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ARTICLE

Assessing Juvenile Chinook Salmon Behavior and Entrainment Risk near Unscreened Water Diversions: Large Flume Simulations

Timothy D. Mussen* and Dennis Cocherell

Wildlife, Fish, and Conservation Biology Department, University of California, Davis,
One Shields Avenue, Davis, California 95616, USA

Zachary Hockett, Ali Ercan, Hossein Bandeh, and M. Levent Kavvas

Department of Civil and Environmental Engineering, University of California, Davis,
One Shields Avenue, Davis, California 95616, USA

Joseph J. Cech Jr. and Nann A. Fangué

Wildlife, Fish, and Conservation Biology Department, University of California, Davis,
One Shields Avenue, Davis, California 95616, USA

Abstract

Juvenile Chinook Salmon *Oncorhynchus tshawytscha* from California's Central Valley must pass thousands of unscreened water diversion pipes during their out-migration to the Pacific Ocean. The number of fish that become entrained into (drawn through) these diversions at different hydraulic and environmental conditions is currently unknown. We tested the ability of juvenile Chinook Salmon to avoid entrainment into a 0.46-m-diameter unscreened water diversion pipe while swimming in a large-river-simulation flume. Fish swimming experiments were conducted at 0.15, 0.38, and 0.61 m/s sweeping velocities (simulating the river current) with 0.42 and 0.57 m³/s water diversion rates during the day and at 0.15 and 0.61 m/s with a diversion rate of 0.57 m³/s in turbid water and during the night. The number of fish entrained during day experiments ranged from 0.8% (SE, 0.3) to 8.5% (SE, 0.3). The percentage of pipe passage events resulting in fish entrainment nearly doubled at the 0.57 m³/s water diversion rate (1.7%) compared with that at 0.42 m³/s (0.9%). In clear water conditions during the day, more fish became entrained at the higher water diversion rate (0.57 m³/s) and slower sweeping velocity (0.15 m/s), with fish entrainments starting 38.6 cm (SE, 1.6) from the center of the pipe inlet, where fish experienced an increased velocity gradient and a mean resultant velocity of 0.74 m/s. Fish entrainment was strongly influenced by the number of pipe passages per experiment, rather than by swimming orientation or time spent in the flume. More fish were entrained at the faster sweeping velocity (0.61 m/s) in turbid water during the day and at night, indicating that juvenile Chinook Salmon may use nonvisual guidance (e.g., lateral line system) to avoid water diversions in slower currents. These results help to provide a scientific basis for protecting out-migrating juvenile Chinook Salmon exposed to unscreened water diversions.

Entrainment (fish removal via water diversions) has been recognized as a threat to fish throughout the world, including in Australia (King and O'Connor 2007), Europe (Turnpenney et al. 1998), and the USA (Gale et al. 2008; Grimaldo et al. 2009). In California, there are over 3,700 water diversions on

the Sacramento and San Joaquin rivers and their tributaries and in the Sacramento–San Joaquin Delta and Suisun Marsh. Of these existing diversions, over 95% are unscreened (CalFish 2012). Many fish species occurring in the Sacramento and San Joaquin Delta, including several native species listed as

*Corresponding author: tdmussen@ucdavis.edu
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threatened or endangered, are known to be susceptible to entrainment (Nobriga et al. 2004; Kimmerer 2008), and these losses are of great concern to fisheries managers and conservation biologists (Bennett 2005; Bureau of Reclamation 2006; but see Moyle and Israel 2005). In California, most unscreened diversions pump river water directly through pipes that vary in size and water diversion rate to irrigate local agriculture. These diversion pipes are commonly situated on top of levees and project down into the water at a 0.5 slope following the slope of the riverbank. The pipe enters the water perpendicular to the water column at a 26.6° angle relative to the river bottom. Because these water diversions are also often unpermitted and unrecorded (Bowen 2004), their overall threat to fish populations is difficult to estimate. A recent investigation found that fish susceptibility to entrainment through unscreened water diversions is greatly unknown in California and that research is needed to help identify what characteristics of unscreened diversions are likely to pose the greatest fish entrainment risk (Moyle and Israel 2005). Understanding how environmental factors, such as light availability or local hydraulics, affect fish entrainment susceptibility will allow the relative impacts associated with water diversions at different locations to be estimated. With these data, time and site-specific water diversion management plans to help protect vulnerable fish populations could be implemented.

California's Central Valley Chinook Salmon *Oncorhynchus tshawytscha* migrate upstream into the Sacramento and San Joaquin rivers and their tributaries to spawn. Juvenile Chinook Salmon rearing in the freshwater habitat encounter a maze of unscreened water diversions during their out-migration to the Pacific Ocean and can become fatally entrained. Recent fish sampling studies determined that small numbers of juvenile Chinook Salmon are annually entrained into select unscreened water diversions in the Sacramento River, but fish entrainment rates varied by year and location, making cumulative Chinook Salmon mortality caused by unscreened water diversions difficult to quantify (Dan Meier, U.S. Fish and Wildlife Service, personal communication). Juvenile fall-run Chinook Salmon, listed as a species of concern, out-migrate during the spring, which can coincide with the beginning of the agricultural irrigation season (particularly in drought years). Furthermore, the endangered Sacramento River winter-run Chinook Salmon out-migrate in the fall and winter when the irrigation season is ending, but their migration can overlap with active water diversion in September (Vogel 2011). The majority of California Chinook Salmon populations are in rapid decline (Katz et al., in press), making it important to identify and reduce their manageable mortality sources.

The numbers of juvenile Chinook Salmon that become entrained at unscreened water diversions are likely related to several factors including the numbers and dimensions of diversion pipes to which the fish are exposed, numbers of fish that approach the pipes' inlets during the irrigation season, underwater light levels during water diversion, river (sweeping) velocities, and water flow rates through the diversion pipes. The effects

of hydraulic conditions on fish entrainment rates are mostly unknown, and there have been few studies monitoring fish entrainment at unscreened water diversions in California waterways (Nobriga et al. 2004; Moyle and Israel 2005). Nobriga et al. (2004) monitored the number of fish entrained into an unscreened diversion pipe (0.61-m-diameter, 0.70 m³/s water diversion rate) in the lower Sacramento River for 3 d in early July 2000 and 2001. Although juvenile Chinook Salmon were not captured during this study, their absence may be due to the brief sampling period or the time of sampling, which was near the end of the out-migration season for fall-run Chinook Salmon. A greater number of fish were entrained during the night than during the day in the study, possibly due to the decreased visual detection of the diversion pipe (Nobriga et al. 2004). Large numbers of Chinook Salmon are entrained at the California State Water Project and Central Valley Project water export facilities, located in the Sacramento–San Joaquin Delta (Kimmerer 2008). Due to the large amounts of water diverted at these facilities, they do not provide a good comparison to fish entrainment through agricultural diversion pipes, but a general trend of increased fish entrainment (nonsalmonid) during periods of increased turbidity and river velocity (Grimaldo et al. 2009) suggest that fish entrainment rates can be affected by environmental conditions.

