

Effects of Water Velocity and Trash Rack Architecture on Juvenile Fish Passage and Interactions: A Simulation

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Abstract.—Many resident and migratory fish species have experienced population declines due to modification of estuarine ecosystems. Fish screens (or louvers) have been designed to guide fish away from the diversion pumps, and trash racks have been placed upstream of the screens to intercept aquatic plants and debris. Although small fish may aggregate around these structures, potentially increasing their vulnerability to predators, we know little about the behavior, performance, and survival of fish near trash racks. To determine how trash rack flow regime and architecture influence fish behavior, we exposed juvenile threadfin shad *Dorosoma petenense* and winter-run Chinook salmon *Oncorhynchus tshawytscha* to three water velocities and two bar-spacing treatments in a circular tank bisected by a simulated trash rack. Our results suggest that relatively small increases in water velocity at diversion facilities will result in the aggregation of juvenile fish near trash racks. In contrast, bar spacing did not influence fish passage frequency or interaction in this study. We also found that threadfin shad selected higher velocities as water current increased, whereas Chinook salmon consistently showed a preference for moderate to low water velocities.

Human populations depend on diverted freshwater from rivers and lakes for many urban, agricultural, and industrial activities (FAO and DVWK 1996). Currently, the Sacramento–San Joaquin Delta in the central valley of California provides water for approximately 18 million people and 1 million ha of farmland (Danley et al. 2002). Nine diversions have been constructed to regulate these river systems, and louvers, screens, and accompanying facilities have been constructed to divert fish away from the pumps and to return the salvaged fish to the Delta. In addition, grate-like trash racks have been placed upstream of diversion facilities to intercept aquatic plants and debris.

Anadromous fishes such as Chinook salmon *Oncorhynchus tshawytscha* and white sturgeon *Acipenser transmontanus* migrate up the Sacramento and San Joaquin rivers to spawn, and juveniles of these species move down these rivers to the ocean, where they depend on high resource availability to grow and reach

maturity. When these migratory routes are blocked, the reproductive success of these species is compromised, and their populations decline below levels required to support fisheries and important ecological functions (FAO and DVWK 1996). Some fish make regular migrations between their feeding and resting habitats or inhabit different areas of a river during their life cycle, depending on which areas satisfy the requirements of their various developmental phases. As a result, these species also experience declines in reproductive success when dams and diversion facilities are constructed (FAO and DVWK 1996).

Because of water demands for irrigation and domestic uses, many diversion facilities in the Sacramento–San Joaquin Estuary currently perform year-round pumping at high rates (Tracy Fish Collection Facility 1995). Yet there is a limited understanding of important aspects of flow-related juvenile fish behavior near trash racks, including timing and frequency of passage (Bates and Powers 1998; Williams 1998). Consequently, studies evaluating the effects of water velocity on juvenile fish passage would provide information essential in determining appropriate pumping rates at diversion facilities. Studies examining how various trash rack configurations

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Received February 21, 2006; accepted March 17, 2007
Published online July 23, 2007

influence fish behavior also are needed for a better understanding of how to facilitate fish passage through these structures. Our objective was to examine how trash rack architecture and flow regime influence fish behavior. To achieve this objective, we addressed two specific research questions: What is the effect of water velocity and bar spacing on the behavior of juvenile fish in front of a simulated trash rack? Are there species-specific traits associated with the behavior of juvenile fish in front of a simulated trash rack? We hypothesized that fish passage would be more probable at moderate water velocities than at low and high velocities and with a wide bar spacing than a narrow bar spacing. We also expected that fish would aggregate near the trash rack at high water velocities and with a narrow bar spacing, a possible result of confusion under turbulent conditions.

Because species may differ with respect to their responses to trash rack architecture and flow regime, we focused on two species found in the Sacramento–San Joaquin Estuary that differ with respect to life history strategy: threadfin shad *Dorosoma petenense* and winter-run Chinook salmon. The threadfin shad is a nonmigratory, schooling species that provides forage for larger predatory fishes in this system (Moyle 2002), whereas winter-run Chinook salmon smolts are anadromous and school relatively loosely as they migrate through the estuary. The winter-run Chinook salmon was listed as endangered under the Endangered Species Act in 1995. Therefore, it is especially important to understand how trash racks influence the behavior and mortality of this species.

Methods

Fish transport.—Threadfin shad ($n = 120$; total length [TL] = 60 mm; mean mass = 2.28 g) were transported in a 1.6-kL, trailer-mounted tank from the U.S. Bureau of Reclamation's (USBR) Tracy Fish Collection Facility in Tracy, California, to the University of California–Davis (UC–Davis), where they were held in 3-m-diameter circular tanks at 3‰ salinity before experimentation. In addition to salt (NaCl) crystals, 25 mg of Novaqua (Kordon Co., Hayward, California)/L of water was added to the transport tanks to minimize stress. Holding tanks located at UC–Davis were cleaned (scrubbed and siphoned), and threadfin shad were fed (4% of body weight) once daily.

