Pulsed Flow Program

ABSTRACTS

Pulsed Flow Conference

Checking the Pulse of our Streams and Rivers

Alumni Center
University of California, Davis, CA 95616
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PREFACE

The Pulsed Flow Program, established in 2002, is funded by the Public Interest Energy Research Program of the California Energy Commission and administered by the University of California's Center for Aquatic Biology and Aquaculture. It is also supported by the Division of Water Rights of the State Water Resources Control Board. The program's main objective is to address the ecological effects of manufactured or augmented flows from hydropower facilities on aquatic resources within California. Since 2003, nine research projects had been awarded funding and most of the projects are now completed. The Pulsed Flow Conference is one means of disseminating the results of the funded research projects to all interested parties. For more information, please visit our website at http://animalscience.ucdavis.edu/Pulsedflow/index.htm.

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Ecological Roles of Natural Pulse Flows in a Boulder-Bedrock Sierra Nevada River: Woody Riparian Vegetation

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Annual snowmelt hydrographs and winter floods are integral to shaping and sustaining woody riparian vegetation (principally white alder (*Alnus rhombifolia*), Arroyo willow (*Salix lasiolepis*), dusky willow (*Salix melanopsis*)) in the Clavey River, a boulder-bedrock Sierra Nevada river. While the mechanisms of desiccation and seedling scour during the snowmelt recession flows are highly effective in suppressing germination and establishment, neither process is 100% effective. Woody riparian plants can become established within the actively scoured mainstem channel, and then routinely survive 5-yr to 10-yr flood peaks. However, the bigger and less frequent floods (> 20-yr flood events), typically winter floods but occasionally snowmelt rain-on-snow floods, act as partial reset buttons. Entire willow or alder stands can be scoured from larger depositional features, and single trees in the lee of boulder ribs can be either entirely scoured or sheared-off. The 75-yr WY1997 flood peak transformed a mature riparian stand on Cottonwood Bar into one almost barren of woody riparian vegetation. But the flood was not the resetting "mega-flood" originally hypothesized because many willows survived below ground. By WY2005, willows had already conspicuously begun recovery, mostly from the re-growth of sheared-off stems that survived the WY1997 flood, rather than from subsequent germination. Pulse flow releases that mimic the magnitude and frequency of larger natural winter flood peaks (e.g., 20-yr floods) will be extremely important in maintaining boulder-bedrock Sierra Nevada river ecosystems. However more frequent pulse flow releases with much lower peak magnitudes, which mimic the annual snowmelt hydrograph, will be as important: preventing the germination or establishment of a 2-yr old seedling is much easier than scouring away a 5-yr old tree.

Effects of Temperature and Flow on *Ceratomyxa shasta* Actinospore and Polychaete Host Survival

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Ceratomyxa shasta is a myxozoan parasite identified as a primary contributor to salmon mortality in the Klamath River. The parasite has a complex life cycle involving a freshwater polychaete host, *Manayunkia speciosa*. The ecological requirements of this polychaete influence the severity of infection in fish and an understanding of what contributes to high densities and infection of this host may provide management opportunities to reduce the parasite effects. This study investigated the effects of temperature and de-watering on the survival of the polychaete host in its two primary substrates, demonstrating an inverse relationship between temperature and polychaete survival. A small percentage of polychaetes survived 24 h de-watering in both substrates, indicating a higher resilience than expected. A laboratory based flow experiment showed that a high flow facilitated the greatest polychaete densities, whereas experimentally induced polychaete infection prevalence was higher at the slower flow. Infected rainbow trout at the slower flow rate had a shorter mean day to death, indicating a higher infectious dose than at the high flow. These findings indicate that high volumes and low residence times associated with high flow rates may decrease *C. shasta* infection rates in both the fish and polychaete host.

Evaluating Pulsed-Flow-Based Disturbances of Stream Benthos

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Understanding the consequences of pulsed flows for resident stream biota is critical for regulatory decision-making given the variety of beneficial uses that must be provided for under modern licensing agreements. However, the effects of pulsed flow manipulations on stream benthos are poorly understood, particularly in terms of differences in the magnitude, frequency, duration, and timing (or seasonality) of pulsed-flow events. Several studies of benthic communities in regulated rivers of California that experience pulsed-flow manipulations are summarized herein. These studies have documented significant event-related impacts in the context of before-after and before-after-control-impact (BACI) comparisons using drift monitoring, representative artificial substrate sampling, and standard kick-sampling techniques.

