects across longer (e.g., seasonal) timescales. The Hydro-MMI was more useful than individual metrics for both discriminating baseline control-to-treated differences and detecting pulsed-flow-related disturbances. The authors thus recommend that benthic macroinvertebrate data from future studies of pulsed-flow effects be compiled and evaluated using the Hydro-MMI.
2.1.3. Reproductive timing of freshwater mussel and potential impacts of pulsed flows on reproductive success (Spring River 2007)

Authors: Maria J. Ellis and Lorrie Haley (Spring Rivers Ecological Sciences, LLC)

Introduction
Native freshwater mussel populations in North America are declining at a catastrophic rate. The construction and operation of dams for hydroelectric generation, flood control, and navigation have contributed substantially to the drastic declines in mussel populations. Downstream of dams, unnatural pulses in stream discharge (i.e., pulsed flows) have the potential to reduce mussel reproductive success if such events occur during the critical periods in the mussel reproductive cycle. Knowledge of mussel reproductive timing in California river systems is scant, and this information is necessary for assessing potential impacts of seasonal pulsed flows (e.g., flushing/whitewater flows for channel maintenance or recreation) on mussel reproductive success and for scheduling these events to minimize reproductive interference.

Purpose
The goal of this study was to pinpoint time periods when mussel species in the Pit River drainage in northeastern California (Shasta County) would be most vulnerable to pulsed flows. These species included Anodonta californiensis, A. nutalliana (a.k.a. A. wahlmatensis), Gonidea angulata, and Margaritifera falcata. Anodonta were not identified to species because the taxonomy of western Anodonta is unresolved. To broaden the applicability of collected data, investigations were conducted in rivers and river reaches with different flow and/or temperature regimes.

Objectives
The primary objective was to collect mussel reproductive data from 3 Pit River reaches that experience different manufactured flows and from 2 spring-dominated Pit River tributaries that have relatively stable flow regimes. These reaches included the Pit 4 Bypass (receives reduced flow via stable releases from Pit 4 Reservoir except during spills); Pit River downstream of Pit 1 Powerhouse (receives full flow, with daily pulsed flows from hydroelectric peaking); Pit 1 Bypass (receives reduced flow, with a base flow release that varies seasonally, daily pulsed flows during the spring and summer from a hydroelectric project in the upper watershed, and pulsed flows for channel maintenance/recreation during three summer weekends); Hat Creek downstream of Hat 2 Powerhouse (run-of-river reach with stable, spring-dominated flow regime); and lower Fall River (unregulated reach with stable, spring-dominated flow regime).

Project Approach
Field investigations were conducted from April through November 2004 and from February 2005 through early May 2006 and focused on the following critical reproductive events:
• spawning (i.e., when males expel sperm into the water column and females move eggs into portions of their gills modified to form brood pouches called marsupia);
• glochidial release (i.e., the end of the gravid period when mature mussel larvae called glochidia are expelled from the marsupia in order to attach to suitable host fish); and
• juvenile excystment from host fish (i.e., when glochidia that have successfully transformed into juvenile mussels drop off of host fish).

To determine the timing of spawning and glochidial release, mussels were periodically collected and examined for gravidity (i.e., incubating eggs or embryos), and samples of eggs/embryos were collected from the marsupia of gravid mussels to determine stages of development. In 2004, samples were also collected from the gonads of non-gravid mussels to determine their sex. In 2005–06, stream drift was sampled downstream of undisturbed mussel assemblages to determine seasonal peaks in glochidial release.

To determine periods of juvenile mussel encystment on host fish and estimate periods of juvenile excystment, fish were collected concurrently with mussels and examined for signs of glochidial infection. Because mussel glochidia may not complete development on all species of fish, a portion of the naturally infected fishes collected during late March–September 2005 was transported to the laboratory and held in freshwater aquaria for monitoring the production of juvenile mussels.

Results
Anodonta in all reaches spawned and released glochidia asynchronously and repetitively throughout most of the 2004 and 2005–06 field seasons, except from roughly late July to mid October, and their glochidia were observed on fish during all months except September and October. Excysted juvenile Anodonta were collected from aquarium tanks containing native hardhead, Sacramento pikeminnow, tule perch, Pit sculpin, and non-native green sunfish during the months of April through July 2005.

Gonidea angulata in the Pit River reaches and Fall River (this species was not found in Hat Creek) spawned and released glochidia asynchronously from late March/early April to mid July in 2004 and 2005, and beginning in late April 2006. In 2005, G. angulata glochidia were more abundant in stream drift samples collected during June in the Pit 4 Bypass, Pit River downstream of Pit 1 Powerhouse, and Fall River. In the Pit 1 Bypass, stream drift was not sampled in June, but glochidia were more abundant in samples collected in early May than in mid April or mid July. Glochidia were observed on fish from late March to late July/early August. Juvenile G. angulata were collected from aquarium tanks containing native hardhead, tule perch, and Pit sculpin during the months of June and July.

Spring/summer gravid periods for Anodonta and G. angulata were similar (within 2 weeks) in all reaches and ended as (or soon after) the hydrograph reached base flow and water temperatures peaked around mid July in 2004 and 2005. Anodonta resumed
spawning in mid to late October in both years, when flows began to increase and water temperatures dropped below 13° C. *Gonidea angulata* resumed spawning the following spring during variable flow conditions and after water temperatures exceeded 10–12° C.

Few gravid *Margaritifera falcata* were found during this study, and the timing of gravidity differed between river reaches and years. This species was not found in Fall River, and was not sampled in the Pit 1 Bypass because it was rare. In the Pit 4 Bypass, spawning females were found in early April and mid June in 2004, when flow regime was stable (200 cfs) and water temperatures ranged from 10 °C to 16 °C; and in early and late April 2005, when flows ranged from 200–2000 cfs and water temperatures averaged 12 °C. In the Pit River downstream of Pit 1 Powerhouse, gravid females were not found in 2004, but were found from early June through early July in 2005. Those collected in early June had just spawned, and spawning occurred after a 5000-cfs drop in average daily river flow, when water temperature averaged 18 °C. The single gravid female collected in early July incubated glochidia. In Hat Creek, one *M. falcata* spawned in early July 2005, but no other gravid *M. falcata* were found in this reach. The glochidia of *M. falcata* were not observed in samples of stream drift or on fish collected in 2005-06.

**Conclusions**

In the Pit River reaches, most adult mussels spawned and released glochidia during the months of April through July, and most juvenile mussels dropped off of their fish hosts to settle on the stream bottom during June, July, and early August. Seasonal pulsed flows or maintenance outages that occur during these critical time periods would have a greater impact on mussel recruitment than those that occur after August. The shorter reproductive periods observed for *G. angulata* and *M. falcata* may make these species more vulnerable to pulsed flows than *Anodonta*, especially during peak periods of glochidial release and juvenile excystment/settlement. In 2005, these peaks occurred for *G. angulata* during June and July in most locations.

Reproductive timing in *Anodonta* and *G. angulata* was similar in unregulated and regulated river reaches with different flow regimes. Reproductive timing in *M. falcata* varied between reaches, indicating that this species may be more sensitive to fluctuations in river flow and/or water temperature. Consequently, the annual timing and duration of *M. falcata* reproduction may be more difficult to predict in the Pit River and other California river systems.

**Recommendations**

Seasonal pulsed flows in the Pit 1 Bypass, which have been in effect since 2003, and maintenance outages in the Pit 4 Bypass and Pit River downstream of Pit 1 Powerhouse should be planned before and/or after peak periods of glochidial release and juvenile excystment/settlement for *G. angulata* and *M. falcata*. Although reproductive timing may vary somewhat annually, these critical events may occur for both species during the months of June, July, and August. In the Pit 1 Bypass, license-prescribed pulsed flows for channel maintenance/recreation occurred in May/June, mid July, and late August in 2004 and 2005. These high flow events could have adversely impacted recruitment in
Continued monitoring and assessment of specific impacts of pulsed flows on freshwater mussels, especially in the Pit 1 Bypass, is recommended. Because the timing of mussel reproduction observed in the Pit River may differ in other California drainages, reproductive data from rivers throughout the state should be gathered and compared to determine if site-specific, regional, or state-wide flow recommendations would be appropriate.

Benefits to California
The data presented in this report benefit California by increasing the knowledge base of native freshwater mussel biology and ecology. This research provides the groundwork for future monitoring and assessment of pulsed flows in the Pit River drainage, and for research of mussel reproductive timing in other regulated and unregulated rivers within California. Data from this and future studies on mussel reproductive timing will help managers of hydroelectric facilities, industry regulators, and policy makers assess potential impacts of seasonal pulsed flow releases on reproduction of California mussel populations and plan these events to minimize adverse effects on mussel reproduction.

2.1.4. Identifying climatic and water flow triggers associated with breeding activities of a foothill yellow-legged frog (Rana boylii) population on the North Fork Feather River, California (GANDA 2006b)

Authors: Joseph E. Drennan, Ronald E. jackman, Karla R. marlow, and Kevin D. Wiseman (Garcia and Associates)

Introduction
The foothill yellow-legged frog (Rana boylii) is an inhabitant of streams and rivers from Oregon and California and has experienced drastic population declines in some parts of its range. Due to the dynamic nature of river discharge levels, selection of oviposition site is critical to avoid desiccation if flows drop significantly during egg development, or conversely, to avoid scouring and detachment of egg masses if late-season precipitation or unseasonable warming accelerates snowmelt thereby increasing stream discharge. The current practice (including on the North Fork Feather River) of releasing pulse flows from dams to mimic the natural hydrograph, for channel maintenance, or for whitewater boating recreation, could be inappropriately timed for foothill yellow-legged frogs and present the danger of egg mass scouring or displacement of small-sized tadpoles in early development.
Purpose

In light of the complications involved between generating hydroelectric power in river systems and conserving the foothill yellow-legged frog populations that inhabit these systems, this study was designed to provide hydroelectric power operators with a model that could predict when frogs breed in order to minimize negative impacts to these populations.

Project Objectives

The primary objectives of this study were to determine:

- How local environmental conditions (e.g. water temperature, stream flow, precipitation) affect the onset of foothill yellow-legged frog breeding activities, specifically,
  a) initial movement from tributary refugia to river breeding sites
  b) the date of breeding; and
- How pulse flows and irregular flow releases associated with high runoff and regulated rivers affect the breeding and movement patterns of adult frogs.

Secondary objectives addressed by this study were to determine:
- How adult foothill yellow-legged frogs use tributaries as movement corridors during the pre-breeding period and,
- How culverts affect foothill yellow-legged frog movements.