Downstream-migrant winter-run Chinook salmon ($n = 110$; TL = 52 mm; mean mass = 1.51 g) were transported from UC–Davis' Bodega Marine Laboratory in oxygenated, 20-L plastic bags of water at 3‰ salinity. These bags were then placed in large coolers and transported to the Center for Aquatic Biology and

Aquaculture at UC–Davis. The fish were held in 3-m-diameter circular tanks and fed (4% body weight) each day with an automatic feeder. Holding tanks for Chinook salmon were scrubbed and siphoned daily.

Experimental setup.—A simulated trash rack was constructed with an aluminum frame and removable, round, 1.25-cm-diameter bars. Although rectangular bars are more commonly used in operational trash racks, we used round bars because they standardize the flow field regardless of possible rotation of the trash rack bars. It is not uncommon for trash rack bars to be bent and rotated to a new orientation by debris moving through trash racks, resulting in hydraulic-field distortion problems when rectangular bars are used. The trash rack bisected a 3-m-diameter, fiberglass circular tank in the J. Amorocho Hydraulics Laboratory (JAHL) at UC–Davis. The bars were 5 cm apart (narrow bar spacing) along the length of the trash rack so that fish could approach the trash rack from the upstream or downstream direction. Every other bar was removed to create the wide-bar-spacing treatment (12-cm space between bars). These bar spacings were chosen because they are within the range of those shown to be effective for vegetative interception (M. L. Kavvas, UC–Davis, Department of Civil and Environmental Engineering, personal communication). The tank was equipped with a screened, electric trolling motor (Model 3HD, Minn Kota) on the edge to generate a circular current, an overhead video camera (Model WAT-902B, Watec), a 10-cm grid on the bottom to facilitate quantification of fish behaviors, and a surrounding opaque plastic curtain to minimize disturbance of fish (Figure 1).

Experimental procedures.—Experimental procedures were the same for threadfin shad and Chinook salmon to allow between-species comparisons of fish behavior near the simulated trash rack. For each experiment, 10 fish were transported quickly (5 min) from holding tanks at the Center for Aquatic Biology and Aquaculture to the tank at JAHL (distance, 1 km) in a small cooler. Water used for transport was aerated and treated with salt crystals (3‰ salinity) and Novaqua (25 mg/L) to minimize stress. At JAHL, we carefully poured the fish out of the cooler into the experimental tank and allowed them a 1-hour acclimation period before beginning experiments. We cross-factored the two bar-spacing treatments with three water velocity treatments (control = 0 cm/s; low = 12 cm/s; high = 24 cm/s) for a total of six 15-min treatments, and each group of 10 fish was exposed to these treatments in random order (total experiment time: 90 min). Our test velocities were between and toward the low end of the minimum (10–20 cm/s) and the maximum (100 cm/s) velocities measured in front

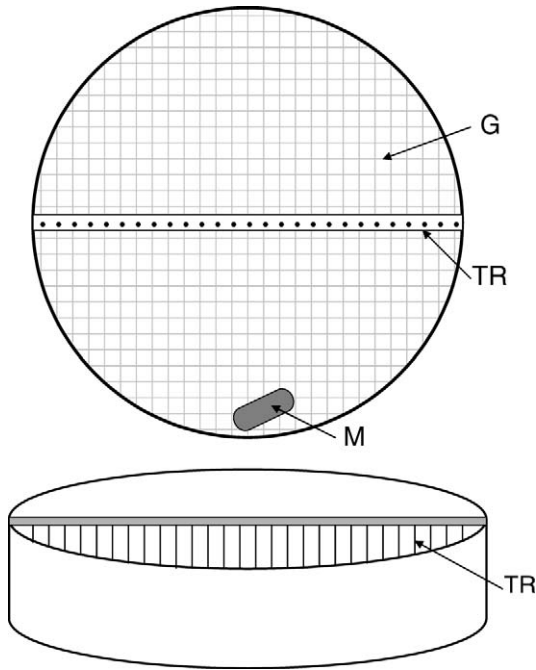


FIGURE 1.—Top and three-quarter views of an experimental tank containing a simulated trash rack (TR), shown with all bars in place (narrow bar spacing [5 cm between bars]). Removal of every other bar created the wide-bar-spacing treatment (12 cm between bars). A screened, electric trolling motor (M) generated a circular current, while an overhead video camera (not shown), a 10-cm grid (G) on the bottom, and a surrounding opaque plastic curtain (not shown) facilitated quantification of fish behaviors.

of the trash racks at the Tracy Fish Collection Facility with all five diversion pumps in operation. The 0-cm/s treatment was chosen as the control because it represents a nonflowing condition that can be observed at parts of trash racks when the diverter is pumping at less than full capacity (K. W. Frizell, USBR, personal communication).

