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MANAGEMENT BRIEF

Effectiveness of Common Fish Screen Materials to Protect Lamprey Ammocoetes

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Abstract
Understanding the effects of irrigation diversions on populations of Pacific lamprey *Lampetra tridentata* in the Columbia River basin is needed for their recovery. We tested the effectiveness of five common fish screen materials for excluding lamprey ammocoetes: interlock (IL), vertical bar (VB), perforated plate (PP), and 12-gauge and 14-gauge wire cloth (WC12) and (WC14). When fish (28–153 mm) were exposed for 60 min to screen panels perpendicular to an approach velocity of 12 cm/s in a recirculating flume, the percentage of ammocoetes entrained (i.e., passed through the screen) was 26% for the IL, 18% for the PP, 33% for the VB, 62% for the WC14, and 65% for the WC12 screens. For all screens, most fish were entrained within the first 15–20 min. Fish length significantly influenced entrainment, with the PP, VB, and IL screens preventing fish greater than 50–65 mm from entrainment and the WC14 and WC12 screens preventing entrainment of fish greater than 90–110 mm. Fish of all sizes repeatedly became impinged (i.e., contacting the screen for more than 1 s) on the screens, with the frequency of impingement events increasing during the first 5 min and becoming relatively stable thereafter. Impingement ranges were highest on the IL screen (36–62%), lowest on the WC14 and WC12 screens (13–31%), and intermediate on the PP and VB screens (23–54%). However, the WC14 and WC12 screens had fewer and larger fish remaining as time elapsed because so many were entrained. For all screen types, injuries were rare and minor, and no fish died after overnight posttest holding. Our results indicate that wire cloth screens should be replaced, where practical, with perforated plate, vertical bar, or interlocking bar screens to reduce lamprey entrainment at water diversions.

Entrainment of fish at unscreened water diversion sites is a direct source of fish mortality, and screens are often installed to protect fish. In the Pacific Northwest, most screen installations at pumping facilities and other diversion sites are designed to protect juvenile anadromous salmon and steelhead *Oncorhynchus mykiss* (anadromous rainbow trout). Design and operational criteria include screen type, approach velocity (the velocity of water passing through the screen surface), screen angle, and screen panel pore size requirements (WDFW 2000; NMFS 2008). Some species of fish are considered to be at high risk at diversion sites and specific changes have been made to salmonid-based screen operation and design criteria to protect them. For example, delta smelt *Hypomesus transpacificus* at water diversions throughout the Sacramento-San Joaquin delta system are protected by ensuring that approach velocities do not exceed 6 cm/s (USFWS 1995). In Canada, approach velocity is limited to 3.8 cm/s at end of pipe screens for the protection of all fish with an anguilliform swim mode, including American eel *Anguilla rostrata*, burbot *Lota lota*, and sea lamprey *Petromyzon marinus*.

Pacific lamprey *Lampetra tridentata*, an important cultural and ecological resource in the Pacific Northwest with declining populations, could also benefit from revised screening criteria. These fish have a complex life history (Beamish and Levings 1991), are poor swimmers compared with salmonids (Mesa et al. 2003; Dauble et al. 2006), and have an elongated body shape that may make them very susceptible to entrainment, injury, and mortality at irrigation diversion sites, especially larval forms. Indeed, biologists have identified the need to study and improve lamprey passage and survival at obstacles such as dams, culverts, and irrigation screens as one of the highest priorities for lamprey recovery.

Currently, the operational criteria for irrigation diversion screens in the Pacific Northwest to protect juvenile salmonids include (1) an approach velocity that does not exceed 12 cm/s for active screens with an automated cleaning device and 6 cm/s for passive screens, (2) a sweeping velocity (the velocity of water flowing parallel to the screen surface) that at least exceeds the approach velocity, (3) screen openings not exceeding 2.38 mm for round (measured as the diameter) and square holes (measured as the diagonal) and 1.75 mm for rectangular slots (in the narrow direction), and (4) an open area for any screen

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material of at least 27%. It is not known whether these criteria also protect juvenile lamprey. Therefore, we evaluated whether common fish screen materials used at diversion sites would prevent lamprey ammocoetes from becoming entrained, impinged, injured, or killed at a simulated screened water intake. This life stage may be particularly vulnerable to screen impacts because of their small size, lack of eyesight, limited swimming capability, and high likelihood of being involuntarily flushed from their burrows during high-flow events.