Project Outcomes

A total of 476 individual adult frogs were identified during the study, with forty-seven frogs captured in both years. In 2005, 46 female and 6 male frogs were radio-tagged and tracked from initial movement periods to post-breeding. Frogs were most often observed in the stream channel, usually basking. Male frogs initiated movement to the river before females in both years. In 2004, the mean date of initial movement to mainstem breeding sites for Cresta Reach females was on May 9 and on May 5 in 2005. Poe Reach females mean date of initial movement was on May 4 in each year. Rate of movement for female frogs (58.1 m/day) was about twice as fast as male frogs. The longest movement was observed in a female frog, which covered a distance of at least 1,899 m in ≤6 days for a minimum movement rate of 316.5 m/day. In general, male frogs were present at mainstem river breeding sites earlier than females and remained for longer durations. Once at the river, oviposition for most frogs occurred when river temperatures were ≥10 °C and river flow was ≤55% of baseflow and on the descending limb of the hydrograph. Observations of radio-tagged frogs during high flows in 2005, provided evidence that most frogs are able to tolerate high flows and not get washed downstream or otherwise harmed. High flows during the early breeding season, natural
or manufactured, apparently do not affect the timing of initial frog movements to mainstem river breeding areas.

**Conclusions**

Results suggest that the timing of breeding is a hierarchical response. Initial movements to the river are triggered by day length but the date when frogs lay eggs is a function of mainstem temperature and flow level.

**Recommendations**

These data suggest that extending the declining limb of spring pulse flows in a manner that will prevent rapid changes in river discharge might be employed as a conservation measure to increase breeding success in foothill yellow-legged frogs.

**Benefits to California**

The results of this research provide critical information about foothill yellow-legged frog movement and breeding patterns and how they are affected by environmental parameters. This information will enable hydroelectric power managers to enhance the breeding success of this California Species of Special Concern, and provide information to resource agencies and stakeholders involved in the relicensing process for hydroelectric power projects in California.
2.1.5. Pulse flow guidelines: Managing the annual snowmelt hydrograph and winter floods in regulated boulder-bedrock Sierra Nevada rivers (McBain and Trush, Inc. 2007)

Authors: Bill Trush (McBain and Trush, Inc.)

Introduction

In the Sierra Nevada, dams and diversions are important causes of aquatic and riparian condition deterioration (Davis: University of California 1996). Given the number of Sierra Nevada dams and diversions and the magnitude of their impacts on river ecosystem health, a methodology is needed that can identify the timing and magnitude of instream flow releases that are affordable and capable of generating a reliable energy supply, yet still promote some acceptable level of river ecosystem health.

Purpose

The purpose of this study is to apply such a methodology to the Clavey River, a boulder-bedrock stream located in the Sierra Nevada, and to determine whether the methodology is feasible.

Project Objectives

The Project objectives were to: (1) quantify mobilization thresholds for depositional features, and establish trends in species habitat availability that are dependent on: (a) the annual snowmelt flow regime, and (b) winter peak floods; (2) as represented by the annual snowmelt hydrograph’s components, assess how altering flows could directly and indirectly affect habitat used by Species of Concern; (3) demonstrate that: (a) variable winter and snowmelt pulse releases can recreate and maintain specific geomorphic and ecological thresholds, and (b) if one impounds flow such that annual snowmelt flows and winter peak floods are altered or eliminated, then geomorphic and ecological responses can be forecasted; and (4) given the results of these demonstrations, formulate example pulse flow guidelines, evaluate uncertainties in the Project’s outcomes, recommend changes in the methodology, and identify further information needed.

Project Outcomes

Hydrologic, geomorphic, and biological data were compiled and analyzed. Typical analytical hydrologic curves were generated for the Clavey River and Cherry Creek. Geomorphic analyses included bed mobility modeling, field observations, and examination of paired ground and aerial photographs. From these analyses, flow thresholds for mobilizing specific depositional features were associated with annual maximum flood recurrences. Biological information was collected through expert habitat mapping and literature reviews.
Once the hydrologic, geomorphic, and biologic characteristics were determined, the synthesis methodology could be started. The methodology is largely graphical. The expert habitat mapping allowed generation of habitat rating curves; when combined with a snowmelt hydrograph, an available habitat area curve can be generated. Additional ecological information such as species life stage windows, species temperature thresholds, and water temperature are then added to the available habitat area curve, creating an annual habigraph. Considering the intersection of all data, the ecologically available habitat area and the number of days it is available can be estimated. In an unregulated environment, that number of days can be considered a reference condition; the management goal would be to optimize the reference condition, while balancing the need for water diversion.

Once all data and analyses were synthesized, the following observations and implications are noted:

The inter-annual migration of a 70°F temperature isotherm up and down the mainstem (the trombone effect) depends on the runoff year, and loosely follows the dominance between cold and warm water aquatic species. Therefore the magnitude, duration, rate, and timing of slow recession flows are important in benefiting either cold or warm water species. In regulated rivers, instead of creating additional rainbow trout habitat, releasing higher than natural summer base-flows could de-stratify (mix) thermal refugia. The annual snowmelt peak and recession flows had a smaller role in geomorphic processes than initially anticipated. Winter floods perform most geomorphic work in the boulder-bedrock Clavey River mainstem. The inter-annual variation of winter peak floods is what maintains a dynamic balance of nested hydraulic controls; this balance ultimately controls small- and large-scale depositional features.

One of the primary biological implications is that variation in water year types is required if a river is to support a variety of species. This goal of desired and required variations in pulse flow releases is not the apparent goal in most reservoir release programs. For rainbow trout, California roach, foothill yellow-legged frogs, western toad, Pacific tree frog, and benthic macroinvertebrates in the Clavey River, ecologically available habitat area depends on the annual snowmelt hydrograph’s magnitude, duration, timing, and rate. No one runoff year remotely approached providing ideal, or even good, habitat conditions for all species examined.

Reference conditions were defined and used to formulate example pulse flow guidelines; this approach differs fundamentally from the classical PHABSIM approach. While using the same basic habitat rating and availability curves, no optimal streamflow concept (the streamflow with the greatest habitat abundance) drives the analysis. Instead, a range of streamflows supplying abundant habitat is established by the Project biologists (and/or by a sub-group of peer biologists) from the habitat rating curves.
Readers are cautioned that these results have general application but should not be specifically applied to other Sierra boulder-bedrock rivers without similar and more detailed study. Examples pulse flow guidelines are:

- Maintain the natural frequency and timing of unregulated 3-yr winter flood peaks up to the unregulated 15-yr winter flood peaks. Most will be short duration winter floods, but a few should be longer duration rainfall/snowmelt peaks in late-winter or early-spring. More than one flood peak can occur annually.
- Divert flows represented by the unregulated snowmelt hydrograph’s rising limb, peak, and fast recession limb, using a fixed percentage of the unregulated streamflow that does not significantly impair the reference condition. This study’s preliminary analyses suggest maximum fixed daily diversion rates of 25% to 35%.
- Do not divert those flows represented by the unregulated snowmelt hydrograph’s slow snowmelt recession limb.

**Conclusions**

The Project outcomes met each project objective. The example pulse flow guidelines indicate that this methodology is feasible and that quantitative detail is possible.

**Recommendations**

Water temperature should be given greater emphasis when evaluating instream flows. The up- and downstream movement of flow isotherms (the trombone effect) changes with water year type and timing and magnitude of flow releases. These aspects of water quality, rather than the almost exclusionary focus on habitat availability or abundance, have not been given sufficient weight in evaluating instream flows.

This methodology should be applied to several existing and theoretical dam operations. Forecasting the probable outcome of only partially satisfying the three example pulse flow guidelines should also be investigated.

A network of photographic points or sites should be initiated, with specific purposes and hypotheses explicitly stated for each photo-point location. The temptation to first invest in hydraulic modeling and bed mobility prediction should be resisted, because existing photographic evidence contradicted the study’s modeling results. A more theoretical approach would require more time, would undoubtedly cost more, and would still require verification with photographs.

**Benefits to California**

The Project provides a successful preliminary test of a methodology for formulating quantitative pulse flow guidelines, which can promote recovery of native Sierra Nevada river ecosystems. The Project demonstrates that flushing flows will not maintain a variable mainstem channel architecture or diverse aquatic species.
2.1.6. Establishing baseline information for assessment of flow management alternatives for mitigating effects of myxozoan pathogens in the Klamath River (Bartholomew and Bjork 2006)

Authors: Jerri L. Bartholomew and Sarah J. Bjork (Oregon State University)

Introduction

The myxozoan parasite Ceratomyxa shasta causes severe intestinal infections in salmon and trout and has been implicated as a significant source of mortality of out-migrating juvenile Chinook salmon in the Klamath River during recent years. The parasite has a two-host lifecycle requiring a salmonid host and Manayunkia speciosa, a freshwater polychaete worm. Another myxozoan, Parvicapsula minibicornis, infects the kidney of these same salmon and uses the same polychaete host to complete its lifecycle. The prevalence of P. minibicornis infections among juvenile fall run Chinook salmon in the Klamath River was over 90% in 2004. Dual infections of these myxozoans are believed to be a major factor in disease mortality. However, the shared polychaete host creates the potential for simultaneous control of both parasites by limiting populations of the polychaete or disrupting the parasite lifecycles. Proposed control measures have included manipulation of river flow to: 1) reduce habitat for the polychaete (e.g. scouring flows), 2) decrease numbers of polychaetes (e.g. low flows that would dry large areas of habitat), and 3) increase amounts of water at key times to decrease infection either in the fish or in the polychaete. Alternative control measures that are independent of flow manipulations include decreasing myxospore input back into the life cycle by removal of heavily infected fish and increasing predation on polychaetes. However, little is known about the effect of such measures on the dynamics of the parasite lifecycles.

The Klamath River and other enzootic rivers in the Pacific Northwest are simultaneously managed for hydropower, agriculture and recreational use with little understanding of how this management affects interactions between fish and pathogens. In the Klamath Basin, decisions on water allocation have been especially controversial and have been severely criticized because of the lack of scientific information to support them. Based on our knowledge of the effects of temperature, exposure dose and flow on the severity of ceratomyxosias infections in salmonids, it is clear that decisions made on water use directly affect the health of the fish. However, prior to the implementation of control measures, the biology of M. speciosa and the effects of environmental changes on this host and the C. shasta lifecycle must be understood.

Purpose

This study aimed to test the effects of water flows, temperature and desiccation on the survival of polychaete populations from different habitat types and to determine the factors likely to have the greatest effect on reducing alternate host densities and C. shasta infection levels in the Klamath River.
**Project Objectives**

The project aims were met by a series of laboratory experiments investigating:

- The effects of water temperature and de-watering (low flows that would dry polychaete habitat) on the survival of the polychaete host in two of its primary habitats.
- The effect of water temperature on the longevity of the life stage infectious to fish.
- The effect of two water flows (velocities) on polychaete survival and both polychaete and fish infection.