For the low- and high-velocity treatments, flow was increased gradually from zero after the 1-h acclimation period. Because we did not vary the rate at which we increased water velocity from zero at the beginning of the experiments, any implications of this increase in flow for behavior should be consistent between and among the low- and high-velocity treatments. Threadfin shad were often observed schooling downstream of the trolling motor, possibly owing to turbulence, noise, or flow created by the motor, while Chinook salmon occasionally hid underneath the motor. Although the motor may have had some effects on the behavior of these two species, the fact that the fish were attracted to it suggests that our data provide a conservative measure

of their interactions with trash racks. The experiments conducted on threadfin shad were performed at 19°C in December 2002, and those conducted on Chinook salmon were performed at 12°C in January 2003. These temperatures reflected Delta water conditions when juvenile threadfin shad are present (early autumn) and when Chinook salmon migrate (early spring) and are most vulnerable to trash-rack exposure in the Delta region. Replication was 12- and 11-fold for the threadfin shad and Chinook salmon experiments, respectively.

Water velocity calibration.—Current directions and water velocities were measured throughout the experimental tank for each of the six velocity and bar-width treatments to quantify each species' velocity preferences. These measurements were made with a flowmeter (Model 201D, Marsh-McBirney, Frederick, Maryland) every 20 cm along the bottom and at mid-depth (45 cm deep). Current direction at each point was determined by rotating the flowmeter probe to the angle of maximum velocity and measuring its angle (protractor on video display screen from overhead video camera image). Maximum and minimum velocities measured at the angle of maximum velocity over a 1-min period were averaged. After water velocity and current direction were quantified at all points for each treatment, flow maps were drawn to determine preferred and avoided water velocities during each experiment. These maps consisted of an image of the circular tank with vectors drawn at each point where velocity was measured showing current direction; colors of the vectors corresponded to the water velocity measured at each point.

Video and statistical analyses.—Video footage was analyzed to determine fish passage frequency (total passage frequency, upstream passage frequency, and downstream passage frequency), and two interaction behaviors: total interaction time and mean interaction distance. Because individual fish were not marked and often moved in groups, we recorded data every time a single fish or group of fish performed the behaviors described above (i.e., passage and interaction) during the 15-min treatment period. These behaviors were quantified for groups when multiple fish were clustered together and were not moving independently. Passage frequency was calculated as the number of times a single fish or group of fish crossed the trash rack during each 15-min treatment period; this variable was selected because this would provide an indication of how readily the fish would pass through the bars of the trash rack. We calculated the total passage frequency for each 15-min period and compared this variable between treatments. We also created an index that indicated the tendency of fish to swim either upstream

TABLE 1.—Number of trials and fish per trial for experiments involving the behavior of threadfin shad and Chinook salmon near a simulated trash rack.

Treatment	Velocity (cm/s)	Bar width	Trials		Fish/trial
			Chinook salmon	Threadfin shad	
1	0	Narrow	11	12	10
2	0	Wide	11	12	10
3	12	Narrow	11	12	10
4	12	Wide	11	12	10
5	24	Narrow	11	12	10
6	24	Wide	11	12	10

or downstream and used these indices to compare upstream versus downstream passage for each treatment. Because we calculated one passage frequency or passage index for each treatment period within each experiment, sample sizes were 12 and 11 for threadfin shad and salmon, respectively (Table 1).

Interaction behaviors were quantified every time a single fish or group of fish lingered in one location for more than 15 s. We defined interaction in this manner because a 15-s delay at a trash rack appeared likely to provide sufficient time for predators to aggregate and attack fish hesitating to pass through the trash rack. Moreover, defining interaction in this way allowed us to quantify interaction behaviors for subsequent statistical analyses. For these analyses, we calculated the total interaction time and mean weighted interaction distance over each 15-min treatment period and compared these variables between treatments. Because fish spent varying amounts of time at different distances from the trash rack, a mean interaction distance was calculated from the weighted average of the amount of time fish spent at each distance. Interaction distance was calculated because it would provide an indication of whether or not fish would aggregate close to the trash rack during periods of hesitation near the structure. Sample sizes for interaction time were 12 and 11 for threadfin shad and salmon, respectively, because we calculated the total interaction time for each treatment in each experiment (Table 1). However, sample sizes for mean interaction distance were variable because no interaction distance could be calculated if the interaction time was zero for any given experiment.

Because a single group of 10 fish was used in all six treatments for each replicate, and there were correlations between the behavior of a group of fish in one treatment and that of the groups in the other treatments, repeated-measures analysis of variance (ANOVA) was performed to evaluate the effects of water velocity and bar-spacing width on fish passage frequency, total interaction time, and mean interaction distance. One major advantage of using repeated-measures ANOVA

under these circumstances is that it increases the power to detect treatment effects when there are consistent differences between groups. For these analyses, fish passage frequency was $\log_e(x + 1)$ transformed to correct for right skewness in these data. Fisher's least-significant-difference (LSD) tests were used to make multiple comparisons if there were significant differences between velocity treatments. We used a sign test to compare the likelihood of upstream versus downstream passage between treatments (Zar 1984).