METHODS

Pacific lamprey ammocoetes were collected from Gibbons Creek, Washington, and from Herman Creek and Fifteenmile Creek, Oregon, using a backpack electrofisher, screw traps, and sediment grab samples. Fish were transported to our laboratory and segregated into five size-groups: group 1 = 28–58 mm, group 2 = 42–62 mm, group 3 = 50–84 mm, group 4 = 74–136 mm, and group 5 = 113–153 mm. They were held in either 19-L or 32-L aquaria, depending on size (N = 15–45 fish/aquarium). Each aquarium contained 5–7 cm of sand with a maximum grain size of 0.5 mm, was provided a constant inflow of sand-filtered water (0.5 L/min) and a simulated natural photoperiod with incandescent lights. Water was from the Little White Salmon River, Washington, and ranged from 8–10°C. During holding, fish were fed twice each week with a suspension of commercial fry food (Gemma Wean 0.1; Skretting, Vancouver, British Columbia) at 0.6 g/small tank and 1.5 g/large tank and active yeast at 5.3 g/small tank and 13.3 g/large tank. The suspension was introduced to the aquaria and water flow was shut off for 6–7 h during feeding.

Ammocoetes were exposed to screen panels in an oval-shaped tank equipped with an adjustable flow-inducing propeller, similar to that used by Zydlewski and Johnson (2002; Figure 1). The test section was one of the straight arms of the tank (102 × 32-cm) and had a water depth of 35 cm. Wire window screens, located 36 cm downstream and 66 cm upstream of the test screen panel, were used to retain fish. Custom-sized pieces of fish screening material were placed perpendicular to the flow 66 cm downstream from the upper barrier screen (Figure 1). Five screen materials were tested: (1) interlock bar screen (IL; Hydrolox at www.hydrolox.com) with a maximum slot width of 1.75 mm in its narrowest direction, (2) vertical bar screen (VB) with a slot width of 1.75 mm, (3) perforated plate (PP) with 2.4-mm round openings, (4) 12-gauge wire cloth (12WC) with square openings of about 4 mm, and (5) 14-gauge wire cloth (14WC) with square openings of about 5 mm (Figure 1). Each section of screen contained a minimum of 27% open area. The entire test section was gray to allow for easy visibility of fish. Prior to each test, water velocities were measured with a Marsh–McBirney electronic meter (Flo-Mate model 2000) at four areas of the test section (10, 33, 58, and 94 cm downstream of the upstream barrier screen). For each area, velocity measurements were taken at three evenly spaced horizontal positions at each of three water depths: 9, 18, and 27 cm from the bottom. Water velocities were adjusted prior to each test to achieve a mean approach velocity of 12 cm/s within the test section. Water in the tank was replaced daily and the tests were done during daylight hours.

Each screen type was tested in random order and consisted of two releases of 7–13 fish from each of the five size groups, for a total of 10 separate releases per experiment. For a test, fish were removed from an aquarium, placed in a small bucket with water, and gently released into the upstream end of the test section, where they were allowed 60 min to explore the chamber and be exposed to the fish screen. After 60 min, the fish were removed, processed (described below), and a new group of fish was added. As a control, we released fish into the test section without a screen panel, which provided general information on the behavior of fish and helped assess any handling effects.

During each 60-min test we observed fish over 16 contiguous intervals of 1 min each for the first 5 min (5 intervals) and 5 min thereafter (11 intervals). During each interval we enumerated fish that were partially entrained through the screen (a fish with at least half its body on the downstream side of the screen), completely entrained (passed through the screen), or impinged (a fish contacting the screen for more than 1 s). Because so few fish were partially entrained, we pooled them with fish that were completely entrained for analysis. Data on entrainment and impingement for each interval were tallied, converted to percentages, and plotted over time for each screen panel test. We used logistic regression to estimate the probability of a fish becoming entrained relative to its length and tested the fit of the logistic regression equation to our data using the likelihood ratio test (LRT; SigmaPlot Software, Version 12.0, San Jose, California). At the end of each release, fish that were entrained or located upstream of the screen were transferred to separate aquaria and held overnight to assess mortality. After this, we recorded the number of fish from each group that survived, then anesthetized them in buffered MS-222 at 250 mg/L of water, measured total length (mm) under a magnifying lens, weighed them (0.01 g), and examined them for injuries to the skin and body, noting any abrasions, cuts, or deformities. We used a Fisher's exact test to compare the proportion of fish that died or were injured during each experiment with values from control fish. We applied a one-way analysis of variance (ANOVA) to compare the mean lengths of fish used in the tests; for all comparisons $\alpha = 0.05$.