**Project Outcomes**

Under laboratory conditions, consistent high water temperature (20°C), de-watering and a slow flow rate of 0.01 m/s all had an adverse effect on polychaete densities and survival. However, a higher percentage of polychaetes (14%) became infected in the slow (0.01 m/s) flow experimental treatments compared with those held at a five-fold faster flow (<2%). It followed that fish infected in the slower flow challenge tanks died more quickly from C. shasta infections than fish infected at the fast flow, indicating they received a higher infectious dose. Interpretation of the decline in polychaete densities at the end of the flow experiment is complicated by a coincidental storm event that generated a large sediment load in the Willamette River water supplying the experiment. These laboratory findings thus support observations in the field, in which changes in environmental conditions affect the host-parasite balance. These data indicate that habitat disruption by way of drying may significantly reduce polychaete densities. In addition, C. shasta infection prevalence in the polychaete host and infection severity in the fish host was lower at the faster water velocity.

**Conclusions**

The findings of this study indicate that changing environmental parameters influence the infection prevalence and survival of both the fish and polychaete host of C. shasta. Temperature has an inverse relationship with polychaete survival, and habitat disturbance such as mechanical disruption or drying may have severe consequences on survival as well. Although polychaete densities increased at the faster flow, the polychaetes had lower C. shasta infection prevalence. In terms of mean day to death, which is a reflection of exposure dose, susceptible salmonids exposed at the fast flow (0.05 m/s) had a longer mean day to death than those exposed at the slow flow (0.01 m/s). Thus, higher water velocities may decrease C. shasta infection prevalence in both the fish and polychaete host.

**Recommendations**

Results of this laboratory study, and research in other rivers, indicate that increased flows may decrease effects of C. shasta by reducing infectious dose and exposure time of
the fish. If the source of water that provides these increased flows are tributaries or reservoirs where the parasite is not present or is in low abundance, there would likely be additional benefit as a result of parasite dilution. Providing increased flows from cooler water sources will slow the rate of disease in fish and may allow recovery. However, the ability to significantly reduce mainstem Klamath River temperatures in the river above the confluence of the Trinity River is limited. Additionally, reducing water temperatures may provide simultaneous indirect benefits for the polychaete host. The effects of pulsed flows would be most beneficial for salmon that enter the mainstem Klamath River as smolts during their peak migration in May through June. This would also benefit salmon that rear in the mainstem as it spans a period of high actinosporic release. Flow alterations (low or high) may also provide benefits at other times by reducing habitat for the polychaete host, although this should be tested under river conditions. Recommendations for timing and magnitude of pulsed flows that would provide optimal benefit will require long-term collection of data to identify trends or manipulation of flows to test these hypotheses.

Benefits to California
The Klamath River and other major rivers in California and the Pacific NW are simultaneously managed for hydropower, agriculture and recreational use with little understanding of how this management affects interactions between fish and their pathogens. Salmon losses in the Klamath basin have had devastating impacts on coastal economies and tribal communities along the river. The effects of declining salmon runs throughout the region have been felt for several decades, but the reduction of the commercial catch by 90% in 2006 was a direct result of the weak returns of Chinook salmon to the Klamath River. Infection by myxozoan parasites has, in large part, been responsible for the declining numbers of juvenile Klamath River fall Chinook salmon and the subsequent predictions of low adult returns. Losses to coastal communities and the salmon troll industry were estimated to be 28 million dollars in 2006 alone. This highlights the need for management strategies that maximize the quantity and survival of Klamath River salmon. In the Klamath Basin, decisions on water allocation have been especially controversial and have been severely criticized because of the lack of scientific information to support them. This research provides baseline data on the effects of temperature and water flow on the C. shasta life cycle. Validation of the hypotheses generated in this study through field studies will be critical to making informed decisions that will allow use of these valuable resources while maintaining healthy fish populations.
2.1.7. Research needs assessment for hydropower relicensing processes in California: Developing tools for more efficient and effective resource management (Cox 2007)

Author: Carson Cox (Sustainable Conservation)

The Research Needs Assessment for Hydropower Relicensing in California: Developing Tools for More Efficient and Effective Resource Management identifies gaps in scientific understanding of instream flows and identifies research needs related to developing economically efficient and ecologically effective management tools for use in Federal Energy Regulatory Commission hydropower licensing processes. Hydropower plays an important role in meeting California’s electrical demand, providing approximately 25% of the state’s total electrical production capacity. However, hydroelectric production also has the potential to result in significant environmental degradation due to alteration of natural streamflow regimes. The Federal Energy Regulatory Commission (FERC), in coordination with state and federal resource agencies, is charged with developing license conditions that balance hydropower production with other beneficial water uses, including environmental flows.

Our assessment used a combination of targeted literature review, review of existing FERC hydropower project licenses, and interviews with knowledgeable individuals representing hydropower industry, government, recreational and environmental stakeholder groups to identify resource issues important to FERC relicensing processes and to identify future research needs. The goal was to identify the areas of scientific uncertainty that are most problematic to the development of instream flow license requirements the research that could be carried out to help bring clarity to these problem areas.

The most commonly identified challenge to developing efficient and effective instream flow management prescriptions was the difficulty of balancing competing demands for a limited water resource. The importance of this issue, which includes competition between power generation and consumptive, recreational, and environmental uses, is predicted to increase in the future due to global climate change and a growing number of special-status species. To overcome this challenge, respondents cited a need for research that would help clarify, refine, expand, and link environmental flow assessment studies carried out during FERC licensing processes.

Methodological assessment, standardization, and comparison studies were identified as a priority research need across the range of stakeholder groups and were seen as a means of increasing both the procedural efficiency and ecological effectiveness of FERC licensing. Stakeholders saw a need for studies that would: a) encourage increased consistency of hydropower relicensing study protocols and b) compare and contrast standard environmental flow assessment methods with a number of less-well-known,
but promising, new approaches. Stakeholders also cited a need for ecological research to fill gaps in scientific understanding of instream flows, including research aimed at refining habitat and temperature management for a range of species.

Overall, our assessment indicates that additional instream flow research would benefit California by improving the economic and ecological effectiveness of FERC hydropower licensing processes.

2.1.8. California native fishes and streamflows: A literature review (Yoshiyama and Moyle 2006)

Authors: Ronald M. Yoshiyama and Peter B. Moyle

Introduction

Most California rivers have been greatly modified in physical structure and hydrological function by water-development or power-generation projects. Despite their modification, some of the rivers retain significant populations of native fishes and other aquatic biota. In our present study, we attempt to initiate a general explanatory framework for the abundance and distribution patterns of native fish species by reviewing and compiling information from previous field studies on selected river watersheds. Our goal is to understand how and why apparently robust, or at least viable, native fish populations have been able to persist in those watersheds despite the pronounced statewide decline of many native fishes.

We present general background narratives on several river systems within the greater Central Valley drainage in regard to the recent-historical alteration of flows in those systems and the occurrence of native fishes. While quite general, the information should be useful in showing the occasionally drastic nature of streamflow changes that occurred in specific rivers and which undoubtedly have been a major factor in the overall decline of native fishes in many areas. Yet, in many cases native fish populations have managed to persist with different degrees of success, and the intent of the narratives is to show the range of flow regimes (or perhaps lack thereof) that presumably have affected their population persistence. In some cases, it may be surprising that native fishes have continued to exist at all, in view of the streamflow regimes of former periods.

The underlying theme of our review is the relationship between streamflow regimes and the presence of native fish populations. The spatial scale encompassed by the studies we reviewed ranges from highly localized sampling areas to large portions of watersheds (e.g., the entire lower Pit River). While our review considers relatively broad aspects of streamflow effects on native fishes, the information we compile nonetheless is important for assessing the ecological needs of native fish populations. To correctly understand the impacts of current natural and human-induced stressors (e.g., water diversions, pulse flows) on natural fish populations, those stressors must be viewed within the
context of the background streamflows and associated conditions (e.g., temperature) that have been experienced by the species during the recent past.

Project Approach

Our overview takes a broad perspective in examining whether the streamflow patterns may be conducive or detrimental to native fishes in specific river areas. To provide general context for our literature review, we first outline a conceptual framework comprising some analytical aspects related to the question of how streamflows and fish populations are connected—e.g., example questions, potential metrics to describe streamflow regimes. We do not attempt any detailed statistical or modeling analyses although such focused quantitative evaluations may be a logical outgrowth of our study. However, we offer some ideas on simple ways to statistically examine the effects of flows on fish populations and we propose a pair of working hypotheses as examples that could provide guidance for such evaluations.

We also briefly present background information on the environmental preferences of several native fish species. California native fishes have life-history schedules that are adaptive for the natural flow regimes that prevailed before the widespread alteration of watersheds. Natural flow regimes for Central Valley rivers generally had large peaks during the spring and early-summer snowmelt period that quickly decreased, followed by an essentially rainless summer and minimal flows during the late summer and early fall. The fishes' physiological attributes even now reflect the environmental challenges that were associated with such natural flow regimes. As examples, we present synopses of the temperature tolerances and microhabitat preferences for three major species (Sacramento sucker, Sacramento pike minnow and hardhead) as summarized from earlier published reviews.

For our study, we compiled abundance data on the major native fish species in selected river systems. The major species of interest were primarily Sacramento sucker, Sacramento pike minnow, rainbow trout and hardhead and occasionally tule perch and sculpins. Those species are, as a group, often the most productive ones in terms of total biomass although other fish species may be important with regard to biodiversity and ecosystem structure. We limited the number of species covered in our project in order to facilitate completion within the planned time-frame.

The selected watersheds—e.g., lower Pit River, lower Tuolumne and lower Mokelumne rivers, upper San Joaquin River and North Fork Mokelumne River—have been the focus of field surveys and the data for their resident fish populations and associated environmental variables are available to varying degrees. For the surveyed rivers, we summarize information on the resident fish assemblages and streamflow characteristics. The eventual goal of this project and possibly future work is to build a compendium of river sections showing where native fishes have persisted and the accompanying flow characteristics that enabled their survival.
Project Outcomes

As a prelude to our review, we broadly summarize the results from an earlier comprehensive review of the effects of water projects (dams) on streamflow regimes and fish in California. That previous review, conducted by Jones and Stokes Associates (Hazel 1976), compiled information on the effects of streamflow regime changes on salmonid fish in California rivers due to dams and other in-river projects.