Our study evaluated juvenile Chinook Salmon entrainment risk and their behavioral responses to a 0.46-m-diameter unscreened diversion pipe in a river-simulation flume. We simulated hydraulic conditions encompassing a range of realistic water diversion rates and river currents common to the Sacramento River. Combinations of three sweeping (river) currents and two water diversion (pipe) rates were tested during the day. Additional flume experiments were conducted in turbid water and during the night at two sweeping velocities and one pipe diversion rate. Our goal was to identify how hydraulic conditions (i.e., river sweeping currents and pipe water diversion rates) affect fish pipe-passage and entrainment behaviors during day, turbid-water, and night conditions. Behaviors investigated for each set of conditions included fish entrainment orientation, location, distance, timing, and susceptibility. To our knowledge, this study is the first to measure fish entrainment into an unscreened water diversion pipe in a controlled laboratory environment, providing a quantitative basis for setting screening priorities or regulating open water diversions to reduce juvenile Chinook Salmon entrainment mortality.

METHODS

Flume operation.—Experiments were conducted in an outdoor flume (Figure 1), which has a 501,000-L water capacity when filled and was designed to simulate a river environment, at the J. Amorocho Hydraulics Laboratory, University of California, Davis (UC Davis). The test section of the flume was 18.29 m long, 3.05 m wide and 3.20 m high (Figure 2). The flume was located beneath a translucent white polyvinyl chloride (PVC)

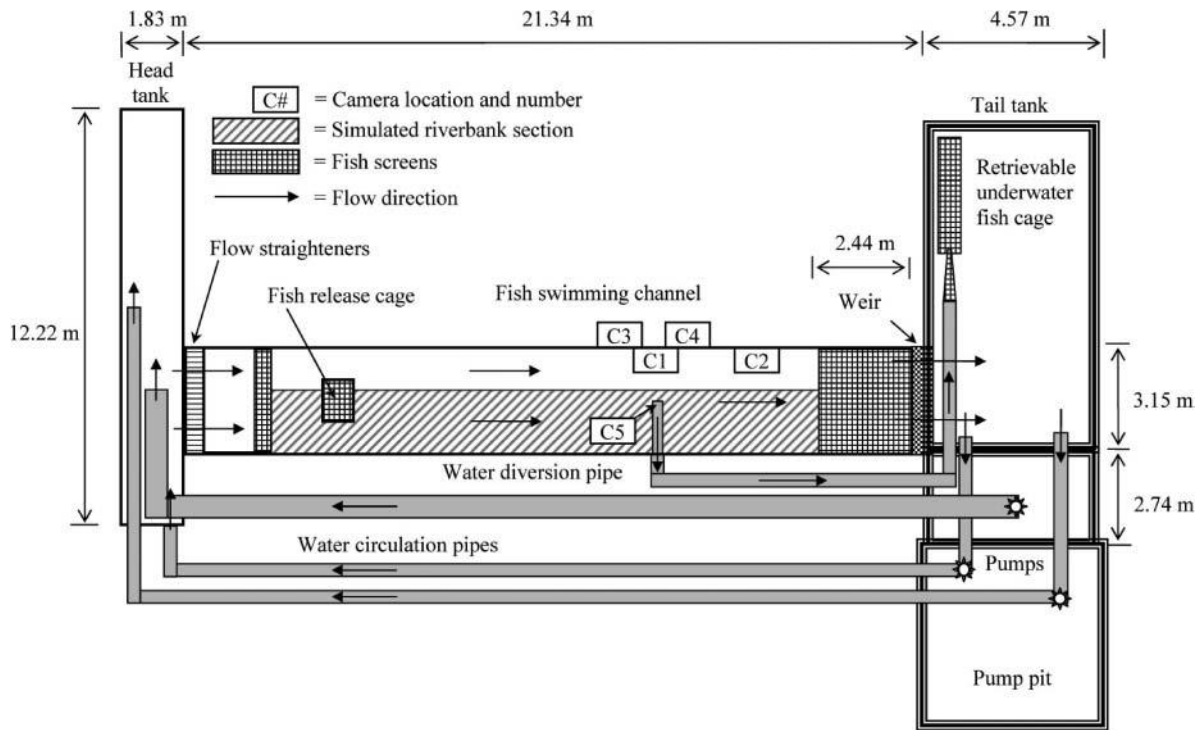


FIGURE 1. Top-view diagram of the flume used in fish swimming experiments, showing flume dimensions, water circulation, and camera locations.

vinyl shelter, which produced diffused light and prevented shadows. Flume sweeping velocities were controlled using three variable-speed pumps. Water from the 12.2-m head tank passed through vertical flow-straightening bars as it entered the main channel to evenly distribute the flow and minimize water turbulence. An unscreened diversion pipe (0.46 m diameter) was located near the center of the flume (Figures 1–3). An angled bank (ramp), simulating a riverbank, was located down the length of the flume at a 26.6° decline from one sidewall to the base of the flume (Figures 1–3). The diversion pipe was mounted parallel to the ramp's slope, with its base located 0.3 m above the ramp, to simulate a typical "over-the-levee" irrigation pipe. Water taken through the diversion was returned into the downstream tail tank by the vertical head difference between the main channel and tail tank. Greater water depth, achieved by adjusting the weir height at the downstream end of the flume, increased the head difference and increased pipe diversion rates. Water depth ranged from 2.0 to 2.2 m between experimental conditions to produce the desired diversion intake rates. This configuration allowed water and fish to be diverted through the pipe without using a pump, minimizing injuries to entrained fish.

The fish were restricted to swimming in the main channel by upstream and downstream stainless steel screens (0.6 cm mesh). The upstream screen was mounted 2 m downstream from the head tank, oriented perpendicular to the base of the flume. The downstream screen was 4.52 m long and mounted at a 46° angle at the end of the channel, with the top of the screen tilted downstream. A fyke located at the diversion pipe

outlet in the tail tank crowded entrained fish into an extractable underwater cage with a removable mesh bag at the cod end. At the completion of each swimming experiment, an underwater cage was hoisted out and entrained fish were quickly (~ 5 s) transported to a recovery tank. Fish remaining in the flume were collected using a 3.7-m \times 3.0-m seine net and placed into a separate recovery tank for postexperiment assessments.

Experimental animals.—The majority of fall-run Chinook Salmon in the Sacramento River system are of hatchery origin (Barnett-Johnson et al. 2007), therefore experiments were conducted with age-0 Chinook Salmon acquired from the California Department of Fish and Game's Feather River Hatchery (Oroville, California). In April 2010 and March 2011, 8,000 fish were transported to UC Davis' Center for Aquatic Biology and Aquaculture. Fish were equally distributed in one of two 455-L flow-through circular tanks equipped with nonchlorinated, air-equilibrated well water (pH = 8.0, dissolved oxygen = 6.0–9.0 mg/l), maintained at 12°C to delay smoltification (Sykes and Shrimpton 2010), and fed a diet of Rangen semimoist fish pellets daily to satiation. Holding tank temperatures were increased ($1^\circ\text{C}/\text{d}$) to 18°C a minimum of 2 weeks before experimentation to match the ambient temperature of the well water used to supply the flume. All animals were handled according to Institutional Animal Care and Use Protocols (IACUC UC Davis # 15836).

Flume water quality was measured at the start and end of each experiment. Water temperature ($^\circ\text{C}$) and dissolved oxygen concentration (mg/l) were measured using an YSI Dissolved



FIGURE 2. Top-view photograph of the fish-swimming flume, taken during fish acclimation under still water conditions. The water diversion pipe is visible below the overhead camera, and the fish-releasing cage is submerged at the upstream end of the flume. [Figure available online in color.]

TABLE 1. Mean \pm SE fish size and flume water quality during the day, night, and turbid-water experiments.