Water velocity calibration maps were used to evaluate water velocity. We created seven water velocity classes (1 = 0.00–8.84 cm/s; 2 = 9.14–17.98 cm/s; 3 = 18.29–30.18 cm/s; 4 = 30.48–39.32 cm/s; 5 = 39.62–48.46 cm/s; 6 = 48.77–60.66 cm/s; and 7 = 60.96+ cm/s), based on the range of water velocities available to the fish over all treatments. The location of single fish or groups of fish during interaction was recorded, and the calibration maps were used to determine the water velocities encountered at each interaction location. Goodness-of-fit tests were performed to identify significant preferences for, or avoidance of, particular velocity classes based on the availability of each class (i.e., the percentage of time fish spent at each velocity class was compared with the percent availability of each velocity class for each treatment). The χ^2 tests were then subdivided, and a Z-score analysis was conducted to identify which preferences or avoidances were responsible for the significance of goodness-of-fit tests.

Results

Fish Passage Frequency

There was a significant difference between species regarding their passage frequencies ($F = 30.02$, $P < 0.001$). Chinook salmon crossed the trash rack an average of 40 times per 15-min treatment, whereas threadfin shad crossed the trash rack an average of only 12 times per treatment (Figure 2). Conversely, bar spacing ($F = 1.78$, $P = 0.196$) and water velocity ($F = 1.08$, $P = 0.349$) had no effect on passage frequency for Chinook salmon or threadfin shad (Figure 2). The sign

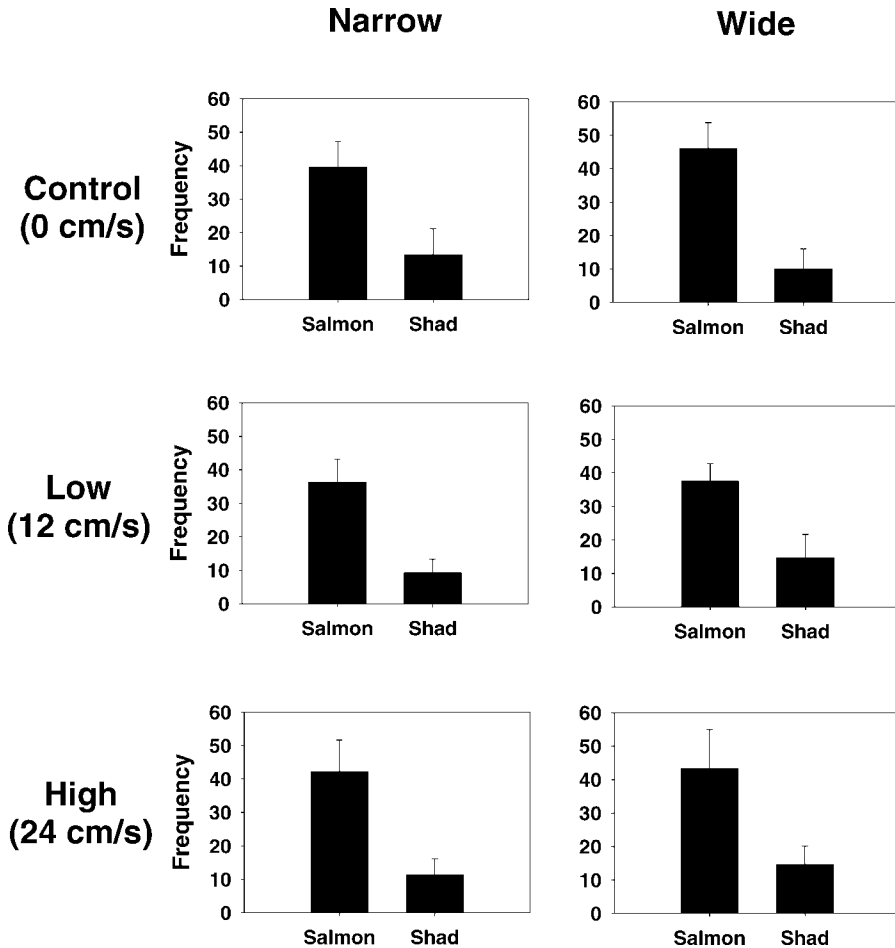


FIGURE 2.—Mean + SE passage frequencies (number per 15-min treatment) for Chinook salmon and threadfin shad exposed to three water velocity treatments (0, 12, and 24 cm/s) and two bar-spacing treatments (narrow and wide).

test evaluating the tendency for upstream versus downstream fish passage indicated that Chinook salmon were significantly more likely to pass through the trash rack moving downstream than upstream at the low and high velocities ($P = 0.007$); they were equally likely to move upstream and downstream during passage under control conditions (Figure 3). At the low-velocity treatment, the salmon initially seemed hesitant to pass downstream. After this initial resistance, they would cease fighting the current and swim headfirst through the trash rack. When a small number (e.g., two) of the salmon in a group swam downstream through the trash rack, the others in the group typically would follow the first two, headfirst, more decisively. At the high-velocity treatment, they seemed even more hesitant to move downstream through the rack and would often go through the rack somewhat broadside, ceasing their station holding in front of the trash rack

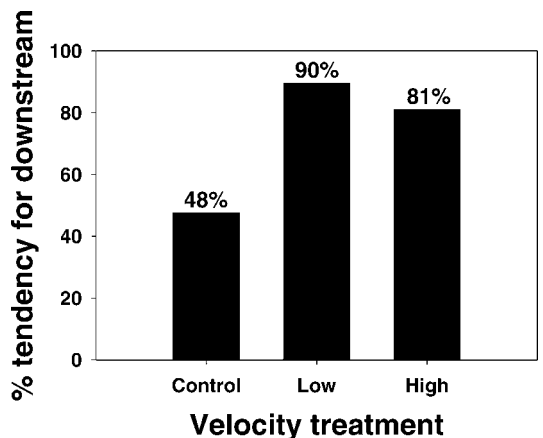


FIGURE 3.—Percentage of trials in which Chinook salmon demonstrated a tendency to swim downstream through the trash rack for three water velocity treatments (0, 12, and 24 cm/s).