RESULTS

Overall, we tested similar numbers of fish in the experiments, their mean (±SD) lengths ranged from 71 mm (±32) to 78 mm (±35), and their lengths did not differ significantly ($F = 2.23$, df = 5, $P = 0.76$; Figure 2). For all experiments, the ammocoetes were competent swimmers, and fish of all sizes were observed moving upstream against the 12 cm/s water velocity. As we discuss below, the level of protection offered by the screen

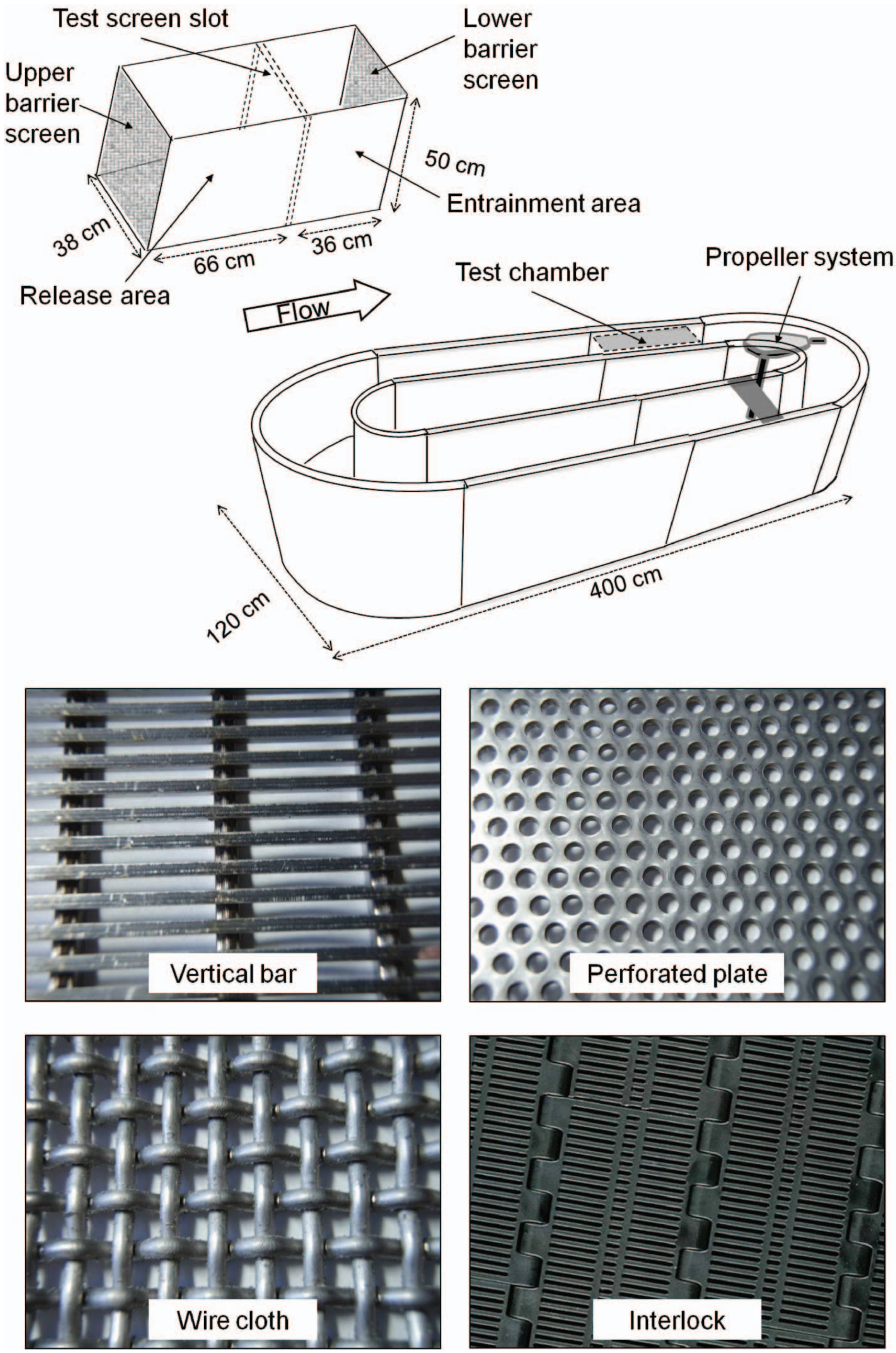

FIGURE 1. Schematic of apparatus used to test the effectiveness of common screen materials for protecting Pacific lamprey ammocoetes and photographs of the screens used. Only one wire cloth screen is shown because pore size differences between 12-gauge and 14-gauge screens are not readily discernible.

