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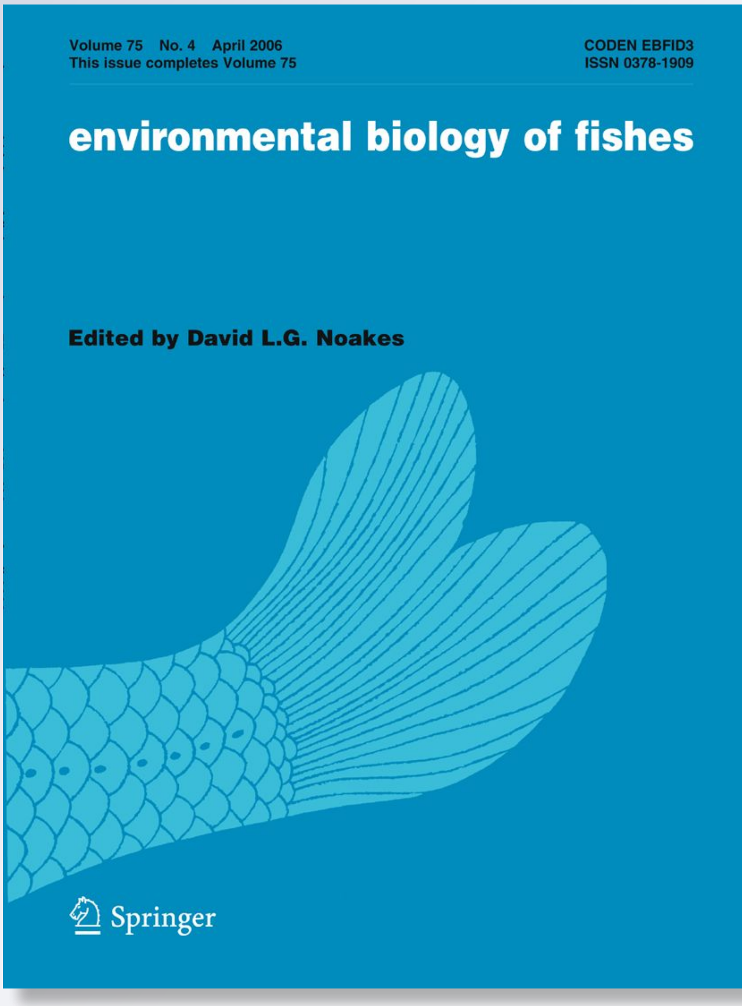

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A lateral-displacement flume for fish behavior and stranding studies during simulated pulsed flows

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Abstract In regulated rivers, fluctuating water depths associated with pulsed discharges may strand small fish in side channels and pools. Quantitative assessments of stranded fish are difficult in field studies (e.g., due to unknown effects of avian and terrestrial vertebrate predators). To assess such lateral displacement and stranding on juvenile stream fishes, we designed, constructed, and tested (with three species) a 2×1-m, lateral-displacement flume. The flume featured a main channel that never drained and a raised, wide "floodplain" channel that alternately flooded, with a simulated pulse, and became dewatered. The floodplain contained four pools, with different shapes and draining capacities, in which fish could become stranded as the water level subsided. Fish-stranding rates (8%) in this relatively compact laboratory flume, after exposure to simulated pulsed stream flows, were comparable to those observed in past investigations using larger, artificial streams.

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Introduction

In pulse-regulated rivers, the flow of water may be increased (e.g., for electrical power generation, recreational white-water rafting, or for flushing flows) for one to several hours. During this pulse period, the water level rises and may form side channels and pools in the floodplain. The subsequent, decreased water release can result in a rapid lowering of the water level as the river returns to its normal river channel (Cushman 1985; Hunter 1992). Unfortunately, the abnormal frequency and timing of anthropogenic water pulses can adversely affect fish due to atypical water flows at critical times during their life cycles. For example, native Californian fish species have evolved with seasonal flow fluctuations, but their increased frequency (e.g., for electricity generation) and late-warm-season timing (for recreational purposes) represent significant deviations from the natural hydrograph.