Means or period	Day, clear water	Night, clear water	Day, turbid water
Fish fork length (cm)	12.8 \pm 0.13	13.3 \pm 0.14	12.5 \pm 0.3
Fish mass (g)	26.5 \pm 0.95	29.2 \pm 1.05	24.2 \pm 0.6
Water temperature ($^{\circ}$ C)	18.9 \pm 0.4	19.5 \pm 0.7	20.6 \pm 0.2
Dissolved oxygen (mg/l)	9.2 \pm 0.3	10.2 \pm 0.3	8.0 \pm 0.1
Experimental period	August 23 to October 28, 2010	September 9 to November 3, 2010	August 16–24, 2011

Oxygen meter (Model 85-10FT). Illuminance was measured 1.2 m above the water surface in lux using an Extech Easy View 30 light meter. Flume water ammonia concentration (mg/l) was measured using a Hach ammonia nitrogen colorimeter (Model 58700-40), and pH levels were measured using an Accumet AB 15 pH meter with a combination electrode (Model 13-620-299). Flume water was drained and refilled every week with nonchlorinated well water to ensure the experimental water temperatures remained below 21 $^{\circ}$ C. During the experimental periods, mean light levels were 2,800 lux (SE, 0.38) during the day and 0.02 lux (SE, 0.05) during the night, pH was 8.01 (SE, 0.01), and ammonia levels were undetectable (<0.00 mg/l). Fish fork length was measured using a metric ruler (mm), and fish mass (g) was measured using Ohaus balances (Model SC4020). Mean fish length and mass, flume water quality, and experimental time periods are listed in Table 1.

Day experiments in clear water.—In pilot experiments we found that juvenile Chinook Salmon started exploring the flume 20 min after being released into the current and that the largest number of fish passing the water diversion pipe occurred at 60 min. Therefore, the experimental period was set at 2 h. Eighty naive Chinook Salmon were tested per experiment to in-

vestigate possible differences in fish entrainment rates between tested flow combinations. Fish were transported (approximately 1.8 km) to the flume from the Center for Aquatic Biology and Aquaculture in an aerated cooler and placed into a submerged releasing cage via a 2.1-m-long, 15.2-cm-diameter PVC tube (fish chute) for a 30-min acclimation. The releasing cage (0.91 m wide, 1.22 m long, and 0.41 m deep) was covered in 0.6-cm mesh of welded stainless steel wire. The downstream wall of the cage was remotely opened at the start of each experiment, allowing fish to exit into an established current. The releasing cage was located 9.3 m upstream from the diversion pipe, providing fish the maximum distance to orient to the current before encountering the pipe.

Fish swimming behaviors and entrainment events were recorded continuously during day experiments, using five video cameras (Sony Model CCD-TRV108, Canon Model ES200A, and Speco Model CVC 627) and five Panasonic DVD-R's (Model DMR-EA18K). Cameras were mounted either underwater using 45.4-kg-force magnets, on tripods outside of the flume, or above the flume's swimming channel. All cameras were directed at the diversion pipe's inlet to capture entrainment events. Camera 1 was magnetically affixed underwater to the flume sidewall, 2.4 m downstream, and at the same depth as the diversion pipe inlet (Figure 1). Camera 2 was positioned underwater directly across from the diversion pipe and 1.5 m above the bottom of the flume. Cameras 3 and 4 viewed the diversion pipe inlet through acrylic windows located 0.61 m upstream and 0.61 m downstream from the pipe inlet in the sidewall of the flume. Camera 5 was mounted 4 m above the surface of the water, providing observation from directly above the diversion pipe inlet. A clear-plastic view plate (1.22 m \times 1.22 m) was floated below the camera to reduce water-surface-related distortion and provide a clear view of the pipe.

Fish swimming experiments were conducted at 0.15, 0.38, 0.61 m/s sweeping velocities with 0.42 and 0.57 m³/s water diversion rates during the day. These flow combinations provide a range of flows commonly present at unscreened water diversions on the middle and lower Sacramento River mainstem (Dan Meier, U.S. Fish and Wildlife Service, personal communication). The six flow combinations tested were each replicated six times (36 daytime experiments, total). Following each swimming experiment, entrained and nonentrained fish were placed in separate recovery tanks and then individually transferred into



FIGURE 3. Underwater view of the flume taken by camera number 2, showing the water diversion pipe inlet and swimming juvenile Chinook Salmon. [Figure available online in color.]

a buffered anesthetic bath of tricaine methanesulfonate acid (0.14 g/l), sodium chloride (10 g/l), and sodium bicarbonate (0.42 g/l) until they lost equilibrium. The numbers of juvenile Chinook Salmon entrained and those that remained in the swimming channel at the end of the experiment (i.e., nonentrained) were recorded. The fork length (cm) and mass (g) of each fish were measured.

Day experiments in turbid water and night experiments.—Turbid-water and night experiments were conducted using the same procedures as those used during day experiments in clear water, except only two sweeping velocities (0.15 and 0.61 m/s) with one diversion rate (0.57 m³/s) were tested. In turbid-water experiments, both flow combinations were replicated six times (12 total experiments), whereas during the night, both were replicated eight times (16 total experiments). Due to limited fish availability, turbid-water and night experiments were conducted using fish that had been tested previously in one daytime experiment, with at least 1 week to recover between experiments.

To create turbid water, soil from an undeveloped field surrounding the UC Davis Hydraulics Laboratory was collected, sieved, and crushed into fine particles. The soil was mixed in an external tank and water from the surface of the mixing tank was pumped to the flume prior to experimentation. Although soil particles slowly settled to the flume floor when the flume's sweeping current was terminated, they rapidly were resuspended when the current was reestablished. Turbidity was measured with a calibrated nephelometer (Eureka Environmental Engineering, Manta 2 multiprobe) and the mean turbidity in the experiments was 20 NTU (SE, 1.1) at 0.15 m/s sweeping velocity and 31 NTU (SE, 1.2) at 0.61 m/s sweeping velocity. The tested turbidity levels were within the upper range of common water turbidity in the lower Sacramento River. During our experimental period, turbidity levels in the lower Sacramento River and Delta ranged from to 5–35 NTU, with a mean of 18 NTU (CDEC 2012).

During the night experiments, fish were placed into the releasing device in the dark using Night Optics night vision goggles (Model AN/PVS-7), equipped with infrared spotlights. The video cameras used in day experiments were inadequate to clearly view fish during turbid or night conditions, limiting the results of these experiments to fish entrainment counts and fish size measurements.

Fish behavior analysis.—Videos from day experiments were analyzed using J-watcher (version 1.0; Blumstein et al. 2006) to note the exact time that each fish became entrained into the pipe, the number of pipe passages per experiment, and the fish's swimming orientation relative to the sweeping current direction during pipe passage. Fish were counted as they moved past the diversion pipe traveling downstream and upstream during the daytime experiments. Fish pipe passage was defined as the total number of times fish were observed passing by the diversion pipe during each experiment. Because individual fish could not be identified, differences in pipe passage rates between individual fish were unknown. Fish passing the pipe were categorized either as fish traveling downstream and

swimming with the sweeping current (negative rheotaxis), fish facing into the sweeping current and being carried downstream by it (positive rheotaxis), or fish swimming upstream into the current (also displaying positive rheotaxis). The percentage of pipe passages resulting in fish entrainment was calculated for each experiment by dividing the number of entrained fish by the observed number of pipe passages that occurred during the experiment (including both successful passages + passages resulting in entrainment), multiplied by 100.