That review---based on instream flow data for 31 of the 46 streams--found that post-project flows, on average, were less than pre-project flows by 20-50% during the natural peak flow periods but the post-project flows were greater than pre-project flows by about 200% during the natural low-flow periods. There also were corresponding changes in the fish faunas--i.e., detrimental shifts in salmonid fish abundance in about half of the 46 case-studies.

It is important to recognize the extent to which changes in streamflow regimes can potentially affect fish populations by desychronizing streamflows from the life-history timings of the fish species. Such desynchronization could have devastating effects on some native fishes by disrupting basic biological functions (i.e., feeding, spawning).

For the principal part of our project, we compiled fish and streamflow summaries for segments of five river systems. Four of those rivers were among the six river systems that we originally considered as potential case-studies. In this report, we present summaries for the lower Pit River, upper San Joaquin River (near Kerckhoff and Redinger reservoirs), lower Tuolumne River and lower Mokelumne River. We also included some fish data from the North Fork Mokelumne River. Although that latter river was not in our original proposed list, we discovered that the amount and quality of fishery information collected there was notable enough to warrant inclusion in our review. Additionally, corresponding streamflow data from the North Fork Mokelumne River exist in report form but were not available within in our project time-frame.

We present separate summaries for each of the reviewed river systems in separate subsections. The information summaries are incomplete to various degrees but they provide reasonable starting points toward the broad purpose of our project which is to lay the groundwork for further evaluations of fish and streamflow relationships.

In general, our review found that the river systems differed in the degree to which the streamflow data could be validly compared with the fish sampling data. In some cases the streamflow information merely represented the required or previously specified streamflows for particular river segments (e.g., over monthly or longer periods) and in other cases they were either actual flow measurements or predicted flows generated by hydrological models. Consequently, we could not construct a reliable pattern between fish abundances and streamflow regimes as we had initially planned. Hence, we gained only an incomplete overall picture of the fish abundance versus streamflow relationship and, therefore, were unable to credibly test our working hypotheses as originally
envisioned. Due to the variation in streamflow data quality, we shifted most of our
effort to compiling as much fish data and streamflow data for selected rivers as was
practicable within the project time-frame.

**Lower Pit River.** The lower Pit River (below Lake Britton) was the most extensively
studied system among those we reviewed. This river had been greatly developed by an
array of reservoirs and power-generating stations but the fish fauna nonetheless
remained diverse and included substantial representation of native fishes. The reason
for the overall high fish diversity and survival of native species generally seems to be
that a wide range of riverine and reservoir habitats occurs which allows a heterogeneous
mixture of fish species with differing life-histories and biological tolerances.
Importantly, adequate streamflows exist in much of the system despite the diversions to
power-generating stations and most of the diverted water returns to the system at
downstream points. Hence, this situation differs substantially from many other major
Central Valley rivers where water-diversion projects permanently remove large fractions
of the water supply from those systems, often with serious consequences for the local
fish faunas.

We summarized fish abundance data that had been collected at sampling localities
throughout the lower Pit River system. We also summarized accompanying streamflow
information for areas roughly corresponding to the fish sampling localities. The
information on this system was the most amenable set for the purpose of our project and
warrants continued analysis.

**Upper San Joaquin River.** The stretch of the upper San Joaquin River in the vicinity of
Kerckhoff and Redinger reservoirs had been surveyed on several past occasions—i.e., in
1977, 1985 and 1995. While those surveys were limited in scope, they showed that viable
populations of at least some native fish species existed. The limited accompanying
physical data (i.e., water temperatures) provided a cursory picture of the suitability at a
few points in the river on various dates but they were not sufficient for a meaningful
quantitative (statistical) evaluation.

**Lower Tuolumne and Lower Mokelumne Rivers.** The lower Tuolumne and lower
Mokelumne rivers represent similar situations where the emplacement of massive dams
for water storage and power generation substantially reduced the streamflow volumes
and shifted the seasonal streamflow regimes. Significantly, however, both those river
systems currently support diverse fish assemblages that include native and introduced
species. Those rivers are possible examples of where some native fish populations were
severely reduced or essentially extirpated in past decades but are now recovering as
more conducive streamflows were restored.

Several detailed quantitative analyses have explored the relationship between fish
distribution and abundance and environmental factors in the lower Tuolumne River and
other San Joaquin basin tributaries. Some of the primary influential variables include
both water quality and physical habitat characteristics such as specific conductance,
mean water depth and stream gradient. Fish assemblage structure in those rivers appears to have a dynamic aspect that reflects streamflow variation through the seasons and from year to year. For example, natural flow regimes with high winter-spring flows have tended to favor native California species which are evolutionarily adapted to such regimes.

**North Fork Mokelumne River.** The North Fork Mokelumne River has been heavily modified by hydropower projects but has a fairly wide range of streamflow conditions over the watershed. We summarize fish sampling data taken from a recent (1999) comprehensive environmental survey. A wide variety of fish species and habitat conditions occur over the range of sampling localities, including some areas completely dominated by introduced trout species. Streamflow data exist for the same or nearby localities to accompany the fish data but were not available for our review. Nonetheless, this river system warrants further evaluation in view of the considerable fish and streamflow information that has been collected at numerous localities throughout the watershed.

**Conclusions and Recommendations**

We compiled information summaries on fish species abundances and streamflow characteristics for five river systems. Our initial goal was to assemble enough information from previous surveys of the selected rivers to draw inferences regarding the sufficiency (or lack thereof) of streamflows for maintaining robust native fish populations. Only two of the five river surveys that we reviewed contained enough pertinent information to allow more than a cursory evaluation of the relationship between streamflow regimes and abundances of certain native fishes.

The reviewed surveys for the lower Pit River and North Fork Mokelumne River provided fish abundance and streamflow information that could be used for further analysis beyond the present project. We were not able to analyze that information deeply enough to identify any meaningful quantitative patterns or relationships within our project time-frame. Recent monitoring activities on the lower Tuolumne River and lower Mokelumne River watersheds have accumulated additional high-quality data that would be suitable for analysis of streamflows and fish population relationships. We recommend that further studies be conducted to quantitatively explore the streamflow-fish relationships in those four river systems.

Our survey focused on the relationship between streamflow regimes and the presence of native fish populations. We reviewed information on spatial scales that ranged from highly localized sampling areas to large portions of watersheds (e.g., the entire lower Pit River). While our study considers relatively broad (and vague) aspects of streamflow effects on native fishes, it consolidates information that is important for assessing the ecological needs of native fish populations. To correctly understand the impacts of current natural and human-induced stressors (e.g., water diversions, pulse flows) on natural fish populations, those stressors must be viewed within the context of the
background streamflows and associated conditions (e.g., temperature) that were experienced by the fish species during the recent past.

Future studies to evaluate the causative relationship between streamflows and fish assemblage structure will need to consider the responses of fish species to flow-related factors (e.g., temperature, turbidity, oxygen concentration) over a range of spatial scales—i.e., ranging from microhabitats to networks of interconnected streams within watersheds. Those studies will require detailed monitoring of environmental variables and linking the data to the physiological, behavioral and reproductive performances of the fishes at the corresponding spatial scales and over a range of time-scales (e.g., daily, monthly, seasonally and annually).

Benefits to California

Our review of selected river systems and fish species in the Central Valley region contributes to a conceptual framework that eventually would explain why native fish species have been able to maintain viable populations in some circumstances but not in others. The broad goal of understanding the detailed ecological mechanisms that operate in each situation will require much further work by laboratory and field researchers. Our study is intended to provide a retrospective conceptual synthesis. Ultimately, we feel that the consolidation of enough information to clarify the key ecological needs of native fish species will likely point to novel ways of managing watersheds to benefit both humans and aquatic wildlife.

2.1.9. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River (Year One; Klimley et al. 2005)

Authors: A. Peter Klimley, Joseph J. Cech, Jr., Lisa C. Thompson, Sarah Hamilton, and Stephanie Chun (University of California, Davis)

Introduction

Human-manufactured increases in water flow (pulses) are common within rivers. There are many reasons for anthropogenic water discharges: generating electricity, providing irrigation water, releases for flood control within reservoirs, flushing streambeds, and facilitating human recreation such as river rafting. California native stream species evolved with seasonal fluctuations, but their increased frequency and late, warm-season timing represents significant deviations from the natural hydrograph.

Purpose

Although water releases provide obvious benefits to humans, the effects of these three types of flow pulses on the community of species present within streams are relatively
unknown. For that reason, we have conducted both experimental and field studies to assess the impact of pulse flows on fish species that inhabit Californian rivers.

Strong pulsed flows may have possible negative effects on fishes such as longitudinal displacement (forcing downstream of normal habitat) and lateral displacement (stranding along changing channel margins).

Project Objectives

The overall objective of this research was to identify the effects of pulsed flows on fishes. We conducted experimental and field investigations on four species, rainbow trout (Oncorhynchus mykiss), hardhead minnow (Mylopharodon conocephalus), brown trout (Salmo trutta), and Sacramento sucker (Catostomus occidentalis).

There were three phases to Year 1 of this study:

1) tracking the movement of subadults and adults (>15 cm TL), tagged with radio transmitters, in a river to ascertain whether individuals are displaced longitudinally in response to pulsed flows,

2) quantifying the distribution of juveniles (<15 cm) in a river from visual censuses of unmarked individuals and those marked with visible implanted elastomer (VIE) before, during, and after releases, and

3) determining the degree of longitudinal and latitudinal displacement as well as substrate preference of juvenile fishes in varying flows in laboratory experiments.

Project Outcomes

Radio Tracking

The research team captured three rainbow trout by hook and line, implanted radio tags into their peritoneal cavities, and released them into the Chili Bar Reach of the American River during the period from July 23 to August 5, 2004. These fish were exposed to one and rarely two pulsed flows per day. The research team searched for these fish during seven days from August 3 through 12, 2004. Rainbow trout (RT) 1 was captured and tagged on July 29 and the tag was relocated 925 meters (m) upstream seven days later; 111 m further upstream on the following day. It exhibited no movement when located twice, three and four days later; and was determined to no longer be in the river. RT 2 captured and tagged and subsequently never relocated by the research team. RT 3 was captured and tagged August 5 and was located four times later within a 100-m radius of its original release location.

One rainbow trout and six brown trout were tagged with radio tags and tracked during a single pulsed flow on September 15, 2004 in Silver Creek, a tributary of the American
River. These individuals were located on the river after capture, later before the pulsed release, during the release, and after the release. No significant differences were found between the distances moved, normalized for their daily movement, between these three periods.