Strong pulses may result in lateral displacement of small fishes and strand them along changing channel margins. Stranding in shallow side channels has been observed in field studies (Maciolek and Needham 1952; Hvidsten 1985) and laboratory investigations (Monk 1989; Bradford et al. 1995; Bradford 1997). These displacements could result in slower growth because of decreased availability of natural prey (e.g., insect hatches) or in increased mortality due to increased predation vulnerability to avian or terrestrial predators in shallow pools. One important reason that fishes may exit the main channel voluntarily and disperse into the floodplain is to seek velocity shelters during a high flow event. This may be a particularly important motivation during short-duration pulses, in which the water velocity in the main-channel changes abruptly and dramatically. Pool areas that dewater at low flows may actually form "attractive nuisances", drawing fish to favorable conditions at high flow but resulting in strandings when the water levels drop. Fish may also be motivated to leave the main channel and enter the floodplain in search of increased feeding opportunities and the wider variety of aquatic invertebrate prey taxa to be exploited (Sommer et al. 2001; Balcombe et al. 2005). Floods allow fishes to inhabit floodplain habitats where fish feeding may lead to the decreased abundance of zooplankton prey in floodplain waters (Grosholz and Gallo 2006), but also to positive growth benefits to fish such as juvenile Chinook salmon *Oncorhynchus tshawytscha*, compared with salmon that remain in adjacent mainstem river habitats (Jeffres et al. 2008).

Various approaches have been used to study fish stranding in pulse-regulated rivers (Murchie et al. 2008), including large scale field studies (Higgins and Bradford 1996), enclosure (net pen) field studies (Irvine et al. 2009), simulation modeling (García et al. 2010), and laboratory flume studies (Bradford 1997; Halleraker et al. 2003). There are a limited number of field studies on fish stranding, given the associated logistical challenges, so controlled laboratory studies can complement field approaches and allow detailed observation of fish behavior during pulses. Laboratory investigations have provided insights regarding impacts of pulsed flows because potentially critical factors were varied individually to assess effects on fish behavior and identify key factors. For example, Bradford et al. (1995) recorded stranding of juvenile coho salmon *Oncorhynchus kisutch* and rainbow trout *O. mykiss* on river bars caused by rapid decreases in river flow in an artificial stream channel under winter conditions. Many of these fish became stranded because they concealed themselves in the interstitial areas in the gravel substrate on the bars and did not leave when water levels receded. Fish showed natural behaviors such as burying themselves in gravel and stranding. However, the apparatus lacked natural features such as pools (neither gravel lined pools nor bedrock-type pools). A flume used by Vilizzi and Copp (2005) was more compact than that of Bradford (1997) but lacked natural slope or substrate. Our objective was to construct and test the realism of a compact, lateral (floodplain) displacement flume that could be used to compare the behavior and stranding potential of juvenile fishes. For this test we were interested in determining at a qualitative level whether fish of three families would display a natural range of behaviors in response to a pulsed flow, with the expectation that larger sample sizes would be necessary for quantitative analyses.

Methods

Lateral-displacement flume design and construction

The lateral-displacement flume was constructed using 2.44-m × 1.22-m sheets of 1.91-cm-thick plywood, a sheet of 1.8-m × 0.45-m × 1.3-cm clear acrylic plastic, PVC pipe, two 3/4-HP centrifugal pumps (Jacuzzi®), a series of reservoirs to hold the flume's water capacity, and three coats of marine-grade topside paint (Rust-Oleum®). The testing arena was 2.0-m long × 1.18-m wide × 59-cm tall and contained a 16-cm-wide main channel that never drained and a 1.02-m-wide floodplain that flooded and dewatered with water-level changes associated with the simulated pulse (Fig. 1). Air-equilibrated well water circulated through the apparatus via channels and tanks, separated from the main channel by plastic mesh screens to ensure that the fish remained in the test area.