Video recordings were converted into MPEG format using MPEG Streamclip version 1.2. and analyzed with Sony Movie Studio HD platinum version 10 to locate the starting and ending locations of each fish entrainment event. Still images of fish entrainment events were created from the recorded video. Images of the fish's position relative to the diversion pipe were captured from the video at the moment when fish started to become entrained into the diversion pipe, indicated by a change in the fish's swimming orientation or velocity as they approached the diversion pipe (entrainment-starting location) and at the final moment the fish was visible before entering the diversion pipe (entrainment-ending location).

Images of the entrainment-starting locations were made for each fish entrainment event from the overhead and side window cameras, allowing distances to be measured from the top and front perspective. The distance and angle from the center of the pipe's inlet to the center of the fish's head were measured in each image using ImageJ software (Rasband 2012). The combined measurements allowed the fish entrainment-starting locations to be defined in three-dimensional space relative to the center of the diversion pipe's inlet. Entrainment-starting distances (cm) were averaged for each experiment and compared between flow combinations. Experiments with no fish entrainment decreased the flow combination's sample size. Fish's swimming orientations relative to the sweeping flow were also recorded at the start of each entrainment event. Because the camera's perspective distorted true measurement distances, measured fish entrainment-starting distances were modified by empirical camera correction formulas to compensate. Ratios of observed distances on a post-experiment, suspended PVC pipe grid to actual distances, at 15.2-cm intervals from the center of the pipe inlet, were used to create the correction formulas.

Water velocity measurements.—Once fish entrainment-starting locations were identified through video analysis, the flow combinations (sweeping flow, diversion rate, and water depth) were recreated in the flume to measure the exact three-dimensional velocities (at 25 Hz, 3-D SonTek ADV probe, $\pm 1\%$) where each entrainment began. The Confidence function in Excel was used to calculate the 95% confidence intervals for water velocity measurements.

Data analyses.—Data were analyzed using analysis of variance (ANOVA) models, primarily, with alpha set at 0.05 and using Tukey's post hoc tests. Mean fish entrainment counts from day experiments were analyzed using a two-way ANOVA with Poisson distributions. Daytime, turbid-water, and night

experiments were analyzed in a separate two-way ANOVA with Poisson distributions using the same daytime results. A Bonferroni correction was used to maintain the familywise error rate of the comparisons, reducing the alpha of these individual tests to 0.025. Fish passage rates at different swimming orientations were analyzed using separate two-way ANOVAs with Poisson distributions. Mean percentages of fish that became entrained per pipe passage, percentages of fish that returned upstream after initially passing the pipe, and the average fish entrainment-starting distances were analyzed using two-way ANOVAs with normal distributions. Percentages were arcsine transformed prior to analysis to normalize the data. Mean fork lengths and masses between entrained and nonentrained fish were compared using *t*-tests for day, night, and turbid-water conditions.

RESULTS

Day Experiments

Overall, entrainment through the unscreened pipe was generally low, from 0.8% (SE, 0.3) to 8.5% (SE, 0.3) of fish entrained over the 2-h experiment, between flow conditions (Figure 4). The flume's hydraulic conditions, however, affected fish entrainment, with differences between sweeping velocities ($F_{2,30} = 7.9$, $P = 0.002$), and water diversion rates ($F_{1,30} = 5.9$, $P = 0.021$), and the interaction between sweeping velocity and water intake rate not being significant ($F_{2,30} = 2.7$, $P = 0.083$). Fish entrainment was significantly higher at the lowest (0.15 m/s) sweeping velocity and the higher (0.57 m³/s) diversion rate, compared with the other tested flow combinations ($P \leq 0.005$). Comparisons of fish entrained among the other flow conditions were not statistically distinguishable ($P \geq 0.637$; Figure 4).

At the slowest sweeping velocity (0.15 m/s), more fish successfully traveled downstream past the diversion pipe with nega-

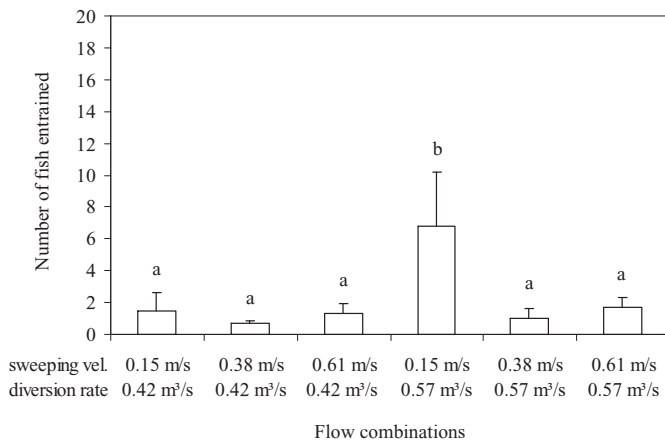


FIGURE 4. Mean + SE number of Chinook Salmon entrained through the unscreened diversion pipe at sweeping velocities of 0.15, 0.38 and 0.61 m/s and water diversion rates of 0.42 and 0.57 m³/s during 2-h daytime experiments (80 fish tested in each replicate, $n = 6$ replicates per flow combination). Significant differences in the number of fish entrained at different flow combinations are marked with different letters ($P \leq 0.005$).

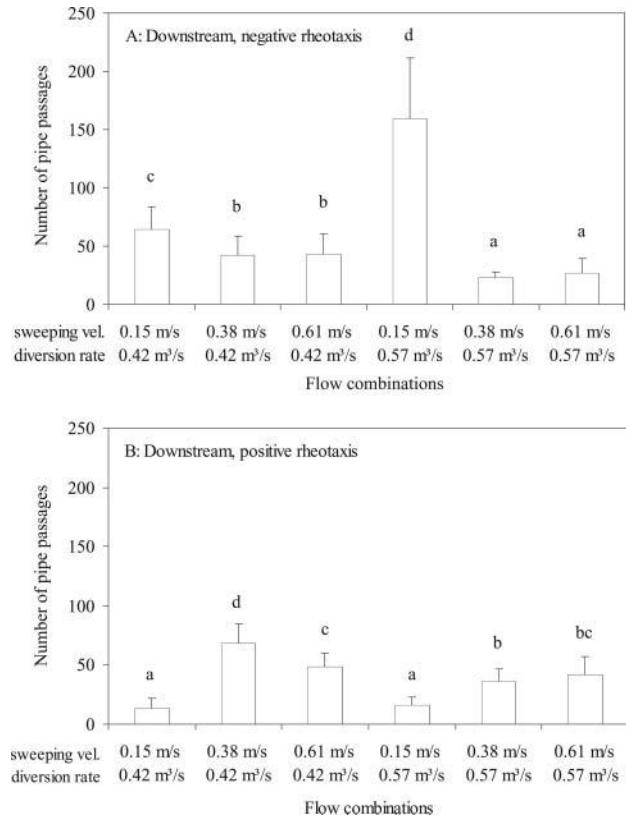


FIGURE 5. Mean + SE number of fish that moved downstream past the pipe with (A) negative rheotaxis (head first) and (B) positive rheotaxis (tail first) at sweeping velocities of 0.15, 0.38 and 0.61 m/s and water diversion rates of 0.42 and 0.57 m³/s during 2-h daytime experiments ($n = 6$ replicates per flow combination). Individual fish could pass the pipe more than once. Significant differences in the numbers of fish passing the pipe at different flow combinations are labeled with different letters ($P \leq 0.001$). Upstream passage is not shown, as the percentage of fish that returned upstream after passing the pipe equaled approximately 60% of the total downstream passage rate at each flow condition.

tive rheotaxis ($F_{2,30} = 289.9$, $P < 0.001$; Figure 5A). In contrast, at the higher sweeping velocities (0.38 and 0.61 m/s), many fish oriented into the current and were carried downstream tail first when passing the diversion pipe. There were no significant differences in downstream fish passage with negative rheotaxis between water diversion rates ($F_{1,30} = 0.96$, $P = 0.336$). The significant interaction between sweeping velocity and water diversion rate ($F_{2,30} = 115.1$, $P < 0.001$; Figure 5A) resulted from significantly fewer fish passing the pipe with negative rheotaxis at the 0.42 m³/s diversion rate, compared with those at 0.57 m³/s ($P < 0.001$) at the 0.15 m/s sweeping velocity. In contrast, at the two higher sweeping velocities, more fish passed the pipe at the 0.42 m³/s diversion rate compared with at 0.57 m³/s ($P < 0.001$, Figure 5A).