In general, these studies found that macroinvertebrate drift increased sharply during pulsed-flow events and that benthic community measures tended to decline following such events. Post-flow conditions were also characterized by greater variability overall. Impacts to stream benthos appear to be primarily related to increases in velocity, shear stress, bedload mobilization, and scour that affect macroinvertebrate density, richness, diversity, and composition through catastrophic drift. While many catastrophic drift responses resulted from physical disturbance and dislodgement of macroinvertebrates (i.e., passive incorporation into the drift), a significant proportion of catastrophic drift during and after pulsed-flow events resulted from behavioral responses (i.e., active incorporation into the drift).

These studies also suggest that the impacts of pulsed flows may be greater when events occur during typical low-flow periods such as late summer and fall, as opposed to earlier in the year when higher flows are more common. Benthic macroinvertebrates are known to have life cycles cued to periods of high food availability and low flow variability, therefore pulsed flows provided during typical low-flow periods effectively create artificial flood conditions when benthic communities are least adapted to experiencing them. In temperate rivers, it is reasonable to expect more flood-adapted assemblages to be present in winter as opposed to summer months, hence the implication that summer pulsed-flow events have greater potential for disturbance.

Adult Hardhead Minnow and Rainbow Trout Preference in a Large, Annular Apparatus

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Traditional thermal preference apparatuses for fishes have significant drawbacks, limiting their usefulness in studies of active or moderately active fishes. To effectively determine adult, American River fishes' preferences, we constructed a 3-m-diameter, annular chamber of acrylic plastic. A smaller version (1-m-diameter) 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 minnows (*Mylopharodon conocephalus,* mean TL: 36.2 cm) and rainbow trout (*Oncorhynchus mykiss,* mean TL: 35.4 cm) were acclimated to 12, 15, and 18 °C and tested, individually, in a 12 - 24 °C bimodal annular gradient. Whereas the trout preferred 16.0 - 18.4 °C, 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. The hardhead acclimation groups avoided water <17 °C.

Identifying Climatic and Water Flow Triggers Associated with the Breeding Activities in a Foothill Yellow-Legged Frog (*Rana boylii*) Population on the North Fork Feather River, California

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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. 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 initiated movements to mainstem breeding sites in late April and early May. Mean daily tributary temperatures were $\geq$10°C when females left home ranges on tributaries to breed on the NFFR. Oviposition dates were clustered in periods when mean mainstem temperatures were between 10 and 16°C and mainstem flow was less than 55% above baseflow. A small percentage of frogs laid eggs at somewhat higher flows, but only during a declining hydrograph. 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 the hydrograph during the breeding season from April through June.

Reproductive Timing of Freshwater Mussels and Potential Impacts of Pulsed Flows on Reproductive Success

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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. Species studied included *Anodonta californiensis*, *Anodonta nutalliana* (*wahlamatensis*), *Gonidea angulata*, and *Margaritifera falcata*.

Anodonta were gravid (i.e., carrying eggs/embryos) throughout most of the field seasons except from late July to mid October, and their glochidia (i.e., larvae that are ectoparasites on fish during transformation into juvenile mussels) 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 *Margaritifera falcata* 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. The glochidia of *M. falcata* were not found on any of the fish collected during this study.

Fish naturally infected with mussel glochidia were collected from March through September 2005 and held in freshwater aquaria to monitor the timing of juvenile drop-off and determine host fish species. At water temperatures approximating those in the Pit River, *Anodonta* juveniles dropped off of their hosts during the months of April through July and *Gonidea angulata* dropped off of their hosts during the months of June and July. Native hardhead, Sacramento pikeminnow, tule perch, Pit sculpin, and non-native green sunfish were hosts for *Anodonta*; and native hardhead, tule perch, and Pit sculpin were hosts for *Gonidea angulata*.

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.

Trout Behavioral Response to Pulsed Flows: Investigations Utilizing Electromyogram Telemetry