The main channel floor was covered with a 5-cm deep layer of pebbles (2.2–4.5 cm diameter size range) and the floodplain was sloped at 10°, simulating the least slope measured during site surveys along the South Fork American River (Fig. 2). We used a minimum slope based on findings that juvenile coho salmon stranded less frequently on steeper slopes (Bradford et al. 1995). Floodplain substrate was constructed from American River materials: a 50–50 mix of gravel and pebbles separated into pools, rock piles, and open areas. Substrate depth increased from 1 cm at the edge of the main channel to 17.7 cm at the flume wall (Fig. 1). Four distinct pools (A, B, C, and

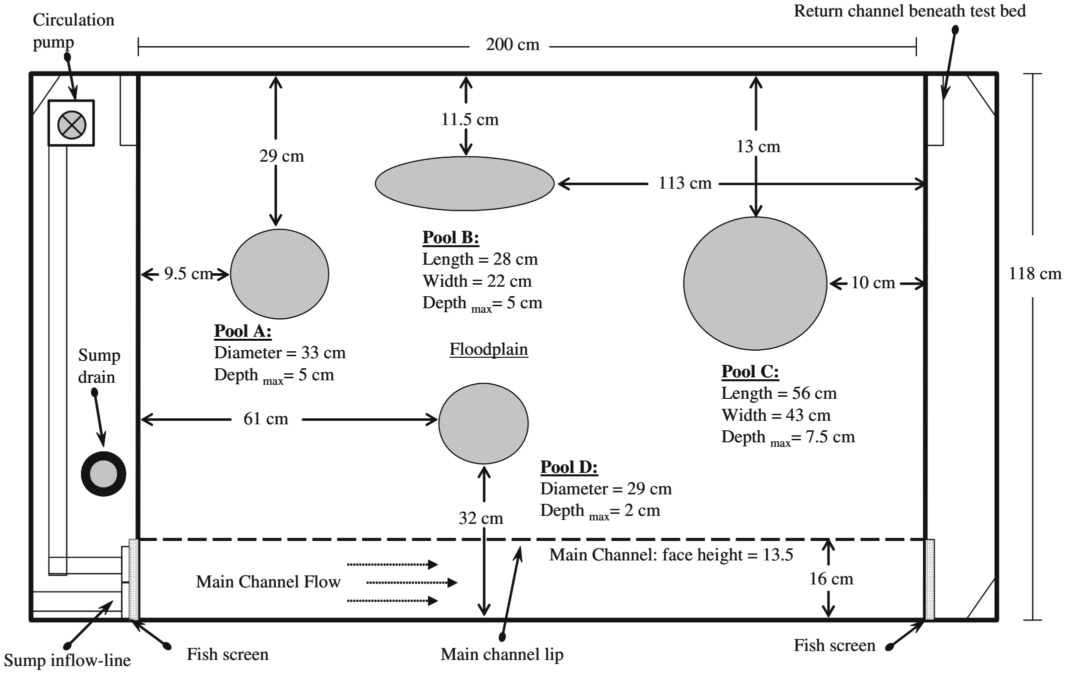


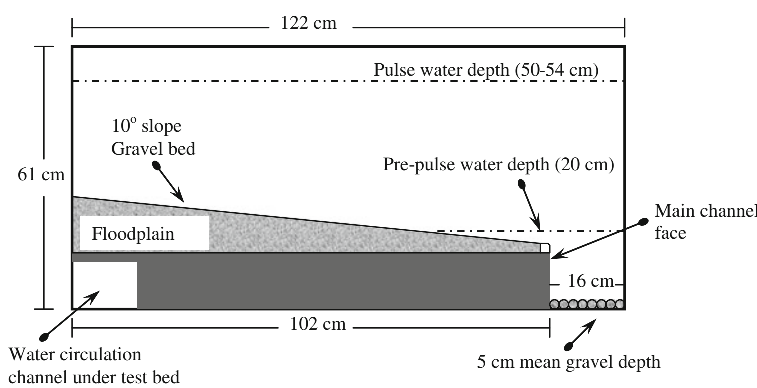
Fig. 1 Overhead diagram of the lateral displacement flume. The main channel was filled with 5 cm gravel, and the floodplain was set to a 10° slope

D) with different draining and water-holding capacities were created in the floodplain.

1. Pool A retained much of its water during flume dewatering. Cobble of 7–13 cm diameter was placed within the pool to provide cover.
2. Pool B had larger cobble (9–25 cm diameter) bordering and slightly overhanging the pool's edge for cover. The water in this pool drained as the flume's water level decreased after the flow pulse.
3. Pool C had a steel-wire, mesh buried in the gravel substrate to assist in maintaining the pools' contours, with larger cobble (8–16.5 cm diameter) placed for cover. The water in this pool drained during dewatering of the floodplain.
4. Pool D had a very slow dewatering rate similar to that of pool A. This pool never entirely lost its water during the experiments, and it included a narrow passage to the main channel for fish to use.