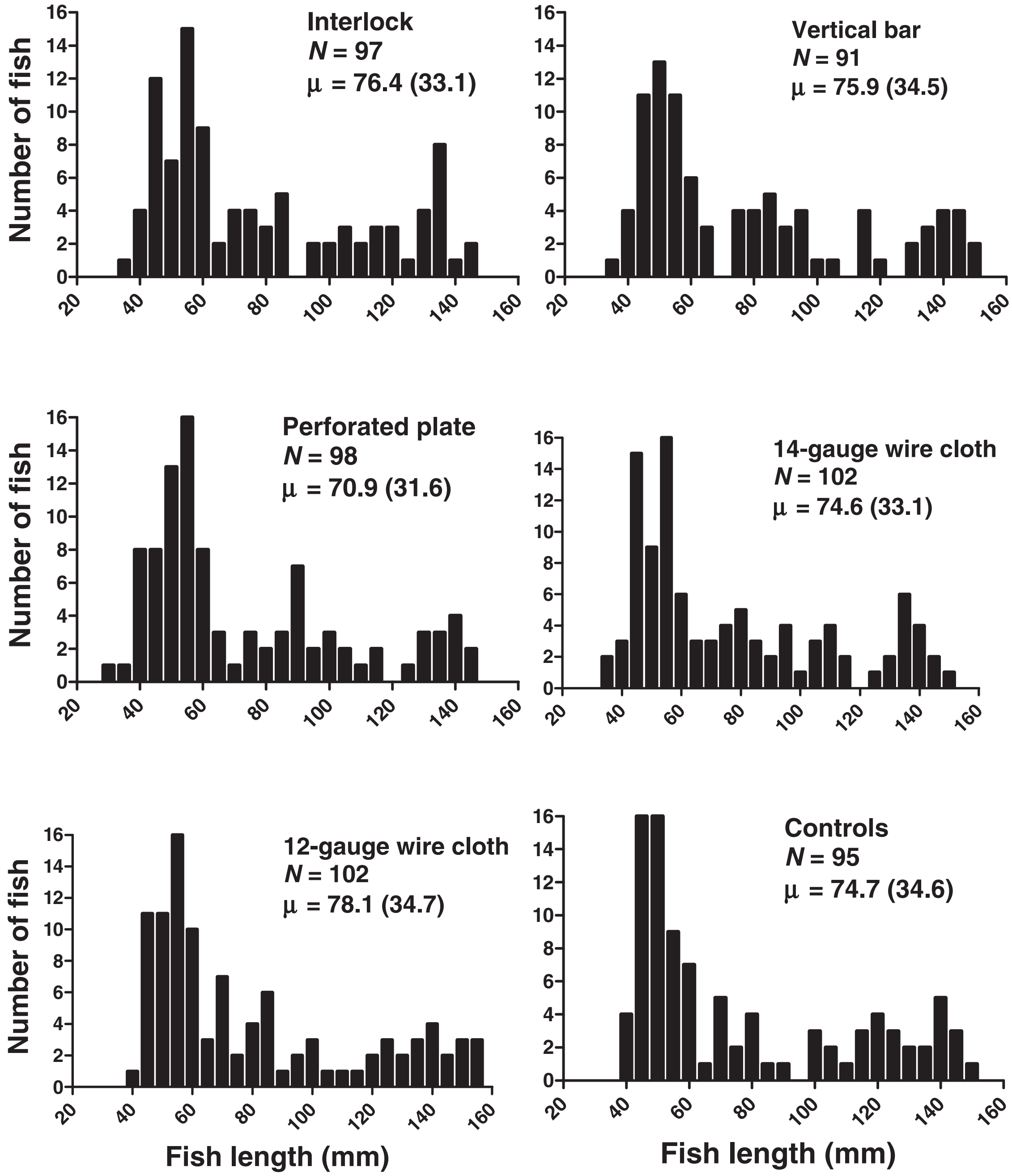

FIGURE 2. Frequency distributions of the lengths of Pacific lamprey ammocoetes exposed to five types of screen panels and controls. *N* is the total number of fish tested for each screen panel and mean (SD) lengths for each group are shown.

panels varied considerably and was dependent on fish size. Most fish were entrained within the first 15–20 min. Once entrained, fish generally became impinged on the wire window screen and none swam upstream through the screen panels.

After 60 min, the percentage of ammocoetes entrained ranged from 18% to 65%, depending on screen type (Figure 3). The two wire cloth screens entrained the most fish and the PP screen entrained the fewest. In general, the mean length and range of lengths of entrained fish increased progressively with entrainment percentage (Table 1). Fish length significantly influenced the odds of entrainment for all screen types (LRT: 65.8–117.3, $P < 0.001$; Figure 4), with PP, VB, and IL screens preventing fish greater than 50–65 mm from entrainment and WC14 and WC12 preventing fish greater than 90–110 mm from entrainment. Entrained fish did not simply pass through the screen pores unhindered, but instead became briefly stuck before weaving