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Small and large rainbow trout carrying radio beacons tracked in the American River were not consistently displaced downstream during pulsed flows. The response of these trout to the increased flows may be more subtle with individuals moving away from the main channel and seeking out the slower counter flows, or eddies, created as water flows past obstacles such as large rocks and tree trunks. The objective of this study was to identify the effect of pulsed flows on the metabolism of trout in the American River. We inserted transmitters into the peritoneum of trout with electrodes that were embedded within the trunk musculature to record the electric voltage potential generated each time the musculature flexed as the fish beat their tails to swim forward. The output of the electromygram sensor was related to tail beat frequency and oxygen consumption for trout swimming at increasing flow speeds produced within a flow chamber. The same trout were released into the American River, and tracked during pulsed flows while recording their muscular activity and oxygen consumption. Three groups of fish, one with four trout, one with a single trout, and a third with five trout, were released during the field phase of the study. They were tracked over a period of pulsed flows, extending from 29 August to 24 October 2005. The flows varied from 5 m^3s^{-1}, when no water was released, to 43 m^3s^{-1}, when water was released on most days. All of the nine trout, except one remained within 1 km of the release site during this period. Linear regressions from laboratory calibrations were used to convert emgs to swimming speeds in the field. The median speed was based on 60 emg measurements recorded during each tracking interval. These measurements were analyzed using a mixed linear model, relating to median swimming speed the following vital statistics or environmental properties: 1) sex, 2) U_{crit}, 3) standard length, 4) mass, 5) river mile, 6) discharge, 7) pulse stage, 8) days in the river, and 9) rate of movement. Pulse stage was statistically significant in this analysis (F-test, p= 0.0002). The pulse stages consisted of low water, rising water, peak, and decreasing water levels. Once significant factors were identified, non-significant terms were eliminated and the model was reduced to include median swimming speed and pulse stage. Second-order interactions were studied during the final stages of this process noting no significant interactions. Very little explanatory power was lost in the reduced model compared to the full model. Pulse stage was still statistically significant in the reduced model (F-test, p = 0.0001). Rising water was associated with the largest increase median swimming velocity (+ 4.7390). There was also a slight increasing trend with low water or baseline flow conditions as well (+ 0.7893), stable or peak pulse stage was negatively associated with median swimming velocity (-1.1536).

Effects of Aseasonal Pulsed Flows on the Foothill Yellow-Legged Frog (*Rana boylii*): Case Studies and Experiments

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The foothill yellow-legged frog (*Rana boylii*) life cycle is synchronized with the seasonality of floods and low flows of a Mediterranean climate. Analysis of time-series data from 5 dammed and 7 un-regulated rivers in California indicates that regulated river populations are much reduced. To test the hypothesis that recruitment limitation associated with breeding season pulsed flows contributes to this pattern, three frog populations in northern California with pre-existing monitoring programs were studied: the South Fork Eel River (Mendocino Co), the North Fork Feather River (Butte and Lassen Cos.), and Alameda Ck (Alameda Co). Seventeen years of egg mass censuses on the unregulated S. Fk. Eel indicate that 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 3 years prior. Comparisons between two regulated reaches in the N. Fk. Feather, Cresta which experienced 4 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 Creek. In this more southern population, a 2-year time lag between recruitment conditions and adult population size may occur. To assess the effects of summer flows on tadpoles, we manipulated velocity in laboratory flumes and field enclosures. Tadpoles could no longer maintain position under rocks at a mean critical velocity of 20.9 ± 1.6 cm/sec. Critical velocity varied negatively with tadpole size and developmental stage, with velocities as low as 10 cm/sec causing 25% 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/sec current, tadpoles reached exhaustion at 7.4 ± 2.6 min. In the field, for recently hatched tadpoles, there were direct lethal effects of velocities as low as 10 cm/sec. While in refugia, there were lethal effects of predation. For tadpoles < 6 weeks old, mortality risk was doubled at elevated, yet sub-critical, velocities. The velocities causing negative effects in field trials were less than typical increases in velocity when aseasonal pulsed flows occur. The circumstantial and experimental evidence linking pulsed flows to decline highlights the pressing need for further demographic study of *R. boylii*.

Pulsed Flow Effects on the Foothill Yellow-Legged Frog (*Rana boylii*): Summaries and Re-analyses of FERC Re-licensing Data and Study Reports

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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. Because of its declining status, *R. boylii* has increasingly become a focal species in water management planning, especially in FERC re-licensing programs for hydroelectric dams. However, due to the dispersed nature and different agencies involved in re-licensing efforts, a comprehensive assessment of pulsed flow effects has been challenging.

The first phase of our study involved compiling and summarizing data from the scientific literature and FERC hydropower re-licensing reports. This review revealed different patterns for different life stages of *R. boylii*. Egg masses were negatively affected by pulsed flows via scouring, if flows occur during or after oviposition. Negative effects associated with 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 needs further research. Methods to quantify suitable *R. boylii* habitat varied among studies. A quantitative graphical analysis of data culled from reports showed that variation in suitable habitat area under differnt discharges, was site specific. Some sites showed increasing area while others showed decreasing area, as discharge increased, indicating the influence of channel morphology and other local geomorphic features.