In contrast to the negative-rheotaxis swimming fish, more fish passed the pipe with positive rheotaxis at higher sweeping velocities ($F_{2,30} = 106.0$, $P < 0.001$; Figure 5B). Also, more fish passed the pipe at the lower water diversion rate ($F_{2,30} = 7.79$, $P = 0.009$; Figure 5B), and there was a significant

interaction between sweeping velocity and water diversion rate ($F_{2,30} = 15.6, P < 0.001$; Figure 5B). The interaction resulted from significantly more fish passing the pipe at the 0.42 m³/s water diversion rate compared with the 0.57 m³/s rate at the 0.38 m/s sweeping velocity. However, at the 0.15 and 0.61 m/s sweeping velocities there was no significant difference in fish passage between the two diversion rates.

The mean numbers of fish that successfully traveled upstream past the pipe diversion were proportional to the mean numbers of fish that successfully traveled downstream in each flow combination. Overall, 59.5% (SE, 2.8) of the fish that traveled downstream past the diversion pipe swam back upstream, past the pipe. The percentages were not significantly different between sweeping velocities ($F_{2,30} = 0.3, P = 0.711$) or diversion rates ($F_{1,30} = 1.07, P < 0.310$) (interaction: $F_{2,30} = 0.3, P = 0.758$). Swimming orientations of entrained fish were difficult to evaluate due to the low numbers of fish entrained in some flow combinations, but in general, the percentage of fish entrained at each swimming orientation was similar to the percentage of fish passing the pipe at each swimming orientation.

During clear-water, daytime experiments the number of fish traveling past the diversion pipe in most flow combinations was relatively consistent throughout the 2-h period, with a mean value of 22 fish (SE, 1.4) passing the pipe every 20 min. A different pattern was seen in the 0.15 m/s sweeping and 0.57 m³/s diversion rate flow combination, where the numbers of fish passing the pipe in the first 20 min was 20.5 (SE, 5.9) but then increased to 79 fish (SE, 21.4) during the 60–80-min period and declined to 58 fish (SE, 17.0) during the last 20 min. The numbers of fish entrained in the different flow combinations followed a similar pattern to pipe passage. The number of fish entrained was consistently low in most flow combinations, with a mean value of 0.2 fish every 20 min (SE, 0.03), and in the 0.15 m/s and 0.57 m³/s flow combination there was an increase in the number of fish entrained from 0.3 fish (SE, 0.2) in the first 20 min to 2.8 fish (SE, 2.1) in the 60–80-min period and then a decline to 1.0 fish (SE, 0.4) during the final 20 min. These results suggest that increased numbers of fish passing the water diversion pipe in the 0.15 m/s and 0.57 m³/s flow combination resulted in more fish entrainment.

Overall, the percentage of pipe passage events that resulted in fish entrainment was <3% at all flow combinations. Although there were no differences among sweeping velocities ($F_{2,30} = 2.5, P = 0.102$; Figure 6), the higher (0.57 m³/s) pipe diversion rate entrained a significantly greater mean \pm SE percentage of fish per passage (1.8% \pm 0.6; $F_{1,30} = 10.1, P = 0.004$) than the lower (0.42 m³/s) diversion rate (0.7% \pm 0.3; Figure 6), with no interaction between sweeping velocity and diversion rate ($F_{2,30} = 0.8, P = 0.458$). Interestingly, the number of pipe passage events resulting in fish entrainment increased 89% with a 33% increase in water diversion rate.

Chinook Salmon became entrained in relatively similar frequencies from all sides of the pipe, with no differences in fish entrainment-starting locations (Figure 7). Although there was

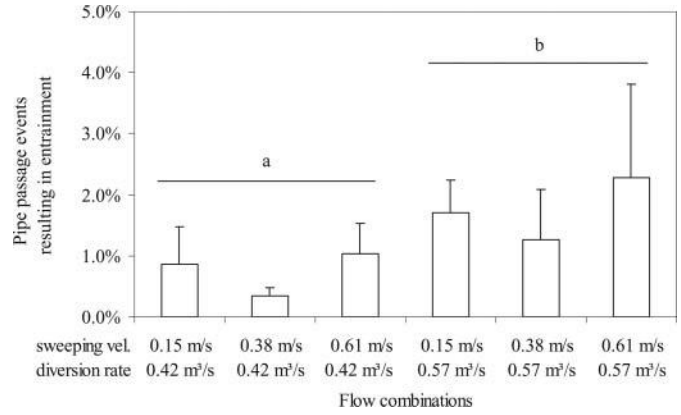


FIGURE 6. Mean + SE percentage of fish that became entrained while traveling past the diversion pipe at sweeping velocities of 0.15, 0.38 and 0.61 m/s and water diversion rates of 0.42 and 0.57 m³/s during 2-h daytime experiments ($n = 6$ replicates per flow combination). Individual fish could pass the pipe more than once during an experiment and 80 fish were tested in each replicate. Different letters indicate a significant difference in the mean percentage of fish entrained between water diversion rates ($P = 0.004$).

no significant sweeping velocity effect ($F_{2,16} = 2.4, P = 0.123$) on mean fish entrainment-starting distance, a significant water diversion rate effect ($F_{1,16} = 4.9, P = 0.043$) was found with a mean of 34.3 cm (SE, 2.0) at 0.42 m³/s compared with 38.6 cm (SE, 1.6) at the 0.57 m³/s water diversion rate (Figure 8). There was no significant sweeping velocity by diversion rate interaction ($F_{2,16} = 0.38, P = 0.692$; Figure 8). Therefore, juvenile Chinook Salmon were entrained from approximately 4.3 cm further away from the pipe opening at the higher diversion rate.

Water Velocity Measurements

The water velocities fish experienced at the start of entrainment events were measured in three directions: upstream or downstream horizontal movement (x -direction), the transverse direction with respect to the tip of the diversion pipe (y -direction), and the vertical change in depth (z -direction). The mean fish entrainment velocity in the x -direction was 0.50 m/s with a 95% confidence interval of 0.34–0.64 m/s, in the y -direction was 0.39 m/s with a 95% confidence interval of 0.23–0.54 m/s, and in the z -direction was 0.20 m/s with a 95% confidence interval of 0.05–0.35 m/s. The mean resultant velocity that fish experienced when becoming entrained was 0.74 m/s with a 95% confidence interval of 0.58–0.89 m/s, suggesting that juvenile Chinook Salmon start losing control of their swimming direction when encountering intake velocities between 0.6 and 0.9 m/s at unscreened water diversions.