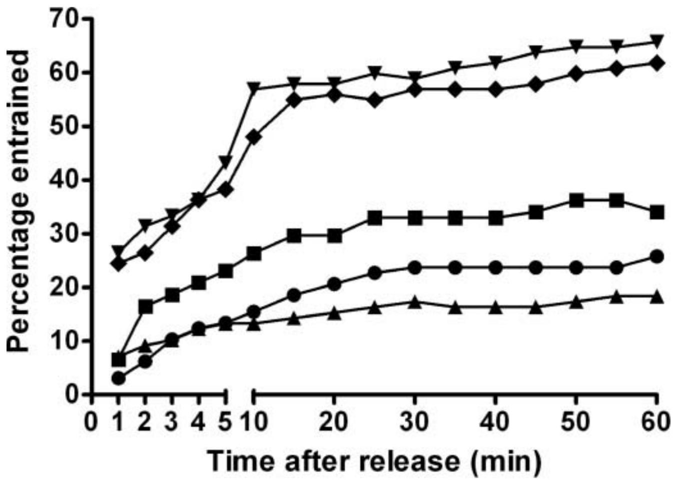

FIGURE 3. Percentage of Pacific lamprey ammocoetes entrained at ends of 16 time intervals during 60-min exposures to one of five types of screen panels: interlock (circles), vertical bar (squares), perforated plate (up-pointing triangles), 12-gauge wire cloth (down-pointing triangles), and 14-gauge wire cloth (diamonds).

their way through the screen. We do not know whether fish passed head or tail first, nor did we record the exact location on the screen panel where they passed through.

Fish of all sizes repeatedly contacted and became impinged on the screens. For all screens, the frequency of impingement events generally increased during the first 5 min and was relatively stable thereafter (Figure 5). The rate of impingements ranged from 36% to 62% on the IL screen, from 23% to 54% on the PP and VB screens, and from 13% to 31% on the WC14 and WC12 screens (Figure 5). However, the WC14 and WC12 screens had fewer and larger (i.e., greater than about 90 mm) fish remaining as time elapsed because so many were entrained.