Our review of studies identified key information gaps relating to effects of pulsed flows on the tadpole lifestage, especially activity level, behavior, growth, and survival responses to variation in water velocity and depth. Our assessment of the transect and polygon methods previously used to quantify suitable habitat at a few discharge levels, identified several weaknesses in these methods and led us to develop 2-D hydrodynamic models. During the course of the review, we also identified several ways in which future FERC re-licensing studies, and other studies of water flow effects, could be improved.

Geomorphic Importance of Winter Peak Flows and Annual Snowmelt Hydrographs in a Sierra Nevada Boulder-Bedrock River

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Considerable study has been conducted on alluvial rivers to evaluate bed mobilization flow thresholds, with some application to pulse flow releases. Boulder-bedrock rivers are also depositional, with a wide range of grain sizes within nested depositional features. Comparatively little study of bed mobilization processes and pulse flow implications has been conducted on Sierra Nevada boulder-bedrock rivers. Geomorphic thresholds of alluvial rivers (e.g., "bed" mobilization by a 1.5-yr flood) have often been applied to boulder-bedrock rivers, but this study shows alluvial thresholds should not be applied to the Clavey River, a Sierra Nevada boulder-bedrock river. Through classifying nested depositional features and analyzing repeat ground photographs before and after floods, we evaluated the geomorphic role of winter floods and snowmelt hydrograph peaks on depositional feature mobility. Two principles emerged: 1) the Clavey River has at least three nested scales of depositional features that provide different hydraulic, geomorphic, and ecological functions, and 2) snowmelt peak flows were substantially less important in mobilizing the larger scale depositional features than winter peak flows. By associating the depositional features with critical ecological functions (e.g., fish habitat, amphibian habitat, and riparian vegetation), ecological impacts and/or benefits of managed winter and snowmelt pulse flow releases can be evaluated quantitatively.

Longitudinal Movement of Fish in Response to a Single-Day Flow Pulse

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We studied the response of fish to a 1-day pulse flow release from Camino Dam on Silver Creek, a tributary of the South Fork American River. On 15 September 2004 flows in the Camino Reach of Silver Creek were increased from a base flow of 0.48 m^3/s to a peak of 18.48 m^3/s by midday, and decreased back to base levels. The study reach began 200 m downstream of the dam, and continued for 600 m downstream. Water temperatures before and after the pulse were 10.7 ^{o}C. Values observed on the day of the pulse ranged between 10.2 and 10.9 ^{o}C. Dissolved oxygen was 11 mg/L during the pulse, and 9.64 mg/L the following day. Concentrations of total phosphorus, soluble phosphorus, ammonia-nitrogen (NH_4-N), and nitrate-nitrogen (NO_3-N), tested before, during and after the pulse were below detection limits. Total Kjeldahl nitrogen concentrations ranged between below detection (<0.1 mg/L) to 0.2 mg/L. One rainbow trout (*Oncorhynchus mykiss*) and six brown trout (*Salmo trutta*) were captured by angling, radio-tagged, released, and tracked prior to, during, and after the pulsed flow. Six fish were observed in the reach after tagging, and remained in the reach during and after the pulsed flow. No significant differences were found between the distances the radio-tagged fish moved prior to, during, and after the release. We also conducted snorkel surveys before and after the pulse in the downstream 300 m of the study reach. Rainbow trout and brown trout in three age classes, young-of-the-year, juvenile, and adult, were observed both before and after the pulse. Counts of young-of-the-year trout were 26% lower after the pulse, and counts of juvenile trout were 9% lower, while counts of adult trout were 12% higher. Our results suggest that most trout were able to remain in the study reach during the pulse.

Ecological Roles of Natural Pulse Flows in a Boulder-Bedrock Sierra Nevada River: Benthic Macroinvertebrates

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Aquatic benthic macroinvertebrate communities are a key component of river ecosystems. Aquatic macroinvertebrate productivity in temperate climates peak in late-spring when daylight and stream temperatures are increasing. An ecologically important process of the snowmelt hydrograph investigated was the creation of abundant, high-quality macroinvertebrate habitat when water temperatures favor high productivity. For expert habitat mapping of benthic macroinvertebrates in riffles, preferred riffle depths were scaled to the size of the cobbles and small boulders. Flow depths from 2/3 the exposed substrate height to twice the exposed substrate height were mapped as good physical benthic macroinvertebrate habitat, if surface velocities ranged between 1 ft/sec and 3.5 ft/sec. Defining highly productive macroinvertebrate habitat within the annual snowmelt hydrograph required establishing a range of highly favorable water temperatures. A daily average temperature range of 41^{o}F to 55^{o}F was adopted as highly productive for benthic macroinvertebrates. In Wet runoff years, abundant productive benthic macroinvertebrate habitat was created by the snowmelt hydrograph's rising limb, peak, and fast recession limb flowing over large depositional features. Pulse flow releases mimicking the shape and timing of the annual snowmelt hydrograph can be released to re-create this natural pulse in springtime habitat encouraging high benthic macroinvertebrate production.