Turbid-Water and Night Experiments

Overall, fish entrainment differed among water visibility levels ($F_{2,34} = 24.9, P < 0.001$; Figure 9). In turbid water, more fish became entrained at 0.61 m/s sweeping velocity than at 0.15 m/s ($P = 0.004$; Figure 9). At 0.15 m/s sweeping velocity

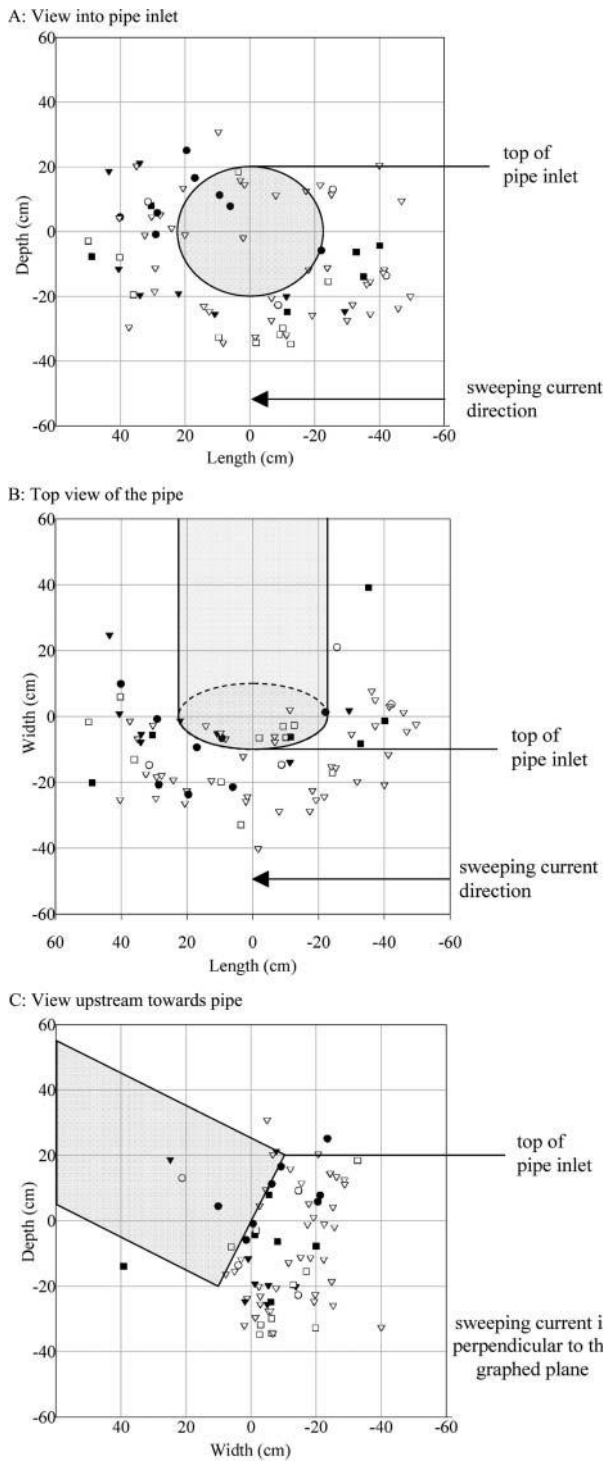


FIGURE 7. The starting locations of fish entrainment events are plotted at three views of the diversion pipe: (A) into the pipe inlet, (B) above the pipe, and (C) upstream view towards the pipe. The 0-cm intercept for depth, width, and length is located at the center of the pipe inlet in all three plots. Entrainment-starting locations for each flow combination are labeled with different symbols as follows: black circles = 0.15 m/s, 0.42 m³/s, white circles = 0.38 m/s, 0.42 m³/s, black triangles = 0.61 m/s, 0.42 m³/s, white triangles = 0.15 m/s, 0.57 m³/s, black squares = 0.38 m/s, 0.57 m³/s, and white squares = 0.61 m/s, 0.57 m³/s.

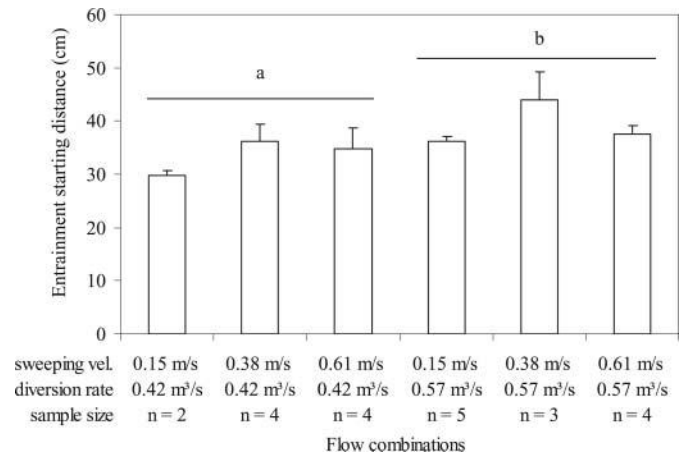


FIGURE 8. Mean + SE distances from the center of the pipe's inlet to the locations where individual fish entrainment events started at sweeping velocities of 0.15, 0.38 and 0.61 m/s and water diversion rates of 0.42 and 0.57 m³/s during 2-h daytime experiments. Different letters indicate a significant difference in the mean distance that fish entrainment started between water diversion rates ($P = 0.043$).

fewer fish became entrained in turbid water compared with those in the daytime control (clear water, $P = 0.008$), whereas at the 0.61 m/s sweeping velocity more fish became entrained in turbid water compared with those in the daytime control ($P = 0.002$).

More fish became entrained during night than in turbid water conditions in both of the tested flow combinations (0.15 m/s, $P = 0.003$; and 0.61 m/s, $P = 0.014$). During the night, significantly more fish became entrained at 0.61 m/s sweeping velocity than at 0.15 m/s ($P = 0.005$; Figure 9). The number of fish that became

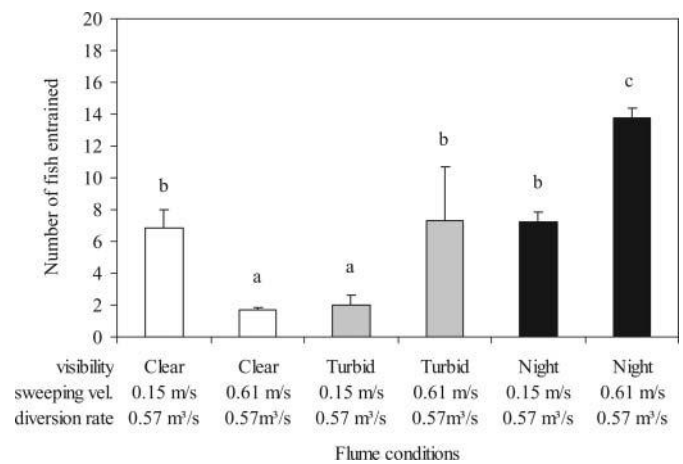


FIGURE 9. Mean + SE number of Chinook Salmon entrained through the unscreened diversion pipe, out of 80 fish tested in each replicate, at sweeping velocities of 0.15 and 0.61 m/s and a water diversion rate of 0.57 m³/s during 2-h daytime experiments in clear water, turbid water (~ 20 NTU at 0.15 m/s and 31 NTU at 0.61 m/s), and during the night ($n = 6$ replicates per flow combination). Significant differences in the number of fish entrained at different water visibility and sweeping velocity combinations are marked with different letters ($P \leq 0.014$).

entrained during the day and night was similar at 0.15 m/s sweeping velocity ($P = 1.0$). However, at 0.61 m/s sweeping velocity, significantly more fish became entrained during the night than during the day ($P < 0.001$), suggesting that during the night juvenile Chinook Salmon encountering a 0.57 m³/s water diversion are more likely to become entrained when swimming in a 0.61 m/s current than in a 0.15 m/s current.