Partial walls, separating the test area from the recirculation tanks, created an eddy in the floodplain (Fig. 3). We measured velocities in the main channel, over the floodplain, and in and near each pool with a

Fig. 2 End view of the lateral displacement flume. The main channel face height was set to 13.5 cm



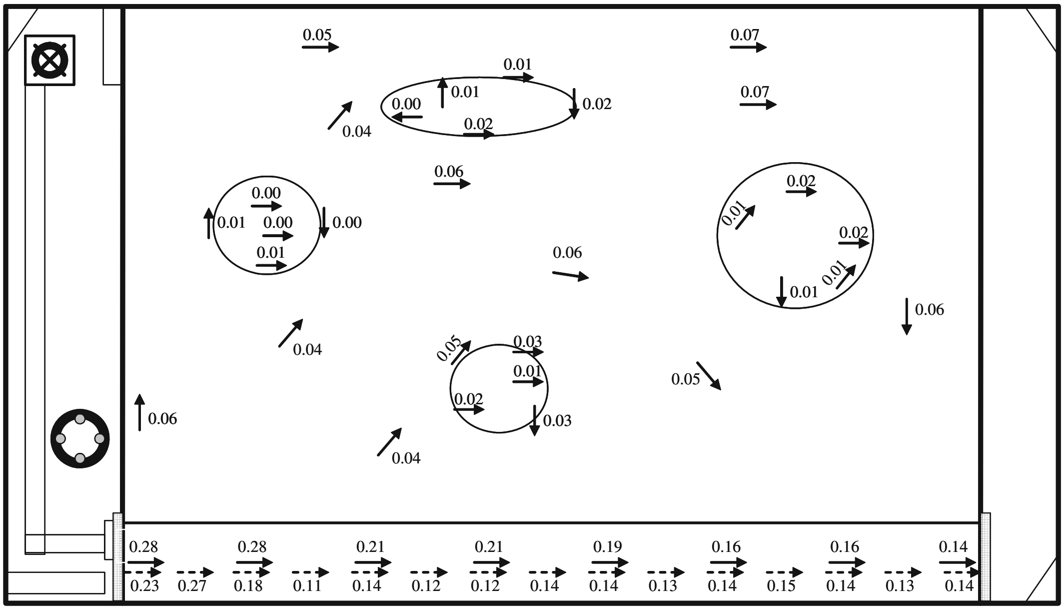


Fig. 3 Overhead diagram of the lateral displacement flume showing velocities (m/s) measured at different locations in the flume during baseflow (*dashed arrows*) and pulsed flow (*solid arrows*) situations. In comparison, for a floodplain in the South Fork American River where water depth ranged from 0 to 0.85 m, velocity ranged from 0 to 0.43 m/s and average velocity was 0.17 m/s

Marsh-McBirney flowmeter (Model 523). This set-up simulated the flow dynamics observed in rivers which have a main channel with continuous, directional flow and floodplain habitats with irregular flows and eddies (e.g., South Fork American River, California). For comparison with water velocities in the flume we took field measurements of flow velocities over the floodplain and nearshore main channel in the South Fork American River at Marshall Gold Discovery State Historic Park during a pulsed flow release from Chili Bar Dam, using a Global Water Instrumentation, Inc. flowmeter (Model FP111).

Lateral-displacement flume testing

To test the lateral-displacement flume, we used age-0 hatchery rainbow trout (American River Hatchery, Rancho Cordova, CA), and wild-caught hardhead (*Mylopharodon conocephalus*; Rock Creek, tributary of South Fork American River) and Sacramento sucker (*Catostomus occidentalis*; Putah Creek). Overall, the rainbow trout (9.8 cm mean ± 4.0 SE SL, 17.6±3.2 g wet mass, n=12) were larger than both the hardhead (5.7±2.0 cm SE SL, 4.6±5.0 g wet mass, n=14) and the Sacramento sucker (5.4±3.0 cm SE SL, 3.4±5.0 g wet mass, n=12). All fish were housed at the University of California, Davis, Center for Aquatic Biology and Aquaculture (CABA) in 250-L, circular tanks with continuous flows of air-equilibrated well water (conductivity 690 μS cm^{-1}, dissolved oxygen 9.2 mg/l, and pH 8.1) under a natural photoperiod at 14°C. An initial, 10-d disease-prevention treatment, consisting of malachite formalin and nitrofurazone, was administered immediately after fish arrived at CABA. Tanks were cleaned and fish were fed semi-moist feed (Rangen, Inc., Buhl, Idaho), daily.