**Snorkel Survey and VIE Marking**

Young-of-the-year (less than one year old) and juvenile brown trout and rainbow trout were captured using minnow traps and angling, and marked by injecting Visible Implant Elastomer (VIE) prior to the pulsed release of water into Silver Creek. VIE is a silicone based material that is used to track fish. VIE tags are injected as a liquid beneath transparent or translucent tissue and then soon turns into a solid that remains externally visible and does not harm the fish. Individuals were marked with different colors in three reaches of the river, each 100 m in length, in order to detect movement between the reaches during the pulsed flow. The VIE marks were not observed on individuals of either species during visual snorkel surveys before and after the survey, but this could be because a relatively small proportion of the total fish populations were marked, and individuals could be observed only from several meters away.

Fish numbers were recorded in 15 pools along a 300 m reach of the river during snorkel surveys before and after the pulsed flow. Fish were identified to species where possible and age was estimated either as young-of-the-year, juveniles, or adults. The total fish density in each pool did not appear to differ markedly before and after the pulse. Some pools contained fewer fish after the pulse, but others contained more fish after the pulse, and there did not appear to be a pattern along the length of the study reach. Numbers of young-of-the-year per pool tended to be lower after the pulse, although some pools contained more fish after the pulse. Numbers of juveniles were generally comparable pre- and post-pulse. Likewise, adult fish numbers did not appear to differ substantially between snorkel surveys. When the counts were examined, and normalized to take into account the different pool sizes, there were still no clear trends in fish distribution.

**Longitudinal and Lateral Displacement Experiments**

The research team determined the responses of juvenile hatchery-reared rainbow trout, hardhead minnows, and Sacramento suckers to simulated pulsed flows within a 16.5-m long longitudinal flume, in which rocks were placed to simulate the substrate of the main stem of the American River. Although fish moved either upstream or downstream, the mean position of each sample of individuals was close to the center of the flume for each of the five periods of increasing and decreasing flows. This indicated that the fish did not swim or were not transported downstream or moved upstream when in the flume, and this may be due to the presence of a substrate, which created a refuge with slower flows for a fish to avoid having to expend the energy to maintain its position in the presence of higher water velocities. Hardhead minnows and the hatchery-reared rainbow trout swam mainly over substrate; Sacramento suckers swam less often over the substrate.
The movements of individuals of these species were also determined in a 2 x 1 m lateral displacement flume, consisting of a rectangular tank separated into a main channel that never drained and a raised wide channel that alternately flooded and became exposed. Water circulated through the apparatus, flowing downward over a 10 degree slope into a series of channels and potential holding areas for this fish. Four pools existed on the raised wide channel with different shapes, holding, and draining capacities. Fish could become stranded in one of these pools as the water level subsided within the apparatus. Three (7.8 percent) of the 38 fish placed within the apparatus became stranded within one of the artificial pools. One Sacramento sucker and two hardhead minnows were stranded in the margin substrate and pools. The three fish were stranded after remaining within the apparatus during a short acclimation period; no individuals stranded after having a long period of acclimation. Rainbow trout did not strand during any experiments. The fish became stranded only in the largest pool.

Conclusions and Recommendations

Radio-telemetry in South Fork of the American River

Conclusions. This pilot study demonstrated that it was possible to tag and track fish on the South Fork. The paucity of individuals tagged and tracked precludes us from making any conclusions as to the effect of the pulsed flows on rainbow trout in the American River. However, the low densities of trout in comparison with other sierra streams would suggest that there are some factors limiting the trout population, which may be correlated to pulsed flows.

Recommendations. More rainbow trout need to be tracked both in the presence and absence of pulsed flows within the Chili Bar Reach of the American River. The research team angled for rainbow trout for a total of nine days during Year 1, for a total of about 23 person-days. With this amount of effort, only three rainbow trout were of suitable size and condition for tagging. For this reason, the research team concludes that it is infeasible to track wild rainbow trout in the main stem of the South Fork of American River. Alternatively, the team will tag and release rainbow trout raised at the local trout hatchery into the American River during Year 2. Hatchery trout may not respond to pulsed flows as wild fish might, but describing their response to these flows is important, because they represent the majority of trout presently inhabiting Californian rivers.

Radio-telemetry in Silver Creek

Conclusions. One rainbow trout and six brown trout were tagged with radio tags and tracked during a single pulsed flow in Silver Creek, a tributary of the American River. These individuals were located on the river after capture, later before the pulsed release, during the release, and after the release. The results indicate that the single pulsed flow did not alter the distribution of fish within the Silver Creek study reach.
Recommendations. This field study indicates that a single, small release of water into a stream does not significantly alter the distribution of subadult trout. More frequent stream channel maintenance (to promote scouring) releases may be of greater magnitude and frequency and could affect the distribution of fishes. Thus, it is necessary to identify the effect of different types of flow releases on fishes in Californian rivers. This is a first-step toward identifying the effect of water releases produced for recreational rafting or hydroelectric power on the local fish.

Snorkel Survey and VIE Marking in Silver Creek
Conclusions. Trout did not appear to experience large downstream displacements due to the one-day pulse in Silver Creek, or if they were displaced, they had moved back upstream by the time of the post-pulse survey. Additional statistical analyses may clarify the response of the local trout population to the pulse, particularly regarding young-of-the-year distribution. Preliminary analyses indicate that a one-day pulse may not be harmful to trout, at least not in a stream with a large number of velocity refugia (for example, crevices, boulders, deep pools), and a bedrock bottom. However, pulses may negatively affect the ability of trout (and other fish) to feed, due to very high flow velocities, and/or increased turbidity (decreased effective search distance). More frequent pulses may eventually result in decreased growth rates, increased vulnerability to predation (smaller fish are more vulnerable), and decreased survival rates.

Recommendations. The short time frame available for trapping and marking fish precluded doing multiple pre-pulse snorkel surveys, in order to determine the variability of fish density per pool in the absence of a pulse.

The pulse flow release occurred in September, when young-of-the-year trout were well developed and likely able to locate and move to low velocity areas to avoid the higher flows. It would be informative to test pulses of similar magnitude at other times of the year, such as early summer, when fry may be newly emerged, and less able to locate and use flow refugia.

The habitat in Silver Creek is relatively complex and heterogeneous, which likely provided a wide variety of flow refugia for fish. It would be useful to test the impacts of a similar pulse in a stream with less complex habitat to see whether fish are more likely to be displaced as habitat complexity declines.

Longitudinal Flume
Conclusions. Using the longitudinal-displacement experimental flume; featuring a long (15+ m) test section, clear panels for behavioral observations, a variable-speed drive to simulate pulsed flows, and rocks to simulate American River habitat characteristics; the research team found that juvenile rainbow trout, hardhead, and Sacramento suckers trended to remain in the section to which they were introduced throughout the pulsed flow period. Thus, despite open channel water velocities up to 0.463 m s⁻¹, these three species were neither displaced downstream nor stimulated to swim upstream during or
after the flow pulse. It is possible, of course, that these flow-pulse-associated behaviors would change at water velocities higher than those that were tested.

Recommendations. The research team will conduct temperature preference tests on adult rainbow trout and hardhead minnows under different flow regimes. These resulting data would complement field-derived temperature measurements of fishes’ selected habitats (for example, before and after pulsed flows associated with hydroelectric or white-water rafting activities). Managers will be able to model adult fish distributions based on this study’s resulting thermal (as well as hydraulic) maps of stream reaches. The value of the laboratory derived data would be their accuracy (especially if derived from fish with different temperature acclimation histories), speed (many species measured within a few months, after set up), and low cost (especially after initial investment in equipment).

Lateral Displacement Flume
Conclusions. Using the lateral-displacement flume; featuring a main-channel and a pulse-flooded, gravel river-bank section with draining and non-draining pools and a 10° slope; juvenile rainbow trout appeared to resist stranding as pulse-flow waters receded down the slope bank. In contrast, with a short acclimation period (simulating the shorter inter-pulsed periods that may characterize days with both morning and evening high-hydroelectric-demand periods), Sacramento suckers, and especially hardhead, may be stranded via pulse-flow associated lateral displacement. All of the stranded fish would be vulnerable to predation in their non-draining pools.

Recommendations. It is necessary to use both laboratory and field methods to determine the energetic costs when exposed to various pulsed flows. After determining the relationships among swimming velocity, tail beat frequency, and oxygen consumption (metabolic) rate in a Brett-type swimming respirometer, it will be possible to estimate the costs (energy, food, or oxygen-based) associated with a flow pulse by measuring tail beats, using special radio tags, over the flow pulse in the field. The field-based tail beat counts will give accurate estimates of stream-habitat energetic costs because the fish’s behavior in a real stream (including the potential uses of hydraulic cover structures) is incorporated into the measurements.

Benefits to California

The field and laboratory studies described in this report provide an evaluation of the effects of pulsed releases of water for recreational and commercial purposes on the behavior and movements of subadults and adults of these species of fishes. The results of these studies may help agencies manage pulsed flows with minimal impacts to the local fish.
2.1.10. Experimental and field studies to assess pulsed, water flow impacts on the behavior and distribution of fishes in the South Fork of the American River
(Year Two; Klimley et al. 2007)

Authors: A. Peter Klimley, Joseph J. Cech, Jr., Lisa C. Thompson, Sarah Hamilton, and Dennis E. Cocherell (University of California, Davis)

Introduction

Human-manufactured increases in water flows (pulses) are common within rivers. There are many reasons for anthropogenic water discharges: generating electricity, providing irrigation water, releases for flood control within reservoirs, flushing streambeds, and facilitating human recreation such as river rafting. California native stream species have evolved with flow fluctuations, but their increased frequency and late, warm-season timing represents significant deviations from the natural hydrograph.

Purpose

Although water releases provide benefits to humans, the effects of flow pulses on the community of species present within streams are relatively unknown. For that reason, both experimental and field studies were conducted to assess the impact of pulse flows on fish species that inhabit California Rivers. Strong pulsed flows may have possible negative effects on fishes such as longitudinal displacement (forcing downstream of normal habitat) and lateral displacement (stranding along changing channel margins).

Project Objectives

The overall objective of this research was to identify the effects of pulsed flows on fishes. Experimental and field investigations were conducted on two fish species: rainbow trout (Oncorhynchus mykiss) and hardhead (Mylopharodon conocephalus).