All of the 585 fish survived the overnight posttest holding period. Injuries were not common, but when present, they consisted of small abrasions to the skin and caudal fin. Overall, the injury rates of fish after 60-min exposures to the screen panels were 5.2% for the IL, 2.2% for the VB, 9.2% for the PP, 2.0% for the WC12, and 4.9% for the WC14. The injury rate for control fish was 4.2%, and this rate never differed significantly from

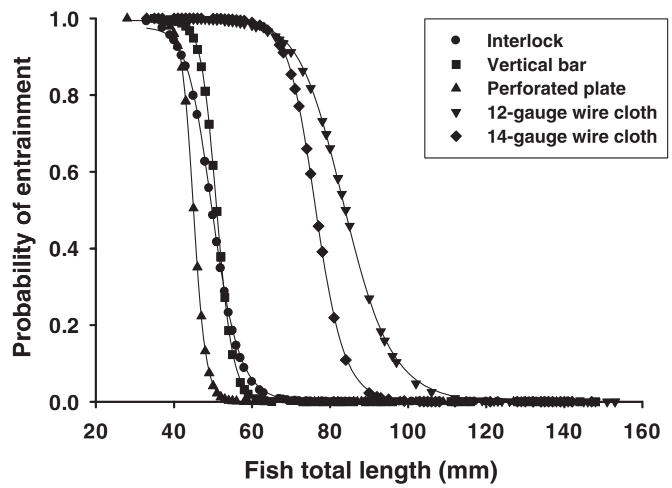

FIGURE 4. Probability of Pacific lamprey ammocoetes becoming entrained behind five types of screen panels relative to fish length.

those of fish exposed to the screens (range of Fisher's exact test P-values = 0.25–1.00). In general, injuries were more common for smaller fish (less than about 50 mm) and only one fish larger than 75 mm was injured. Of the 23 fish that were injured, 13 were entrained and 10 were upstream of the screen panels at the end of the experiments.

DISCUSSION

Common fish screen materials used at water diversions offered varying levels of protection for juvenile lamprey ammocoetes. Our results indicated that the PP screen material offered the best protection for lamprey ammocoetes; this material also works well for juvenile salmonids (Bates and Ruller 1992). The IL and VB screens performed almost as well. Unfortunately, the screens that performed the worst in our tests—the wire cloth screens—are common throughout the Columbia River basin, due in part to their superior strength and durability compared with other materials. For all screen types, fish less than about 40 mm were vulnerable to entrainment; prevention of entrainment for larger fish varied by screen type, with PP, IL, and VB performing the best and WC12 and WC14 the worst. Fish of all sizes frequently contacted and became impinged on the screens

TABLE 1. Descriptive statistics for Pacific lamprey ammocoetes that were entrained after 60-min exposures to one of five types of screening panels. The range is the difference between the maximum and minimum lengths.

			Total length (mm)			
Screen type	Number released	Number (%) entrained	Mean (SD)	Minimum	Maximum	Range
Interlock	97	25 (25.8)	45.1 (5.9)	33	58	25
Vertical bar	91	30 (33.0)	45.1 (4.8)	35	55	20
Perforated plate	98	18 (18.4)	40.1 (4.7)	28	48	20
12-gauge wire cloth	102	67 (65.7)	56.5 (12.3)	40	90	50
14-gauge wire cloth	102	63 (61.8)	52.1 (10.6)	33	78	45