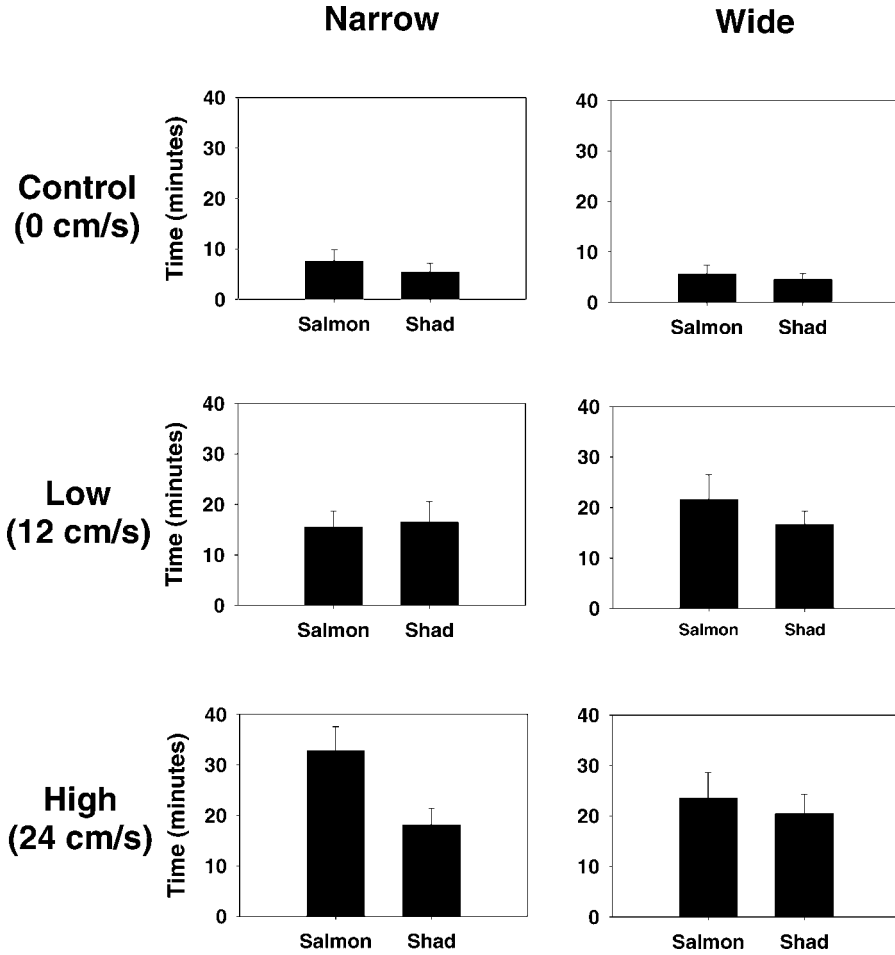


FIGURE 4.—Mean + SE interaction time for Chinook salmon and threadfin shad exposed to three water velocity treatments (0, 12, and 24 cm/s) and two bar-spacing treatments.

and attempting to turn downstream in the last seconds before passing. Occasionally, the salmon would swim downstream, headfirst, without hesitation. We were unable to test the likelihood of upstream versus downstream passage for shad because we had insufficient data once trash rack crossing data were split into upstream and downstream categories.

Interaction Time

Bar spacing had no effect on interaction time ($F = 1.02, P = 0.325$), and there was no difference in interaction time between species ($F = 1.89, P = 0.185$). Water velocity, however, had a significant effect on total interaction time ($F = 43.54, P < 0.001$). There was also a marginally significant interaction between water velocity and species because Chinook salmon demonstrated a more significant increase in interaction

time with velocity relative to threadfin shad, yet this interaction explained only 6% of the variation in interaction time. Because water velocity explained 64% of the variation in total interaction time, we performed multiple comparisons of the velocity treatments only (treating bar spacing and species as replicates). These analyses showed that both species interacted with the trash rack for significantly longer times at low (grand mean: 17.5 min) and high (23.5 min) water velocities than controls (5.8 min; Figure 4). There was also a significant difference in interaction time between low- and high-velocity treatments ($P < 0.05$; Figure 4).