There were three components to Year 2 of this study:

- Track the movement of larger adult rainbow trout (≥ 25 cm TL), tagged with radio transmitters, to ascertain whether individuals are displaced longitudinally in response to pulsed flows in the River.
- Assess and estimate the energetic costs of adult rainbow trout experiencing pulsed flows by implantation of an electromyogram (EMG) transmitter, calibrating the fish’s energetics in the laboratory, and tracking their movements and energetics in the river.
- Assess the behavioral temperature preferences of adult rainbow trout and hardhead utilizing a large laboratory annular apparatus.
Project Outcomes

Radio Tracking: We tracked the movements of ten intermediate (SL 25.5 - 31.0 cm) and ten large (SL 32.0 - 38.5 cm) radio-tagged adult rainbow trout in response to frequent pulsed flow releases in the South Fork American River (California) from July to October 2005. During this period the river had base flows of 5 m³s⁻¹, with 4-h midday releases of 40 m³s⁻¹ on most days for whitewater rafting, plus higher releases on many days with peaks up to 110 m³s⁻¹. Fish were released into the river 12.9 and 16.1 km upstream of Folsom Lake and tracked on a weekly basis. In week 1, the small trout dispersed within 1 km upstream or downstream of their release sites. Eight of ten small trout moved little in the following 8 weeks. Between weeks 4 and 7, one small trout moved 2.0 km upstream, while between weeks 5 and 7, another small trout moved 2.0 km downstream. In weeks 1 to 3, eight of ten large trout moved from 1.0 to 4.5 km downstream. Between weeks 5 and 6, one large trout moved from a position 1 km downstream to a position approximately 3.5 km downstream, and then moved to a position 8.0 km downstream of the release site between weeks 7 and 8. Large trout spent most of their time in runs (41%), followed by pools (30%), and rapids (29%). Small trout were most often observed in runs (42%), followed by rapids (30%), and pools (28%). Repeated measures ANOVA analyses showed no significant relationships between fish movement and water flow variables, release site, location within river, fish size, or fish condition (p > 0.05 for all variables). Our results suggest that rainbow trout with SL > 25 cm are not forced downstream by daily pulsed flow increases from 5 to over 40 m³s⁻¹.

Electromyogram Telemetry: We utilized radio telemetry with EMG sensors to study the energetic output of rainbow trout in response to pulsed flows. Previous years investigations suggested that the fish within the watershed exhibit minimal directional movements. Nine rainbow trout (≥ 30 cm SL) were implanted with these sensors to investigate movement patterns, swimming speed, and oxygen consumption of hatchery fish experiencing pulsed flows. Swimming activity was calibrated in a Brett-type respirometer and fish were released into the river implanted with EMG sensors. Each individual’s EMG outputs were recorded before the water pulse, as the water increased, stabilized, and decreased on three separate occasions. EMG measurements were converted to swimming speeds by using laboratory calibrations. Factors potentially related to median swimming speeds, such as river discharge, time, sex, location, and pulse stage (no pulse, rising, peak, and decreasing) were analyzed using a hierarchical mixed linear model. Pulse stage was found to be statistically significant; increasing pulse stage was correlated with increasing swimming speeds. In addition, above a river flow of 44 m³s⁻¹ (1554 ft³s⁻¹), swimming activity decreased. These results indicate that the rainbow trout’s ability to respond to pulsed flows without being displaced incurs other costs such as increased energy expenditure and decreased foraging opportunities at high flows.
**Temperature Preference:** Past temperature preference chambers had design limitations handicapping their usefulness in determining aquatic animal preferences. To effectively determine adult stream fishes’ preferences, we constructed a 3-m diameter, annular chamber of acrylic plastic. A smaller version of this annular apparatus proved to be effective in recent studies. The annular design decreases possible confounding variables of differential light intensities, water depths, and cover found in other chambers. Our annular chamber presented uniform light intensities, constant water depths and velocities, and stable vertical and horizontal temperature gradients for the experimental fish. Hardhead (mean TL: 36.2 cm) and rainbow trout (mean TL: 35.4 cm) were acclimated to 12, 15, and 18 °C and tested, individually, in the 12 - 24 °C annular gradient. The hardhead preferred temperatures in the range of 19.6 - 20.0 °C, while the trout preferred a significantly cooler range: 16.0 - 18.4 °C. All of the hardhead avoided water < 17 °C, whereas the 12 and 15 °C trout acclimation groups avoided water > 19 °C, and the 18 °C trout avoided water < 16 °C and > 20 °C. Presumably, stream fish temperature preferences can be used to optimize environmental characteristics in regulated systems for resident and migratory species.

**Conclusions and Recommendations**

**Radio Tracking:**

Conclusions --- We tracked the movements of ten small (SL 25.5 - 31.0 cm) and ten large (SL 32.0 - 38.5 cm) radio-tagged rainbow trout in response to frequent pulsed flow releases in the South Fork American River (California) from July to October 2005. During this period the river had base flows of 5 m³s⁻¹, with 4-hour midday releases typically of 40 m³s⁻¹ on most days for whitewater rafting. Plus higher releases on several days, with peaks up to 110 m³s⁻¹. Fish were released into the river 12.9 and 16.1 km upstream of Folsom Lake and re-located weekly. In week 1, the small trout had dispersed within 1 km upstream or downstream of their release sites. Eight of ten small trout moved little in the following 8 weeks. Between weeks 4 and 7, one small trout moved 2.0 km upstream, while between weeks 5 and 7, another small trout moved 2.0 km downstream. In weeks 1 to 3, eight of ten large trout moved from 1.0 to 4.5 km downstream. Between weeks 5 and 6, one large trout moved from a position 1 km downstream to a position approximately 3.5 km downstream, and then moved to a position 8.0 km downstream of the release site between weeks 7 and 8. Large trout spent most of their time in runs (41%), followed by pools (30%), and rapids (29%). Small trout were most often observed in runs (42%), followed by rapids (30%), and pools (28%). Repeated measures ANOVA analyses showed no significant relationships between fish movement and water flow variables, release site, location within river, fish size, or fish condition (p > 0.05 for all variables). Our results suggest that rainbow trout with SL > 25 cm are not forced downstream by daily pulsed flow increases from 5 to over 40 m³s⁻¹.

**Recommendations:** The rainbow trout in this study did not appear to be displaced downstream by the pulsed flow regime of the South Fork American River in the summer of 2005, in spite of over 20-fold daily flow fluctuations. The fact that hatchery-reared rainbow trout were used for this study may have influenced our results. These fish
would not have experienced natural pulsed flood flows during their development. Yet they did not permit themselves to be swept downstream during the increased flow velocities. It would be informative to repeat this study in a river reach that contained adequate numbers of wild trout of a size suitable for radio-tagging.

Over the time intervals that we tracked fish they did not seem to respond to increased flows by moving longitudinally upstream or downstream. However, the largest movements upstream were accomplished during weeks of lower pulsed flows (weeks 11 and 12). This suggests fish may move upstream more readily when pulsed flow peaks are lower, and that larger pulsed flows may limit the degree to which trout will move upstream. River regulators may wish to limit the magnitude of summer pulsed flow peaks at times when trout are expected to moving upstream in search of rearing habitat.

Initially after their release the large trout in our study moved downstream, but in subsequent weeks, they tended to remain in approximately the same location. The smaller trout did not show this same initial downstream displacement. The larger fish would have had higher caloric requirements relative to the smaller trout. If the larger trout were unable to find habitat with an adequate food supply, they may have traveled downstream in search of areas with greater food abundance, thus spacing themselves out relative to the locally available food supply. It is possible that the pulsed flow regime of the river has indirect effects on trout feeding through impacts on the species composition and abundance of benthic macroinvertebrates. It would be beneficial to study the impact of pulsed flows on this community composition and biomass in conjunction with fish movement and fish diet in order to separate the direct (i.e., velocity) and indirect (i.e., food depletion) impacts of pulsed flows on fish in regulated systems. Also field tracking studies on the movements of juvenile rainbow trout (15-25 cm TL) would help the understanding of how pulse flows impact fish through various life stages.

**Electromyogram Telemetry:**

**Conclusions:** We utilized radio telemetry with EMG sensors to study the movement patterns of adult rainbow trout in response to pulsed flows. Previous years investigations suggested that the fish within the watershed exhibit minimal directional movements. Nine trout (SL ≥ 30 cm) were implanted with these sensors to investigate movement patterns, swimming speed, and oxygen consumption of hatchery fish experiencing pulsed flows. Swimming activity was calibrated in a Brett-type respirometer and fish were released in the river with EMG sensors. Each individual’s EMG outputs were recorded before the pulse and as the water increased and stabilized on three separate occasions. EMG measurements were converted to swimming speeds using laboratory calibrations. Factors potentially related to median swimming speeds, such as river discharge, time, sex, location, and pulse stage, were analyzed using a hierarchical mixed linear model. Pulse stage was found to be statistically significant; increasing pulse stage was correlated with increasing swimming speeds. In addition, above a river flow of 44 m$^3$s$^{-1}$ (1554 ft$^3$s$^{-1}$) swimming activity decreased. These results indicate that the rainbow trout’s ability to respond to pulsed flows without being
displaced incurs other costs such as increased energy expenditure (elucidated via metabolic measurements) and decreased foraging opportunities at high flows.

**Recommendations:** EMG telemetry results suggest that rainbow trout are increasing their energy expenditure by increasing their swimming speed to maintain position when experiencing increasing flows. This increased energy output may alter a fish’s metabolic balance and decrease resources available for growth and reproduction. We recommend that increases in flows be gradual or stepped to allow rainbow trout time to adapt to these changes in flow. In addition, based on their decreased activity at river flows above 44 m3s⁻¹, flows should not regularly exceed that level. More studies should be conducted with different fish species that are common in that stretch of river such as the Sacramento sucker (Catostomus occidentalis) and Sacramento pikeminnow (Ptychocheilus grandis). Efforts should also be made to investigate fish behavior at night, especially because late night pulses tend to be larger than pulses during the daylight hours. Temperature, turbidity and increased macroinvertebrate drift associated with pulsed flows may also have relevance in determining fish behavior and energetics during pulsed flows.

**Temperature Preference Experiments**

**Conclusions:** Temperature preference chambers used previously have had design limitations handicapping their usefulness in determining aquatic animal preferences. To effectively determine adult stream fishes’ preferences, we constructed a 3-m diameter, annular chamber of acrylic plastic. A smaller version of this annular apparatus proved to be effective in recent studies. The annular design decreases possible confounding variables of differential light intensities, water depths, and cover found in other chambers. Our annular chamber presented uniform light intensities, constant water depths and velocities, and stable vertical and horizontal temperature gradients for the experimental fish. Hardhead (mean TL 36.2 cm) and rainbow trout (mean TL 35.4 cm) were acclimated to 12, 15, and 18 °C and tested individually in an 12 - 24 °C bimodal annular gradient. Whereas the trout preferred temperatures in the 16.0 - 18.4 °C range, the hardhead preferred a significantly warmer range: 19.6 - 20.0 °C. The trout acclimation groups of 12 and 15 °C actively avoided water > 19 °C, whereas the 18 °C trout showed a pronounced avoidance of water < 16 ° and > 20 °C. All hardhead acclimation groups avoided water < 17 °C.