In each trial one randomly selected fish was removed from its holding tank and placed into the main channel of the flume for either a short (2-h) or long (16 to 17-h) acclimation. A minimum of six fish of each species was tested for each acclimation type. The short-acclimation period was conducted during the day just prior to a simulated pulse experiment, and fish acclimating for the long period were placed into the flume at the end of the day and exposed to the simulated pulse the following morning. The artificial lighting over the flume simulated the natural photoperiod. Water depths during acclimation were 19–21 cm, measured from the base of the main channel, thereby allowing exposure to 5 cm of the floodplain margin without access to the substrate pools.

To begin flume tests, the water level was raised to a depth of 50–54 cm over a 20-min period using water from the reservoirs, kept at that depth for a 90-min peak-pulse period, and then decreased over 30 min to the pre-pulse depth. Fish experienced a change in water depth of approximately 30 cm. The depth change and ramping rate were similar to that experienced by fish during a recreational pulsed release in the South Fork American River (L.C. Thompson, pers. obs.). During the 90-min peak-pulse, the fish had access to the entire floodplain (Fig. 2). Thus, the test simulated the daily flooding and dewatering (but not necessarily the complete range of velocity gradients) experienced by fish during a pulsed release of water for hydroelectric power generation. Water temperature was a mean 13.6°C (± 0.06 SE) for the acclimation and the tests. Observations of fish location (XYZ locations) and behavior were made without disturbing the fish, with observers hidden behind a screen made of landscape fabric, with several small peepholes. A fish was considered stranded during tests when it became isolated on the floodplain (e.g., in a pool) as the floodplain drained, and it was unable to return to the main channel. The test was planned to end immediately if the fish was stranded in a pool that completely drained, whereas it continued if the fish was stranded in a pool that remained full of water.

Data analyses

We made comparisons of stranding incidences and floodplain use between species or between acclimation times using the Fisher exact test (Zar 1984). For each species we used a Mann–Whitney rank sum test (non-parametric) to compare the time spent in the different habitat types (main channel, floodplain, or floodplain pools) for each acclimation time. Significant tests were followed by an all pairwise multiple comparison procedure (Dunn's method). We considered results significant at $\alpha<0.05$ for all tests. We compared the water depths used by different species for short and long acclimation periods graphically, using box and whisker plots for median depth and 10th, 25th, 75th, and 90th percentiles. Data were analyzed using Microsoft Excel®, SigmaStat® 3.0, and SigmaPlot® 8.0 software packages.

Results

The lateral-displacement flume provided useful laboratory data on pulsed-flow effects on juvenile fishes' behavior, including stranding. Although there were no significant differences in stranding incidences between species or between acclimation times (Fisher exact test, $p=0.45$ to 1.0), three (8%) of the 38 test fish were stranded: two hardhead and one sucker (Table 1). All stranded fish were from the short-acclimation tests and all were isolated in pool A, which was the deepest pool and retained water (Fig. 1). Although only three fish were stranded after a pulse, sixteen fish entered the simulated river floodplain during tests (Table 1). Most (67% and 83%) of the trout entered the floodplain after both short- and long-acclimation periods, respectively (Table 1). In contrast, 43% (short acclimation) and 0% (long acclimation) of the hardhead and 33% (short and long acclimation) of the Sacramento suckers entered the floodplain. Rainbow trout were significantly more likely than hardhead to use the floodplain after long acclimation (Fisher exact test, $p=0.0046$).