Interaction Distance

Similarly, bar spacing had no effect on mean interaction distance ($F = 0.52, P = 0.489$), and there was no difference in interaction distance between

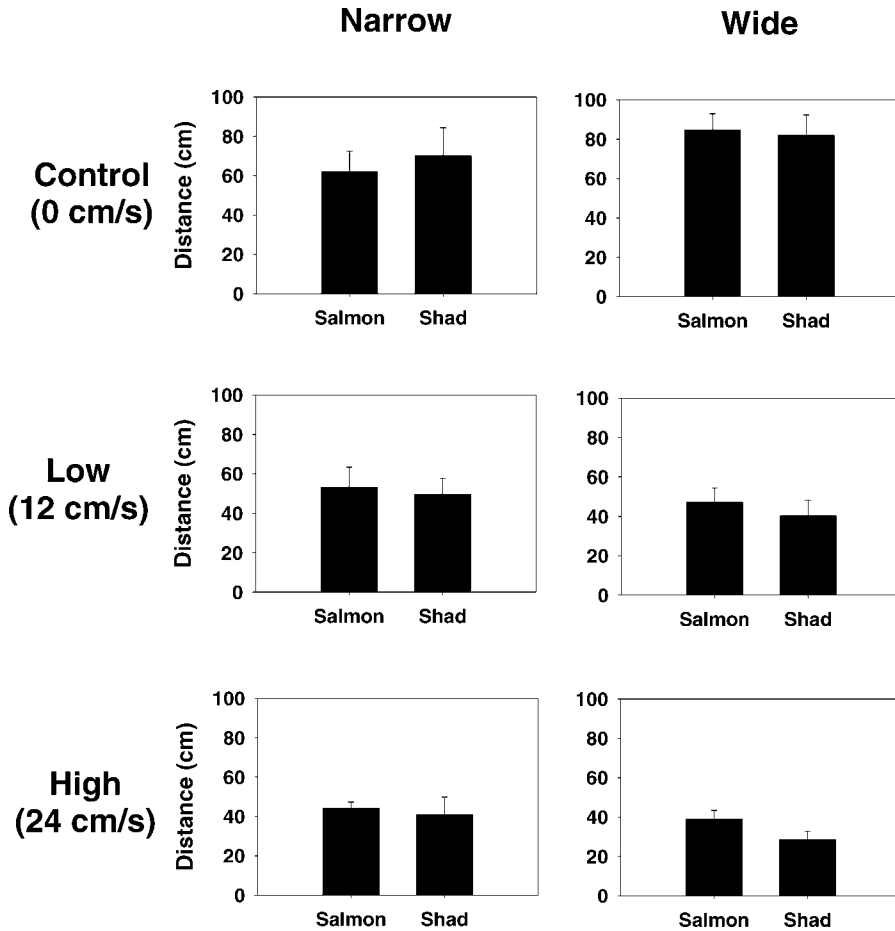


FIGURE 5.—Mean + SE interaction distance for Chinook salmon and threadfin shad exposed to three water velocity treatments (0, 12, and 24 cm/s) and two bar-spacing treatments.

species ($F = 2.52$, $P = 0.143$). Again, water velocity had a significant effect on interaction distance ($F = 9.70$, $P = 0.001$); both species aggregated closer to the trash rack during low- and high-velocity treatments than did the controls (Figure 5). There was also a significant difference in interaction time between low- and high-velocity treatments ($P < 0.05$; Figure 5). Fish interacted approximately 75 cm, 49 cm, and 39 cm from the trash rack in the control, low-velocity, and high-velocity treatments, respectively.

Water Velocity Preference

Both species exhibited significant preferences for, or avoidance of, particular water velocity classes in all treatments (treatments 3–6 in Table 1; $P < 0.001$ for each treatment). Overall, threadfin shad preferred a moderate to low velocity (class 2) in low-velocity treatments, whereas they selected moderate water velocities (class 4) when exposed to high-velocity treatments (Figure 6).

Threadfin shad were typically observed cruising around the tank in tight schools of 3 to 10 fish and often held station directly in front of the trolling motor or trash rack. While holding station, shad would perform some burst swimming movements to maintain their position. Chinook salmon preferred moderate to low water velocities (class 2) in all treatments except for the low-velocity, wide-bar-spacing treatment (Figure 7). Generally, the Chinook salmon schooled more loosely than the shad and would occasionally take shelter underneath the trolling motor and next to the edge of the trash rack by the tank wall. While swimming upstream, they performed some burst and glide movements and often allowed themselves to be swept downstream.

Discussion

Our results suggest that relatively small increases in water velocities at diversion facilities would result in the aggregation of juvenile fish near trash racks (there