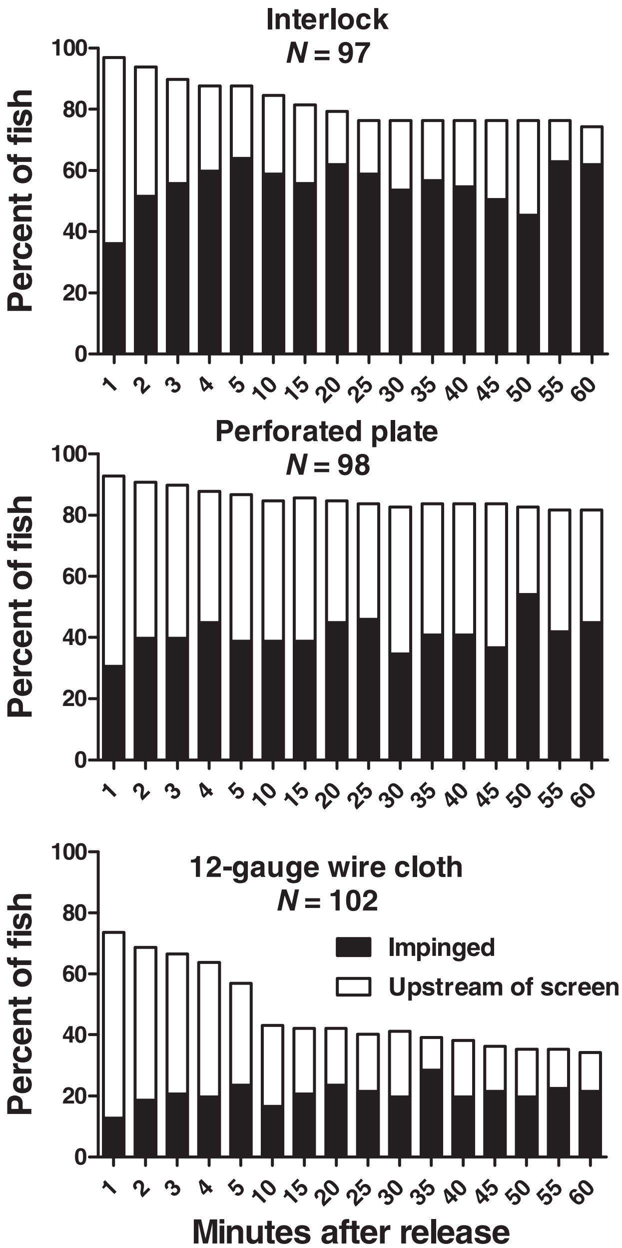

FIGURE 5. Percentage of Pacific lamprey ammocoetes that were impinged (black fill) or upstream of the screen (clear fill) at the end of each of 16 intervals during 60-min exposures to one of five types of screen materials tested. The bars do not add up to 100% because of entrainment occurring over time; *N* is the total number of fish released.

but were not severely injured or killed. The entrainment rates of lamprey ammocoetes in our study were higher than values reported for juvenile salmon (44–79 mm; Bates and Ruller 1992; Swanson et al. 2004), bull trout *Salvelinus confluentus* (median length, 25 mm; Zydlewski and Johnson 2002), delta smelt (25–40 mm; Swanson et al. 2005), Pacific lamprey macrophthalmia (mean length, 145 mm; Ostrand 2007), and rainbow trout (45–250 mm; Rose et al. 2008). This indicates that the small size, elongated body shape, and relatively weak swimming ability of lamprey ammocoetes may make them more vulnerable to entrainment at screened water diversions than deep-bodied teleosts or larger lampreys.

Despite frequent screen contacts and impingements, only a few fish in our tests had minor injuries, and all fish showed high survival. Similar results have been reported for other fishes exposed to such screens (Zydlewski and Johnson 2002; Swanson et al. 2004; Rose et al. 2008). The injuries observed were minor abrasions and were more common in fish less than 50 mm. That fish frequently contacted the screens, yet incurred only minor injuries, indicates that the smooth materials used in these screen panels did not hurt their bodies. However, frequent or prolonged contact with a screen could fatigue or be stressful to juvenile lampreys, which may put them at higher risk of predation, disease, or other hazards that may exist downstream. A similar concern was also raised by Swanson et al. (2004) for juvenile Chinook salmon *O. tshawytscha*. Prolonged impingements by young lampreys may be especially problematic at active screen sites where automated cleaning devices, such as wire brushes or rotating screen parts, could harm impinged fish.

Our tests probably represent a worst-case scenario for lamprey ammocoetes that encounter fish screens because we tested vertical screens positioned perpendicular to the flow without a bypass route or a sweeping velocity. Also, fish were allowed to interact with the screen panels for 60 min, which may be excessive in field situations. The screen angle, bypass configuration, and sweeping velocity are important characteristics of a properly designed and protective fish screen. Current salmonid-based criteria require that screens greater than about 1.8-m in length be constructed at an angle to the flow, have an effective bypass route, and a sweeping velocity that is greater than the approach velocity (NMFS 2008). These criteria help provide a safe and efficient return of fish back to the stream and reduce the exposure time of fish at a screen, which improves fish passage efficiency (Rose et al. 2008; Swanson et al. 2004). Future work with lampreys should be directed at evaluating these criteria.

Overall, our results indicate that lamprey ammocoetes may be highly vulnerable to entrainment at screened intakes, such as pumping facilities and water diversion sites. Potential losses from such entrainment could be a major factor contributing to the decline of lamprey populations in watersheds having a large number of screened diversions. Because of this risk, we recommend that, where practical, wire cloth screens be replaced with IL, PP, or VB screens to reduce lamprey entrainment while continuing to protect salmonids and other fishes.

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