Although fish entered the floodplain frequently and rarely became stranded, they still spent the majority of time in the main channel during tests (Table 2). All species spent significantly more time in the main

Table 1 Frequencies (and percent totals) of rainbow trout, hardhead, and Sacramento sucker, for both short and long acclimation periods, that were stranded, and that entered the floodplain habitat during pulsed flows

Species	Acclimation	*n*	# stranded	% Stranded	Enter floodplain habitat	% Enter floodplain habitat
Rainbow trout	Short	6	0	0	4	67
	Long	6	0	0	5	83
Hardhead	Short	7	2	29	3	43
	Long	7	0	0	0	0
Sacramento sucker	Short	6	1	17	2	33
	Long	6	0	0	2	33

Table 2 Time (min; mean ± SE) spent in different sections of lateral-displacement flume after experiencing the short or long acclimation periods. All three species spent the majority of their time in the main channel rather than the floodplain habitat

Species	Acclimation	Mean ± SE (min)		
		Main channel	Floodplain substrate	Floodplain pools
Rainbow trout	Short	133.2±3.3	0.8±0.4	6.0±3.0
	Long	126.2±6.3	4.8±3.8	7.2±6.2
Hardhead	Short	110.7±16.0	15.57±11.4	13.7±9.9
	Long	140±0.0	0	0
Sacramento sucker	Short	114.3±11.7	1.3±0.6	24.3±11.7
	Long	137.2±2.0	2.5±1.9	0.3±0.3

channel than in either the floodplain or floodplain pools after either the short or long acclimation periods (Mann–Whitney rank sum test; rainbow trout, T=732,182, n=846, P<0.001; hardhead, T=872,015, n=987, P<0.001; Sacramento sucker, T=775,177, n=846, P<0.001). During the flow pulse, we observed that some rainbow trout swam up into the expanded water column, above the substrate of the main channel and floodplain, whereas the hardhead and Sacramento sucker spent most of their time closer to the bottom (Fig. 4). This may be of interest for future studies with larger sample sizes.

Discussion

Our experimental flume's smaller size, compared with that of stream models that have been used in past fish-stranding studies (Bradford 1997; Halleraker et al. 2003), led to easier hydraulic control of pools and main channel flows and observations of fish behaviors. Temperature control and light intensity can be more uniform in smaller flumes compared with those in a large-scale artificial stream. Using a recirculating-flow system under the gravel bed maintained a consistent main-channel flow to mimic a larger river system. The range of flow velocities produced in our flume encompasses a range of velocities similar to that observed in the wild (Fig. 3). Our flume incorporated a simulated floodplain with representative pools that produced stranding rates similar to those observed in an artificial stream (Halleraker et al. 2003) despite our flume's relatively compact size. The device simulated ramping rates observed in local rivers, but the compact size of the device limited its ability to simulate the actual depth changes for the length of pulse (e.g., 30 cm increase in depth over a 20-min period in the device versus a 90 cm increase in the South Fork American River over a 1-h period).

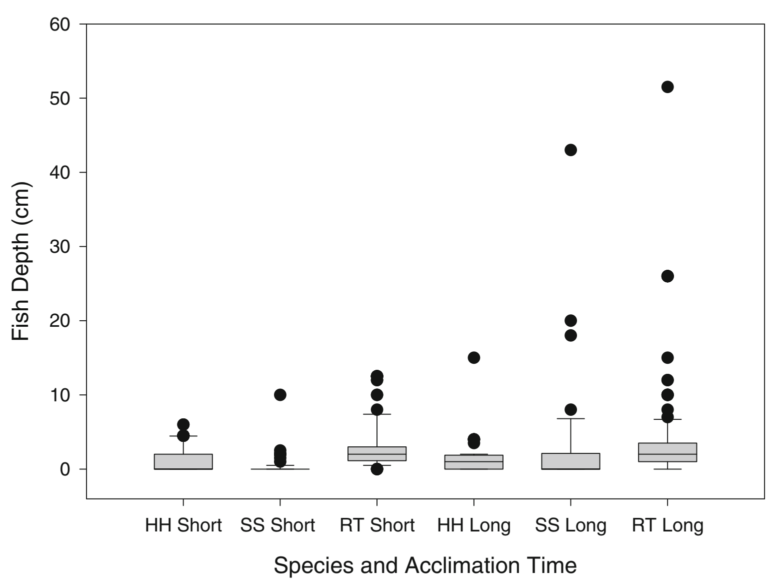


Fig. 4 Fish depth (vertical position of fish relative to substrate below) of hardhead (HH), Sacramento sucker (SS), and rainbow trout (RT) following either a short or long acclimation time. Box and whisker plots show median plus 10th, 25th, 75th, and 90th percentiles; outliers are indicated by *round symbols*