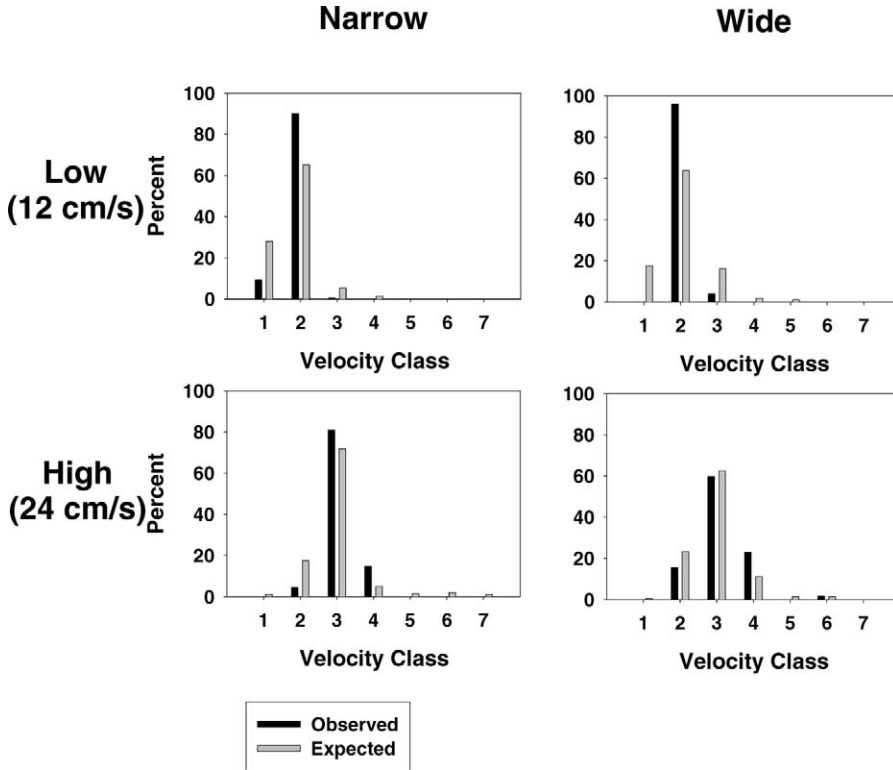


FIGURE 6.—Expected and observed percentages of time that threadfin shad spent interacting with the trash rack by bar spacing and water velocity class (1 = 0.00–8.84 cm/s; 2 = 9.14–17.98 cm/s; 3 = 18.29–30.18 cm/s; 4 = 30.48–39.32 cm/s; 5 = 39.62–48.46 cm/s; 6 = 48.77–60.66 cm/s; and 7 = 60.96 cm/s or more).

were significant increases in interaction time and decreases in mean interaction distance from trash racks as water velocity increased for both species). However, water velocity had no effect on fish passage frequency, and bar spacing did not influence fish passage frequency or interactions in this study. Water velocities through trash racks vary with rates of runoff (outflow) and water diversion, and with tidal stage, and these data can facilitate predictions of how juvenile fish will respond to these fluctuations. Unlike Reading (1982), who observed increased passage of juvenile Chinook salmon and American shad *Alosa sapidissima* through a trash rack as channel velocity increased, we did not observe any effect of water velocity on passage frequency; however, the water velocities used in Reading’s study (range: 30.5–91.4 cm/s) were greater than those used in our study. Because the water velocities we used appear to be similar to the minimum velocities measured in front of operational trash racks (K. W. Frizell, USBR, personal communication), we may have underestimated the effects of water velocity on fish passage.

Previous studies have produced conflicting results

regarding the effects of bar spacing on fish passage, making it difficult to determine how trash racks should be constructed for maximum passage efficiency. Hanson and Li (1983) found that juvenile Chinook salmon were hesitant to pass through a trash rack with bar spacing less than 15 cm, decreasing transit times for trash racks with bar spacing greater than 15 cm. Conversely, Reading (1982) found that juvenile Chinook salmon passage was independent of trash rack bar spacing, where the bar spacings used ranged from 7.6 to 30.5 cm. It is possible that the lack of bar-spacing effects in our study was due to the relatively narrow spacings (5 cm and 11 cm) that were used. Additional studies using a wider range of bar spacings (corresponding to the widest bar-spacing treatments used for operational trash racks) may be necessary to further clarify how trash rack architecture affects fish passage and interaction.

Several species-specific behaviors were observed in this study. Chinook salmon crossed the trash rack significantly more frequently than threadfin shad because of increased mobility in the experimental tank during control treatments and the fact that they moved