**Recommendations:** Consideration of the species’ behavioral preferences is integral to explaining the distribution of native fishes in the South Fork American River. The temperature preferences of adult rainbow trout were elucidated in experiments conducted on three groups of fish, acclimated to different temperatures. The non-anadromous trout preferred a cool or an intermediate water temperature throughout the years’ seasons. When ambient water temperatures are elevated, as is typical during California summers, the trout choose a narrower water temperature range of 15-18 °C. During this season trout avoid the coolest water temperatures in favor of intermediate
temperatures. During the cooler parts of the year, the trout would presumably prefer cooler temperatures (< 16 °C). Because the 18 °C-acclimated rainbow trout showed a bimodal locational preference in their seeking their 18.4 °C preferred temperature, these results argue for temperature, rather than some other influence in the laboratory, to be the dominant behavioral cue in this apparatus.

Understanding the temperature preference of hardhead will require a greater understanding of their life history, swimming, metabolic, and growth performance throughout the South Fork. This ecological information will aid in determining why hardhead occurred in limited numbers at warmer temperatures in the South Fork, and occurred in large numbers in colder reaches of the river, while they preferred warmer temperatures in our laboratory experiments. Hardhead could seek refuge in colder river stretches and reservoirs due to: 1) resource competition from native or non-native fishes, 2) parasitic infections decreasing survival at warmer temperatures, or 3) lower quality forage in the warmer river. River water temperatures should be managed to simulate the natural temperature range throughout the year, which best suits the native species present.

Benefits to California
Human-manufactured water flow increases (pulses) are common within California’s Rivers. Although native stream species have evolved with seasonal fluctuations, the increased frequency (e.g., for peaking hydroelectric operations) and late-summer timing (for recreational purposes) represents significant deviations from the natural hydrograph. The effects of flow pulses on the community of species present within the streams are relatively unknown. The field and laboratory studies described in this report provide a description of the impacts of pulsed releases of water for recreational and commercial purposes on hardhead and rainbow trout. The knowledge resulting from these studies may help agencies to manage their pulsed flows to minimize their effects on the resident fish fauna.
2.1.11 Pulsed flow effects on the foothill yellow-legged frog (Rana boylii): Integration of empirical, experimental and hydrodynamic modeling approaches (Kupferberg et al. 2005 and 2007)

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Introduction

The foothill yellow-legged frog (Rana boylii) is one of a few California amphibians whose complete life cycle is associated with fluvial environments. The life history stages of R. boylii occur along a mobility continuum from immobile (eggs) to highly mobile (adults), such that adaptations that improve survival vary in relation to life stage. To avoid disturbance, the timing of this complex life history and set of habitat preferences is synchronized with the seasonality of runoff during the predictable cycle of wet winters and dry summers occurring across R. boylii’s range.

Over the last half century, R. boylii has declined dramatically, especially in Southern California and the southern Sierra Nevada mountains. Dams and reservoirs have been cited as likely factors in this decline because they drastically alter the flow regime and sediment budget of rivers in which this species has evolved, resulting in permanent alteration to in-stream habitats. The ensuing impact on R. boylii status has been a focus of study over the last decade, but many knowledge gaps remain. Perhaps one of the largest gaps in understanding the effects of dams is determining the role of large aseasonal fluctuations in water discharge, referred to as pulsed flows, in R. boylii decline. Under a natural flow regime, discharge gradually declines in early summer so eggs and larvae do not frequently encounter large magnitude flood events. In regulated rivers the altered timing, duration, and magnitude of discharge do not match R. boylii’s flow regime adaptations. Although the magnitude of summer and fall pulsed flows in regulated rivers may not be greater than historic discharge, the timing and frequency of such pulses can be out of synch with the timing of R. boylii’s life cycle. Those life stages that are confined entirely to the aquatic environment, eggs and tadpoles, are particularly vulnerable to changes in flow.

In this study pulsed flow effects on R. boylii were examined by combining: (1) analyses of existing empirical data; (2) laboratory and field experiments that quantify the physical tolerances and behavioral responses of tadpoles to changes in velocity; and (3) development of a 2-dimensional (2D) hydrodynamic modeling approach that evaluates the effects of pulsed flows on breeding and rearing habitat. This report is divided into six chapters. Chapters 2, 3, 4, and 5 present the bulk of the research. Chapters 1 and 6 introduce the research problem and synthesize the collective results, respectively. Our broad conclusion, that hydrologic conditions during the spring breeding and summer larval rearing season are central to the conservation of R. boylii, is supported when the multiple lines of evidence presented in Chapters 2-5 are evaluated in aggregate.
Review of Statewide Published Data and FERC Study Reports

As a result of its declining status, the foothill yellow-legged frog (R. boylii) has increasingly become a focal species in water management planning, especially in Federal Energy Regulatory Commission (FERC) re-licensing programs of hydroelectric dams. However, due to the dispersed nature of re-licensing efforts, conducted on a project by project basis, and the multiple agencies involved, a comprehensive assessment of pulsed flow effects on R. boylii has been challenging. The objective of Chapter 2 was to develop such an assessment and identify remaining information gaps for the experimental (Chapter 4) and modeling (Chapter 5) components of this study. Chapter 2 provides a compilation, review, and summary of empirical data from the scientific literature and FERC hydropower re-licensing reports. During the course of the review, means for improving future FERC re-licensing studies, and other studies of water flow effects, were also identified.

The literature/FERC report review revealed several patterns specific to the different life stages of R. boylii. Egg masses were negatively affected by pulsed flows via scouring and desiccation occurred if oviposition took place during high flows followed by rapid flow recession. Thus the timing, magnitude, and duration of pulsed flows are the critical characteristics that can be managed to reduce impacts to egg masses. Stranding of tadpoles following pulsed-flow releases was observed in some studies. There was also an indication that pulsed flows lead to a lower abundance of tadpoles, though this result was not consistent across all study locations. Effects of pulsed flows on post-metamorphic life stages were not clear and preliminary evidence for short-term behavioral responses of juvenile frogs to these flows needs further research.

Methods to quantify suitable R. boylii habitat varied among studies. Stationary polygon and transect methods were most relevant to the requirements of immobile stages (eggs and early tadpoles). Shifting transect methods provided information on the overall area of suitable habitat, while polygon methods provided information on the number of suitable habitat patches as well as overall area. A quantitative graphical analysis of data culled from reports showed that variation in suitable habitat area due to changes in discharge was very site specific. Some sites showed increasing areas while others showed decreasing areas, as discharge increased, indicating the influence of channel morphology and local geomorphic features.

The review of studies identified key information gaps relating to effects of pulsed flows on the tadpole life stage. Effects on activity level, behavior, growth, and survival responses to variation in water velocity and depth were addressed by the experimental component of this study (Chapter 4). The assessment of transect and polygon methods previously used to quantify suitable habitat at a few discharge levels identified several weaknesses in these methods and led to development of a 2D hydrodynamic modeling approach that can assess suitable habitat at varying discharges (Chapter 5).
Case Studies in Three Watersheds: Pulse Effects on R. boylii populations in Regulated and Unregulated Rivers

Three river systems in Northern California were selected with pre-existing hydrologic and frog population monitoring programs to examine the relationship between pulsed flows and changes in R. boylii abundance through time. The sites are the South Fork Eel River (SF Eel), Mendocino Co, the North Fork Feather River (NF Feather), Butte and Lassen Cos., and Alameda Creek (Alameda Ck), Alameda Co. Seventeen years of egg mass censuses on the unregulated SF Eel indicate that: (1) Annual fluctuations in population growth are not associated with the magnitude of winter peak discharge, but rather are associated with spring and summer conditions for recruitment three years prior. Spring pulsed flows that cause egg and larval mortality can change population dynamics. (2) Timing of breeding in the spring is not associated with stage height; there is only a very weak trend for frogs to breed later in years with higher water levels. It is likely that increasing water and air temperature cue the initiation of breeding, not the amount of shallow slow habitat area inundated at the channel margin. (3) The magnitude and timing of spring pulse flows have an important influence on whether embryos survive to hatching. While large magnitude pulses decrease egg survival, smaller magnitude pulses later in the season can cause higher mortality.

Comparisons between two regulated reaches in the NF Feather, Cresta which experienced four years of monthly spring and summer whitewater boating flows, and Poe that did not, corroborates the three year lag time hypothesis. The Cresta reach R. boylii population has declined significantly relative to the frogs in Poe. Divergent population trajectories were also observed when comparing an unregulated and a regulated reach in Alameda Ck. In this more southern population, a two-year time lag between recruitment conditions and adult population size may occur.

This observational evidence linking pulsed flows to decline highlights the pressing need for demographic study of R. boylii and the development of matrix projection models that could forecast population trajectories under varying scenarios of pulsed flow frequency.

The Effects of Velocity Manipulation on Larval R. boylii

To assess the effects of pulsed flows on tadpoles, a life stage that does not typically experience floods, velocity was manipulated in laboratory flumes and field enclosures. Focal questions were: 1) On a short time scale, what is the behavioral response to increasing velocity; 2) can tadpoles swim back to patches of preferred depth and velocity; 3) what is the cumulative impact of the observed behavior patterns on growth and development; and, 4) are behaviors in the relatively artificial, yet highly replicated, lab and field enclosure settings consistent with observations from the difficult to replicate, but more realistic, open river manipulations?

In our experiments, tadpoles across a wide developmental and size range sought refuge in substrate as soon as velocity increased. Behavioral responses and performances were
consistent among experimental venues. In a laboratory flume, tadpoles could no longer swim or maintain position under rocks at a mean critical velocity of 20.9 ± 1.6 cm/s. Critical velocity varied negatively with tadpole size and developmental stage, with velocities as low as 10 cm/s causing 25 percent of tadpoles to be displaced. The most easily displaced individuals were the largest, especially those closest to metamorphosis. In the lab flume without flow refugia, swimming against a 5 cm/s current, tadpoles reached exhaustion at 7.4 ± 2.6 min. For recently hatched tadpoles in the field, there were direct lethal effects of velocities as low as 10 cm/s. While in flow refugia, there were also lethal effects of predation. For tadpoles < 6 weeks old, mortality risk was doubled at elevated, yet sub-critical velocities. The velocities shown to have negative effects in these trials were less than the typical increases in velocity near shore when aseasonal pulsed flows occur (chapter 2).