Ecological Roles of Natural Pulse Flows in a Boulder-Bedrock Sierra Nevada River: Fish and Amphibians

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Each component of the Clavey River snowmelt hydrograph has its characteristic magnitude, duration, frequency, and timing that profoundly influence habitat abundance and quality for native fish and amphibians. Expert habitat mapping for rainbow trout (*Oncorhynchus mykiss*), Foothill yellow-legged frog (*Rana boylii*), Pacific treefrog (*Pseudacris [Hyla] regilla*), and Western toad (*Bufo Boreas*) during snowmelt and summer baseflows quantified habitat – streamflow relationships (habitat rating curves) in depositional and bedrock-controlled channel morphologies. No single runoff year type (e.g., Dry or Wet) provided good habitat conditions for all species examined. Habitat rating curves and annual habigraphs (X-axis: Day of runoff year and Y-axis: habitat abundance (ft^2)) showed that large depositional features provide most of the ecologically available habitat during higher snowmelt runoff years, yet comprised less than 15% of the mainstem's length. The magnitude, duration, rate, and timing of the slow snowmelt recession limb dominated the transition from cold to warm stream temperatures and therefore strongly influenced habitat abundance and quality. An ecological goal for annual pulse flow releases should be to allow "good and bad" conditions for any given species to happen naturally over many years.

Guidelines for Prescribing Pulse Flows in Sierra Nevada Boulder-Bedrock Rivers

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Ecological roles of the annual snowmelt hydrograph in the Clavey River, a tributary to the Tuolumne River, were investigated and quantified to propose 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. Pulse flow guidelines, developed solely from our investigation of the Clavey River and Cherry Creek, are:

Pulse Flow Guideline No. 1: 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.

Pulse Flow Guideline No. 2: 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, exploring only one of many possible diversion scenarios, suggest maximum fixed daily diversion rates of 25% to 35% during snowmelt runoff.

Pulse Flow Guideline No. 3: Do not divert those flows represented by the unregulated snowmelt hydrograph's slow snowmelt recession limb.

An Assessment of Hydrologic Variability on *R. boylii* Habitat Hydraulics Using 2-Dimensional Hydrodynamic Modeling

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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. We employed River2D at two study sites in Northern California, one on the unregulated South Fork Eel River and the other on the regulated North Fork Feather River. We first completed an evaluation of the precision and accuracy of the model in predicting local hydraulics, particularly in the near-shore environment where preferred habitat exists. Changes in velocity magnitude were then directly related to *R. boylii* success using data obtained from concurrent controlled experiments, and changes in local hydraulics were related to habitat suitability in order to predict reach-scale habitat quality and availability at different flow regimes.

Results from the modeling analysis indicate that simulated depths and velocities from River2D generally agreed well with measured field values, with greater precision in mid-channel areas than in the near-shore environment. Absolute differences between modeled and measured velocities at egg locations averaged 0.04 m/s, with 90% of the difference values falling below 0.11m/s. 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, the model accurately predicted suitable breeding locations throughout the survey reach.

Using results from previous and concurrent studies that provided data on percentages of egg mass and larval loss associated with increased velocities, we assessed how two scenarios of increasing flow affected habitat availability and suitability at each study site. As discharge increased, habitat availability decreased at both sites, with the lowest baseflow discharges providing the greatest weighted usable area. However, in a modeled scenario where flows were increased from various baseflows to a high spring runoff flow, the highest baseflow discharges provided the greatest buffering capacity against lethal increases in velocity in breeding habitats. In an aseasonal pulse scenario, the highest baseflow discharges also provided the greatest buffering capacity in tadpole rearing habitats; however, only 20-30% of the suitable habitat in the unregulated site and <5% of the suitable habitat in the regulated site remained suitable during the pulse regardless of baseflow level. In both the spring pulse and aseasonal pulse scenarios, the unregulated study site provided 2-3 times the buffering capacity of the regulated site. We surmised that these differences between the regulated and unregulated sites were due to differences in cross-sectional shape. The regulated site had an entrenched channel with steep banks, while the unregulated site had an asymmetric cross-sectional shape where depths changed gradually as flows fluctuated.

This type of model-based methodology that can evaluate effects on individuals and local habitat conditions for multiple life stages as well as evaluate habitat suitability at a reach-scale would be useful for managing *R. boylii* in regulated river systems.