It is possible to make inferences from laboratory simulations that can inform flow management decisions, for example regarding swimming capability of different fish species at different velocities in the presence of flow refuges (Chun et al. 2011). However, it is unlikely that a flume simulation alone can reproduce the full range of conditions observed in nature, due to the small scale and consequent limitations placed on the natural processes (e.g., predation, temperature fluctuations, wetted history) that can be simulated. For this project we complemented our flume-based pulsed flow study with field-based studies using techniques such as radio tracking (Cocherell et al. 2010; Thompson et al. 2011); snorkel observations (Thompson et al. 2011), and electromyogram telemetry (Cocherell et al. 2011).

In the flume our test fish were stranded as a result of entrapment (i.e., caught in water pools; Young et al. 2007). The floodplain slope in our tests was set to 10° (ca. 19% grade), while other investigators measured increased stranding rates of small fishes using more gradual slopes (Hunter 1992; Bradford et al. 1995; Adams et al. 1999). Both the limited (ca. 32-cm) water-depth range and limited (90-min) pulse period in our flume may have resulted in lower fish stranding rates than those observed in studies with greater depth changes or longer pulse periods (Hunter 1992). However, other artificial streambed studies have measured similar stranding rates to ours (Halleraker et al. 2003).

The greater use of floodplain habitat by rainbow trout, compared with those of the hardhead may have resulted from the trouts' increased food requirements associated with their larger size and their higher maintenance metabolic rates (Cech et al. 1990). Perhaps this species specific difference was an anomalous result due to the small sample sizes of this demonstration study. Hardhead did not enter the floodplain during the long acclimation trial, but they demonstrated the capability to exhibit this behavior in the flume during the short acclimation trial. We would need a larger sample size to determine how representative these results are of hardhead behavior during pulses. The trouts' use of the floodplain may have also been related to search for lower flow velocities, whereas Sacramento suckers attempted to bury themselves in the substrate in deeper parts of the flume.

In conclusion, we designed, constructed and tested a lateral-displacement flume featuring a main-channel and a gravel floodplain section with draining and non-draining pools. While experimental variables such as pulse-flow velocities, flood-plain inundation depth, and pulse duration can be set to simulate pulsed flows in relevant, regulated streams, the flume's compact size facilitates quantitative estimates of floodplain use and stranding potential by resident and migratory fishes. Such estimates are difficult to make in field studies, due to the extensive flooded area, and the unknown effects of avian and terrestrial vertebrate predators. In spite of the small sample sizes used in this design phase, the qualitative range of behaviors displayed by the three fish families in the flume encompassed a range expected in the wild, including foraging on the floodplain, stranding, and seeking cover under gravel in deeper water. These observations provide proof of concept that the flume design is adequate to study fish response to pulsed flow effects, but our sample size was too small to allow prediction of which behaviors would be shown by each species under these flow conditions in the wild. Further research is needed to quantitatively assess fish behavior and stranding when physical (e.g., water velocities and depths, floodplain slopes) and biological (e.g., use of more than one species, including potential prey and predators) attributes are added.

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References

Adams SR, Keevin TM, Killgore KJ, Hoover JJ (1999) Stranding potential of young fishes subjected to simulated vessel-induced drawdown. Trans Am Fish Soc 128:12–30

Balcombe SR, Bunn SE, McKenzie-Smith FJ, Davies PM (2005) Variability of fish diets between dry and flood periods in an arid zone floodplain river. J Fish Biol 67:1552–1567

Bradford MJ (1997) An experimental study of stranding of juvenile salmonids on gravel bars and inside channels during rapid flow decreases. Regul Rivers: Res Manage 13:395–401

Bradford MJ, Taylor GC, Allen JA, Higgins PS (1995) An experimental study of the stranding of juvenile coho salmon and rainbow trout during rapid flow decreases under winter conditions. North Am J Fish Manage 15:473–479

Cech JJ Jr, Mitchell SF, Castleberry DT, McEnroe M (1990) Distribution of California stream fishes: influence of environmental temperature and hypoxia. Environ Biol Fish 29:95–105