Assessment of Hydrologic Variability on R. boylii Habitat Hydraulics using 2-Dimensional Hydrodynamic Modeling

A 2-dimensional model, River2D, was used to evaluate changes in habitat-scale hydrodynamics and the related changes in habitat suitability and availability for R. boylii egg masses and tadpoles. Two study sites in Northern California, one on the unregulated SF Eel and the other on the regulated NF Feather, were selected for modeling. The precision and accuracy of the model in predicting local hydraulics at scales relevant to R. boylii, particularly in the near-shore environment where preferred habitat exists, was determined first. Changes in local hydraulics were then related to R. boylii habitat suitability using data obtained at the study sites and from concurrent controlled experiments in order to predict habitat quality and availability at the breeding sites under different flow regimes.

Results from the modeling analysis indicate that simulated depths and velocities from River2D generally agreed well with measured field values, with similar error in mid-channel areas and the near-shore environment. Modeled velocities at exact egg locations however were over predicted, with a mean error (observed-predicted) of -0.04 ± 0.04 m/s. In shallow habitats with large poorly sorted substrates, the resolution of surveyed bed topography was not fine enough to depict the microhabitat (<0.25m2) variability in depth, particularly behind large cobbles where eggs were laid. As a result, the model averaged local depths and calculated velocities higher than was observed at point locations behind the cobbles. When coupled with a definition of breeding habitat suitability that encompassed the variability of field-measured values and the range of error within the model output however, the model accurately predicted suitable breeding locations throughout the survey reach.

Using previously published data and information gathered in this study, the impact of flow changes on habitat availability and suitability was modeled at two study sites representative of R. boylii breeding habitat. The sites differ in channel morphology, with the SF Eel site exhibiting a slightly asymmetric wide, shallow cross-section, and the NF Feather site exhibiting an entrenched cross-section with steeply sloping channel banks.
At both sites, modeled increases in discharge above typical late spring flows led to decreased habitat availability, with lower discharges providing the greatest weighted usable area. However, in a seasonal pulse modeling experiment where flows increased from various low spring flows to a high spring runoff flow, higher initial discharges provided the greatest buffering capacity against lethal increases in velocity in breeding habitats. At higher initial discharges, larger proportions of suitable breeding habitats are located in shallow overbank areas, so subsequent increases in discharge result in relatively smaller increases in depth and velocity. In a modeled aseasonal pulse scenario, higher initial discharges also provided the greatest buffering capacity in larval rearing habitats; however, only 20-30 percent of the suitable habitat in the SF Eel site and <5 percent of the suitable habitat in the NF Feather site remained suitable during the pulse regardless of initial flow level due to the low tolerance of tadpoles to even small increases in velocity. In both the spring pulse and aseasonal pulse scenarios, the SF Eel study site provided 2-3 times the buffering capacity of the NF Feather site. These differences between sites were surmised to be due to the differences in channel morphology. The steep channel banks at the NF Feather site provide little refuge from increased velocities as flows increase, while the shallow overbank areas at the SF Eel site provided refuge from high velocities as flows fluctuated.

Management of *R. boylii* may benefit from model-based methods such as those used in this study as long as the limitations and inherent error in 2D modeling is understood and taken into account. A 2D model can simulate mesohabitat-scale conditions for multiple life stages as well as evaluate habitat suitability at a reach-scale; however, the precision of the model is not high enough at typical topographical resolutions to differentiate point velocities in shallow microhabitat locations with coarse substrate where eggs may be located.

**Conclusions and Recommendations**

*Rana boylii* has evolved several adaptations to the Mediterranean climate and associated hydrologic regime (wet winters and dry summers) of California rivers. Their life history stages are tied closely to the natural flow regime, including the timing, magnitude, duration, frequency and rate of change of flows. A fundamental conclusion of this report is that within regulated rivers, flow manipulations can be used to meet—or reduce the impact on—the life history needs of *R. boylii*.

The specific conclusions include:

- Adults breed and lay eggs in areas where the river channel morphology reduces the impact of scour during natural spring run-off pulses. Breeding locations do not experience as much velocity change with change in stage as other locations. Adults select egg laying sites that have low water velocities and relatively shallow water depths. In addition, frogs typically attach eggs to large substrates that provide a local velocity refuge. Suitable breeding sites also have the characteristic of being connected to suitable rearing areas as flows decline.
throughout the summer. That is, recently hatched tadpoles would be able to follow the receding shoreline into a highly suitable rearing location and not be trapped in isolated pools that may dry or become lethally hot. Nonetheless, significant losses of *R. boylii* egg masses occur due to scouring (pulse flows after egg laying) and stranding/desiccation (eggs laid during spring release and flows dropped quickly). Thus, in regulated rivers, timing and magnitude of spring pulses can be manipulated to reduce impacts.

- Tadpoles respond to increases in water velocity and depth by seeking refuge in stream substrates. This response, while potentially protective in the short-term, may result in losses to predation by fish if tadpoles are displaced to the water column or are forced to stay under rocks where predators like crayfish and other aquatic invertebrates dwell. Displacement of tadpoles from substrate refugia can occur at relatively low water velocities (10-20 cm/s) over short periods of time (< 2 hours). Larger (older) tadpoles are more susceptible to increases in velocity than smaller (younger) ones. Tadpoles are also stranded by summer pulse flows. Future research focusing on rate and magnitude of change in discharge should take into account factors such as bank slope, particle size, sorting, and embeddedness. For a small tadpole (< 1 cm) even moderately sized cobbles and boulders could be obstacles to following a receding shoreline. Recommendations for benign ramping rates would thus be site specific.

- Post-metamorphic life stages (juveniles and adults) may be less at risk from pulsed flows, due to their greater mobility. However, if manufactured pulsed flow events are decoupled from fall rain events that might cue frog migration to off-channel over-wintering sites, these life stages may still be susceptible. Issues such as these, which integrate *R. boylii*’s use of multiple habitats at a watershed scale, remain open for future research.

- Overall population dynamics appear to be driven by successful egg laying and tadpole rearing, which is strongly related to spring and summer flow conditions. This relationship is only apparent when incorporating a two (Central Coast streams) or three (Northern Coast and Northern Sierra streams) year lag time, representing time to maturity, into the analyses.

- Areas of suitable habitat can be modeled for both egg and tadpole life stages, but error in precision of point water velocities in shallow microhabitats with coarse substrate may lead to higher than desired risk to these life stages if model results are used carelessly in water management.

- Future FERC related studies would be improved by: integrating data on hydrology and geomorphology, clearly quantifying the sampling effort (e.g., number sites, search time, or area), using consistent, clearly defined life stages, and improving abundance/population estimates through the use of more rigorous field techniques such as mark-recapture.
Recommendations for Management include:

- For populations of *R. boylii* that are considered to be at risk, the primary management recommendation is to minimize fluctuations in flows (i.e. rapid rising and falling of flows above base flow) during the oviposition and tadpole rearing periods. This can be accomplished by directly monitoring breeding, oviposition, and metamorphosis in a given river reach and then regulating water releases based on the monitoring data. A second option, involving less direct monitoring, is to set precautionary dates between which flow fluctuations will be minimized. However, these dates cannot be set until several years of monitoring in a variety of water year types provide valid boundaries.

- Habitat modeling (either 1 or 2-dimensional approaches) can provide a starting point for examining the connectivity between spawning and rearing locations as discharge fluctuates and estimating the effects of pulsed flows on near shore depths and velocities. This information is useful for setting flow conditions during FERC re-licensings, with the following caveats. If base flows are increased, post-license studies will be needed on changes to water temperature, riparian vegetation, bank steepness, and channel morphology, all of which could affect *R. boylii* growth, survival, and habitat suitability. Finally, the hypothesis of a positive relationship between habitat area containing suitable velocities and depths (defined in habitat models as “weighted usable area”) and *R. boylii* population size or stability needs to be tested before management approaches based primarily on habitat area are implemented.

- For populations that are apparently not at risk in regulated river reaches, flows should be managed to simulate the natural pre-regulation hydrographs, and the flow release pattern should differ for different water year types.

- The analytical methods developed in this report can be used as tools to evaluate the potential success of repatriation of *R. boylii* to reaches where there have been known extirpations or where frogs are absent, but present in contiguous reaches.

A number of open questions or information gaps remain. The following recommendations for future research are based on questions that derived directly from this study. However, it is important to recognize that other aspects of this species’ ecology are still not well known and may be critical for the conservation of *R. boylii* over the long-term.

- Exploratory research on short-term behavioral responses to pulsed flows by post-metamorphic life stages. Particular attention should be paid to determining what environmental conditions may cue recently metamorphosed frogs to leave mainstem channels for tributaries and other off-channel water bodies (e.g. seeps and springs).

- A demographic study of *R. boylii* and the development of matrix models that can predict population trajectories under varying scenarios of pulsed-flow frequency.
• Monitoring of one or more reference populations of *R. boylii* in unregulated Sierra Nevada rivers coupled with a peer-reviewed survey and monitoring protocol.

• Studies of water temperature effects on growth and survival of tadpoles.

• Definition and validation of habitat suitability criteria for egg and tadpole life stages.

• Research on how 2D modeling and other habitat assessment methods focused on short segments of rivers can be extrapolated to larger scales and river lengths. This is related to a need to better understand how *R. boylii* is distributed within and among heterogeneous habitats over long sections of rivers and in associated tributaries (i.e. the metapopulation dynamics of the species).
3.0 Benefits to California

This program has provided background information, potential concerns, and priority research needs for California research studies to address the ecological impacts of hydropower pulsed flow on fishes, amphibians and macroinvertebrates in California streams and rivers.

This program also administered funds from the California Energy Commissions on research projects that provided immense benefits to California’s stream biota. The benefits of the projects from this program are multi-faceted in their scale and scope. Research results filled the knowledge gaps regarding the patterns of negative effects of hydropower pulsed flows on species of special concerns such as the foothill yellow-legged frogs and the hardhead minnows, and other riverine biota. These filled knowledge gaps are fundamental to the conservation of these California species.

Results and recommendations from the research projects in this program will assist California’s managers of hydroelectric facilities, industry regulators and policy makers on:

- establishing appropriate methods for evaluating California’s natural resources;
- assessing impacts of seasonal pulsed flow releases on California’s stream fishes, amphibians and macroinvertebrates;
- avoiding unnecessary curtailment of hydropower operation and river recreational opportunities due to lack of knowledge;
- improving future FERC-related studies on species of special concern and other riverine biota;
- balancing the various economic, social, recreational, and environmental demands of the regulated rivers; and
- Providing for the widest variety of beneficial uses in conjunction with hydropower generation.

More informed management decisions will ultimately improve stream habitat conditions, particularly in regards to future California hydropower relicensing projects. Improvements in managing regulated rivers will ideally result in perpetuating and enhancing the quality of California’s natural resources and heritage while also improving opportunities for the people of California to enjoy and benefit from them.
4.0 References