Fish Sizes

Regarding possible fish-size-related effects on entrainment, the mean fork lengths and masses of entrained fish were compared among day, turbid-water, and night treatments with t -tests. No significant differences in mean fork length or mass were found between entrained and nonentrained fish ($P \geq 0.16$), suggesting that all sizes of fish (within the range tested) were equally vulnerable to entrainment when passing the diversion pipe. Also, there was no significant difference in mean fork length ($F_{9,54} = 1.2$, $P = 0.337$) or mean mass ($F_{9,54} = 1.1$, $P = 0.386$) between treatments.

DISCUSSION

Day Experiments in Clear Water

In clear water during the day, juvenile Chinook Salmon could presumably detect the diversion pipe's location both visually and by sensing the change in water velocity and direction with their lateral line system (Dijkgraaf, 1963) prior to entering water velocities challenging to their swimming capabilities. Most fish were able to move past the pipe's inlet at a "safe" distance (e.g., >44 cm) to avoid becoming entrained. Juvenile Chinook Salmon were likely visually deterred from entering the darkened diversion pipe inlet in our daytime experiments, as these fish have been shown to actively avoid following water currents into darkened structures (low internal light intensity) during their out-migration (Kemp et al. 2005a). Juvenile Chinook Salmon have also been shown to avoid entering areas of increased water velocity (Kemp et al. 2005b), suggesting that encountering the rapidly increasing velocity near the diversion pipe inlet may have deterred most fish from swimming close to the diversion. However, a small number of fish swam too close to the water diversion inlet and were entrained rapidly (<1 s). The mean timing and orientation of fish entrainments closely matched the mean timing and orientation of fish pipe passage, suggesting that fish were equally susceptible to entrainment (1) throughout the duration of the experiment, (2) when traveling upstream or downstream past the pipe, and (3) when swimming with positive or negative rheotaxis.

Fish dispersed throughout the length of the flume during the experiments, swimming individually or in small groups (3–5 fish), with no preference shown for any particular location. When holding their position in currents, Rainbow Trout *Oncorhynchus mykiss* are known to swim downstream of stationary objects, using these objects as hydraulic cover and reducing their energetic swimming costs (Cook and Coughlin

2010; Przybilla et al. 2010). In our flume experiments, juvenile Chinook Salmon did not hold station at any location near the diversion pipe. The diversion pipe's size, close proximity to the base of the flume, and suction of water through the pipe inlet would have disrupted downstream flow characteristics (small frequent eddies) that can provide fish hydraulic refuge (Przybilla et al. 2010). These experiments were conducted with juvenile, fall-run Chinook Salmon that were somewhat larger in size than would be expected for fish out-migrating through the Sacramento River in the spring and more closely resembled out-migrating, late-fall-run Chinook Salmon in this river system. The responses of smaller-sized Chinook Salmon should also be studied in future experiments to determine if entrainment susceptibility changes with fish age.

In the clear-water daytime experiments, which presumably allowed the fish a clear view of the diversion pipe, most fish actively swam past the pipe with negative rheotaxis at the 0.15 m/s and 0.57 m³/s flow combination. Fish appeared to actively explore the flume under these conditions, and they passed the pipe numerous times. In the two faster sweeping conditions, most fish oriented into and swam against the sweeping current, preventing the fish from being carried rapidly downstream. Fish also swam throughout the flume at the higher sweeping currents' conditions and passed the pipe frequently. The observed, relatively high percentage (59.5%) of fish that returned upstream after passing downstream of the pipe may have resulted from the flume's relatively confining dimensions, compared with a large river. Models based on out-migrating juvenile Chinook Salmon tracking studies in the Snake River, Washington, have determined that the fish frequently stop during their downstream migration and reside in various locations for prolonged periods of time (Steel et al. 2001). This behavior could result in fish encountering the same unscreened water diversion numerous times during their out-migration, as observed in our experiments.

Although it is not surprising that a greater percentage of fish passing the pipe became entrained at the higher water diversion rate, the overall increase in fish entrainment was greater than what might be expected. A 0.15 m³/s (35.7%) increase in water diversion rate (from 0.42 to 0.57 m³/s) resulted in an 89% increase in the number of fish entrained per passage (from 0.9 to 1.7%). Using these data to predict the implications of variable water diversion rates on juvenile Chinook Salmon entrainment rates reveals that operating a 0.42 m³/s water diversion for 33% more time (in order to divert an equivalent volume of water as a 0.57 m³/s diversion) would be predicted to decrease the total number of entrained fish by 29.4% (calculated as $[(0.9 \times 1.33)/1.7] - 1$). This type of analysis could be very useful in designing management strategies that best balance agricultural needs with the conservation needs of juvenile Chinook Salmon, including runs listed as threatened or endangered by the The National Marine Fisheries Service.

The percentage of fish that become entrained into open irrigation channels during downstream migration has been found to vary significantly between years. Annual measures of

entrainment in juvenile Westslope Cutthroat Trout *Oncorhynchus clarkii lewisi* trout migrating downstream through irrigation channels on Skalkaho Creek, Montana, have been shown to vary significantly (range, 40–70%), likely resulting from increased proportions of river water extracted during low rainfall years (Gale et al. 2008). In our experiments, a greater percentage of water moving through the flume was diverted through the pipe at the lower sweeping velocities and higher water diversion rates. In the 0.15 m/s and 0.57 m³/s flow combination, 64% of the water entering the flume was diverted through the pipe, while at 0.61 m/s and 0.42 m³/s only 14% of the water entering the flume was diverted. Although fish entrainment was highest in the 0.15 and 0.57 m³/s flow combination, the percentage of fish entrained per pipe passage (1.7%) was substantially lower than 64%. One study conducted in the Sacramento River (California) also found that the percentage of juvenile Chinook Salmon entrained into an unscreened water diversion, after being released upstream of its location, was smaller than the percentage of water extracted. Hanson (2001) released >100,000 juvenile Chinook Salmon upstream of an unscreened water diversion extracting 1.03% of passing Sacramento River water and recaptured only 0.05% of the released fish in the water diversion.

The increase in water velocity approaching the diversion pipe varied between flow conditions and was highest at the 0.15 m/s and 0.57 m³/s flow combination, when fish entrainment rates were also the highest. In 0.15 m/s sweeping currents, water velocity (flume to diversion pipe gradient) was increased by a factor of 17.0 at 0.42 m³/s and a factor of 22.6 at 0.57 m³/s, whereas in 0.61 m/s sweeping currents mean water velocity was increased by a factor of 4.25 at 0.42 m³/s and 5.65 at 0.57 m³/s. An increased water velocity gradient into the diversion pipe may have provided fish less time to detect and avoid the diversion causing the higher observed percentages of fish entrained per passage at 0.57 m³/s (compared with 0.42 m³/s) and the highest total numbers of fish entrained during the day at the 0.15 m/s sweeping and 0.57 m³/s diversion rate flow combination. Our experiments only tested fish swimming near one size of diversion pipe at two pipe diversion (i.e., water withdrawal) rates. Smaller water diversion pipes with higher intake velocities or larger water diversion pipes that withdraw greater amounts of water may pose a significantly greater fish entrainment risk than that found in these experiments. Predictions, based on this study's findings, for entrainment losses at larger- or smaller-sized water diversion pipes or at pipes diverting greater than 0.57 m³/s of water would be speculative.