Chun SN, Cocherell SA, Cocherell DE, Miranda JB, Jones GJ, Graham J, Klimley AP, Thompson LC, Cech JJ Jr (2011) Displacement, velocity preference, and substrate use of three California stream fishes in simulated pulsed flows. Environ Biol Fish 90:43–52. doi:10.1007/s10641-010-9716-8

Cocherell SA, Jones GJ, Miranda JB, Cocherell DE, Cech JJ Jr, Thompson LC, Klimley AP (2010) Distribution and movement of domestic rainbow trout, *Oncorhynchus mykiss*, during pulsed flows in the South Fork American River, California. Environ Biol Fish 89(2):105–116. doi:10.1007/s10641-010-9701-2

Cocherell SA, Cocherell DE, Jones GJ, Miranda JB, Thompson LC, Cech JJ Jr, Klimley AP (2011) Rainbow trout *Oncorhynchus mykiss* energetic responses to pulsed flows in the American River, California, assessed by electromyogram telemetry. Environ Biol Fish 90:29–41. doi:10.1007/s10641-010-9714-x

Cushman RM (1985) Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. North Am J Fish Manage 5:330–339

García A, Jorde, K, Habit E, Caamaño D, Parra O (2010) Downstream environmental effects of dam operations: Changes in habitat quality for native fish species. River Res Appl n/a. doi:10.1002/rra.1358

Grosholz E, Gallo E (2006) The influence of flood cycle and fish predation on invertebrate production on a restored California floodplain. Hydrobiologia 568:91–109

Halleraker JH, Saltveit SJ, Harby A, Arnekleiv JV, Fjeldstad HP, Kohler B (2003) Factors influencing stranding of wild juvenile brown trout (*Salmo trutta*) during rapid and frequent flow decreases in an artificial stream. River Res Appl 19:589–603

Higgins PS, Bradford MJ (1996) Evaluation of a large scale fish salvage to reduce the impacts of controlled flow reduction in a regulated river. North Am J Fish Manage 16:666–673

Hunter MA (1992) Hydropower flow fluctuations and salmonids: a review of the biological effects, mechanical causes, and options for mitigation. State of Washington, Department of Fisheries Technical Report 119. Olympia, Washington

Hvidsten NA (1985) Mortality of pre-smolt Atlantic salmon, *Salmo salar* L., and brown trout, *S. trutta* L., caused by fluctuating water levels in the regulated River Nidelva, central Norway. J Fish Biol 42:1922–1927

Irvine R, Oussoren T, Baxter J, Schmidt D (2009) The effects of flow reduction rates on fish stranding in British Columbia, Canada. River Res Appl 25:405–415

Jeffres CA, Opperman JJ, Moyle PB (2008) Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environ Biol Fish 83:449–458

Maciolek JA, Needham PR (1952) Ecological effects of winter conditions on trout and trout foods in Convict Creek, California, 1951. Trans Am Fish Soc 81:202–217

Monk CL (1989) Factors that influence stranding of juvenile Chinook salmon and steelhead trout. Thesis, University of Washington, Seattle

Murchie K, Hair K, Pullen C, Redpath T, Stephens H, Cooke S (2008) Fish response to modified flow regimes in regulated rivers: research methods, effects and opportunities. River Res Appl 24:197–217

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ (2001) Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Can J Fish Aquat Sci 58(2):325–333

Thompson LC, Cocherell SA, Chun SN, Cech JJ Jr, Klimley AP (2011) Longitudinal movement of fish in response to a single-day flow pulse. Environ Biol Fish 90(3):253–261. doi:10.1007/s10641-010-9738-2

Vilizzi L, Copp GH (2005) An analysis of 0+ barbel (*Barbus barbus*) response to discharge fluctuations in a flume. River Res Appl 21:421–438

Young PS, Conklin DE, O'Hagan J, Canaday J, Cox C, Cech JJ Jr, Sih A, Thompson LC (2007) Hydropower-related pulsed flow impacts on stream fishes, amphibians, and macroinvertebrates. Prepared for California Energy Commission-Public Interest Energy Research Program, Sacramento, 38 p

Zar JH (1984) Biostatistical analysis, 2nd edn. Prentice-Hall, Inc., Englewood Cliffs