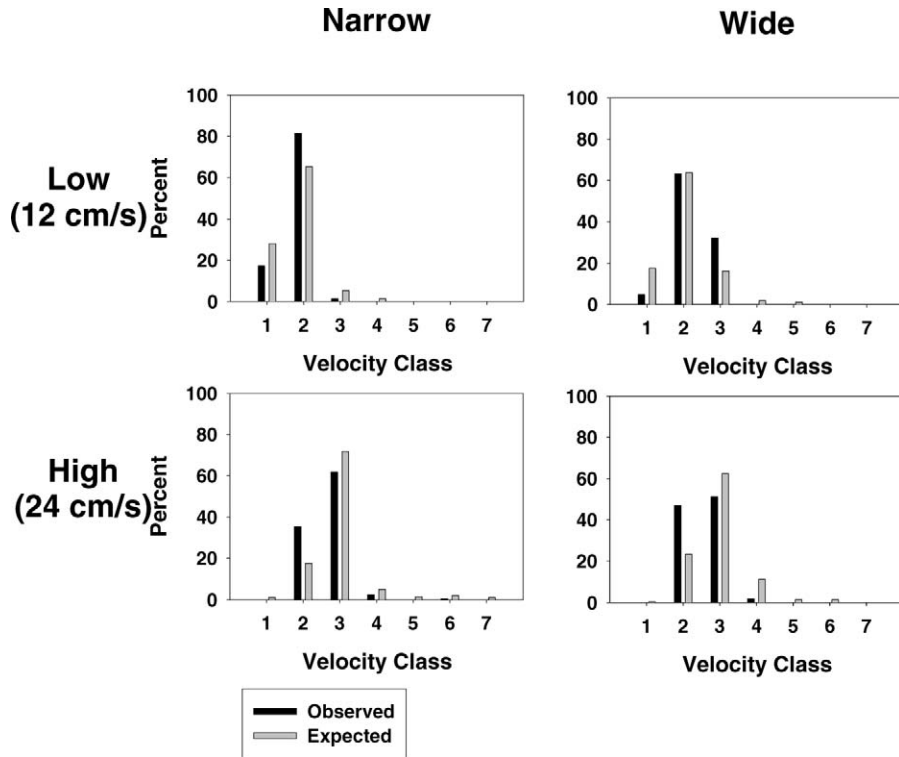


FIGURE 7.—Expected and observed percentages of time that Chinook salmon spent interacting with the trash rack by bar spacing and water velocity class. See Figure 6 for additional details.

downstream repeatedly during low- and high-velocity treatments. Species-specific or life stage-specific differences in swimming performance may explain the relative inability, or decreased desire, of the Chinook salmon to hold station. Chinook salmon of the body length used formed the largest size-group of those emigrating downstream as smolts in the South Umpqua River (Oregon) basin (Roper and Scarnecchia 1999), indicating that salmon from this size-class may allow themselves to be carried downstream.

We also observed species-specific patterns when evaluating water velocity preferences surrounding the trash rack. Chinook salmon selected moderate to low water velocities in all cases except for the low-velocity, wide-bar-spacing treatment, suggesting that they have more difficulty adapting to increasing water velocities or that they prefer relatively low water velocities. The selection of somewhat higher water velocities in the low-velocity, wide-bar-spacing treatment could be explained by the greater representation of slightly higher velocities downstream of the presumed lower-resistance trash rack with wide spacing. These results agree with other studies, which have shown that when salmon fry are exposed to approach velocities greater

than 12 cm/s, they rapidly become exhausted and are swept against fish screens and killed (Clay and Eng 1995). Fish often select areas with low current speeds because they are associated with lower turbulence intensities, where maintaining position is less energetically costly (Fausch 1984; Webb 2004). It is also possible that the salmon selected velocities that would reflect what they typically encounter or select in their natural habitat during different life history stages. Swanson et al. (2004) found that smolt-size Chinook salmon showed negative rheotaxis (swam downstream, actively) at “moderate” velocities (31 cm/s) compared with those exposed to “high” velocities (62 cm/s) in a large (3-m diameter), laboratory-based annular swimming path. Conversely, their parr-size juveniles showed positive rheotaxis at both test velocities (Swanson et al. 2004). In contrast, our threadfin shad were more flexible, selecting higher water velocities when the high-velocity treatment was used. Because of their preference for lower water velocities, juvenile Chinook salmon of the size-class used in this study may be restricted to a small area when aggregating near trash racks, potentially becoming more vulnerable to predation than are other species (Hanson and Li 1983).

These species-specific results suggest that studies evaluating multiple species are necessary for adequate protection of all species and that management strategies may require alteration, depending on which species are migrating at any particular time (Kynard and O'Leary 1993; FAO and DVWK 1996).

Delays in passage through trash racks and diversion facilities can cause dramatic reductions in adult recruitment and spawning success. Delayed juvenile fish may experience increased mortality because they do not reach the marine environment within the "smolt window," during which they are able to osmoregulate in both salt- and freshwater. Fish that are delayed for long periods while migrating downstream may drift against fish screens owing to exhaustion and remain there until they die if velocities through the screens are too high (Clay and Eng 1995).

Laboratory studies such as these provide a mechanistic understanding of anthropogenic effects on fish behavior, suggesting appropriate water velocities and bar-spacing architectures to facilitate fish protection. For example, the behavior and swimming performance of migrating life stages of diadromous species and vulnerable life stages of resident species can be balanced with diverted water demands and effective debris interception of optimal trash rack operation. However, further studies are necessary for a complete understanding of how trash racks influence fish behavior and mortality. These studies should incorporate factors such as the influence of predators, the presence of natural debris, and the presence of multiple species on fish passage, interaction, and survival.

Acknowledgments

We thank B. Bridges (USBR) and K. Arkush (Bodega Marine Laboratory), in cooperation with the U.S. Fish and Wildlife Service, for providing fish; L. Kavvas for space at the JAHL; D. Portz for useful discussion; D. Cocherell for drawing Figure 1; K. Bork, R. Henery, B. Kammerer, and T. McGowan for manuscript review; M. Karagosian for ideas and advice during the development of the project; and the California Department of Water Resources for funding.

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