The juvenile Chinook Salmon started to avoid entrainment when encountering 0.74 m/s water velocities, which likely approached the fish's maximum swimming speed. Portz (2007) measured the maximum burst swimming speed of juvenile Chinook Salmon (10.3 cm total length) in startle response experiments to be 0.60 m/s. We suspect that the entrained fish were attempting to return to areas of lower velocity, which were within their swimming ability, in the flume.

Turbid-Water and Night Experiments

The majority of the fish tested in turbid water and night conditions successfully avoided entrainment throughout the 2-h experiment. This indicates that many salmon avoided swimming in close proximity to the water diversion in flume conditions with limited visibility, either by detecting the water diversion with their lateral line system and limited vision or by holding station in one section of the flume throughout the experimental duration after being released. Juvenile Chinook Salmon are known to avoid areas with hydrodynamic complexity during the night (Kemp and Williams 2008), suggesting that the rapid changes in hydraulic velocity and direction near the diversion pipe inlet may have deterred most fish from approaching the pipe in turbid water and night conditions.

Turbidity has been shown to decrease juvenile Chinook Salmon's reaction distance when foraging by $\geq 45\%$ at the turbidity levels tested in our experiments (20–31 NTU) compared with that in clear water (Gregory and Northcote 1993). The reaction time for fish to visually detect and start avoiding the diversion pipe may have been decreased in our turbidity experiments, resulting in the increased fish entrainment found at 0.61 m/s sweeping velocity. In our turbid-water experiments, fish swimming in 0.61 m/s sweeping currents may have approached the pipe at a greater velocity, compared with fish swimming in 0.15 m/s, and had less time to escape from the diversion after visually detecting it. Also, juvenile Chinook Salmon have shown reduced avoidance behavior (swimming into deeper water), and faster recovery times from the behavior, when presented with model predators during laboratory experiments in turbid water (~ 23 NTU; Gregory 1993). If these fish are less cautious when swimming in turbid water (e.g., with turbidity providing some cover from visual predators) they may also take more risks when approaching water diversions in turbid water, resulting in greater numbers of entrained fish at 0.61 m/s sweeping velocity.

Although Chinook Salmon entrainment was higher at the 0.61 m/s than at the 0.15 m/s sweeping velocity in both turbid water and night conditions, the number of fish entrained during the night was significantly higher than that found in turbid water. These results argue for a significant reliance on visual cues for fish to navigate safely in swift currents. In contrast, the similar entrainment rates between day and night experiments at 0.15 m/s sweeping velocity, and the low entrainment rates in turbid water conditions at 0.15 m/s, indicate that at low sweeping velocities, Chinook Salmon may be able to use cues from other sensory systems to avoid entrainment when visual cues are reduced or absent. Fish detecting the change in flow direction and velocity with their lateral line systems might perceive the diversion as threatening and attempt to avoid entering it. Fish swimming in the 0.15 m/s sweeping velocity might have perceived the steeper velocity gradient at the diversion inlet as more threatening than did those swimming in 0.61 m/s, resulting in more successful avoidance responses at 0.15 m/s. Fish approaching water diversions in the slower sweeping velocity also might have had more

time to avoid being drawn into the diversion after detecting it, resulting in fewer numbers of fish entrained.

Because we could not observe the fish's movements in turbid water or at night, the mechanisms associated with increased fish entrainment at higher sweeping velocities are unknown. One possible explanation is with reduced visual cues to maintain their swimming position in the flume more fish were carried downstream in the 0.61 m/s sweeping velocity, increasing the total number of pipe passages per experiment and consequently total fish entrainment, compared with fish swimming at 0.15 m/s in the same light level condition. Juvenile Chinook Salmon are known to migrate down the Sacramento River during the night in the fall (Ingram and Wilder 2006) and therefore the fish tested in our night experiments may have been more active and more likely to follow water flows during the night (including into the open diversion pipe). Four other fishes occurring in the Sacramento and San Joaquin Delta, threadfin shad *Dorosoma petenense*, delta smelt *Hypomesus transpacificus*, inland silverside *Menidia beryllina*, and striped bass *Morone saxatilis*, are also known to entrain through unscreened diversion pipes in greater numbers during the night and crepuscular periods than during the day (Nobriga et al. 2004).

Conclusions and Applications for Chinook Salmon Management and Conservation

Changes in sweeping velocity and water diversion rate can significantly affect the number of fish entrained into unscreened diversion pipes. Both of these variables can be managed, to a degree, to reduce the entrainment risk of out-migrating juvenile Chinook Salmon. Decreased water diversion rates through unscreened pipes can significantly decrease the entrainment risk of passing juvenile Chinook Salmon. During the day, in clear water, the percentage of fish that became entrained when passing the pipe was 89% higher at the 0.57 m³/s water diversion rate than at 0.42 m³/s. Using diversion pumps that extract smaller amounts of water over longer periods of time may decrease the total Chinook Salmon entrainment-related mortality in river systems. Although fish entrainment rates in our experiments were generally low at all tested flow conditions, out-migrating Chinook Salmon in the Sacramento River system may encounter hundreds of unscreened diversion pipes before reaching the ocean, multiplying their entrainment risk. Continually monitoring the number of juvenile Chinook Salmon entrained into a number of unscreened water diversions located in the Sacramento River throughout the migration season, or laboratory experiments monitoring individually identifiable fish swimming past an unscreened water diversion pipe in an annular flume, may allow further estimations of entrainment risk for out-migrating fish.

Water diversion velocities above 0.74 m/s may pose a serious entrainment risk to juvenile Chinook Salmon passing within 36 cm of a water diversion inlet. The percentage of Chinook Salmon lost to entrainment rapidly increases when fish repeatedly encounter unscreened diversion pipes during their out-migration. Our results suggest that after passing within 1.5 m

(the distance between the pipe inlet and flume wall) of 18 unscreened water diversion pipes (with a 0.46-m-diameter inlet and 0.57 m³/s water extraction rate) 25% of out-migrating Chinook Salmon would be entrained, and after passing 41 unscreened pipes 50% of the fish would be entrained. Fish-detering devices that decrease the number of fish that come within 36 cm of the pipe, or modifications that decrease the pipe's intake velocity below 0.74 m/s at its inlet, may allow these fish to pass by unscreened water diversion pipes with reduced entrainment risk. Fish guidance devices and pipe modifications designed to reduce fish entrainment should be tested under multiple environmental light levels because in clear water during the day more fish became entrained at the slower sweeping velocity (0.15 m/s), but the highest level of fish entrainment was found at the faster sweeping velocity (0.61 m/s) during turbid water and during night conditions.

Entrainment protection for juvenile Chinook Salmon is most critical during the night, particularly in higher (0.61 m/s) river currents. Water diversions situated in rivers with fast sweeping velocities (e.g., 0.61 m/s) might entrain fewer fish if the diversions were active only during the day. River turbidity levels and velocities commonly increase following storm events, resulting in river conditions with increased fish entrainment risk. More fish became entrained at the faster sweeping velocity (0.61 m/s compared with 0.15 m/s) in turbid water. Therefore decreasing water diversion rates after storm events when river velocities and turbidity levels are both high could offer fish protection from entrainment during a period of increased susceptibility.

The findings of these experiments provide a scientific basis for developing management strategies to help protect out-migrating juvenile Chinook Salmon exposed to unscreened water diversions and direct the development of potential future fish guidance devices at unscreened water diversions.

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