BIOLOGICAL EVALUATIONS OF AN OFF-STREAM CHANNEL, HORIZONTAL FLAT-PLATE FISH SCREEN—THE FARMERS SCREEN

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Introduction

Diversions from natural or manmade waterways are common in the United States and used for many purposes. Many diversions are screened with devices meant to prevent fish and other aquatic life from becoming entrained, injured, or killed. However, many thousands of water diversions remain unscreened. Some screening technology (e.g., submersible traveling screens or rotary drum screens) and design criteria meant to protect fish (NOAA 2004) result in relatively expensive and high maintenance facilities (McMichael et al. 2004), which can limit the installation of screens in areas where they are needed. Recently, however, the development of unique horizontal flat plate fish screens offer designs that are less expensive to install, offer simpler, more passive operation, and may have fewer detrimental effects on aquatic communities. Research on the hydraulic characteristics and biological effects of some flat plate screens has been promising (Beyers and Bestgen 2001; Frizell and Mefford 2001; Rose and Mesa 2008), but more work is needed. Evaluating different designs and sizes of horizontal flat plate screens, both in the laboratory and in the field, would allow further verification of their performance, provide data for comparison with criteria for more traditional fish screens, and perhaps facilitate their installation. Also, evaluating the impacts of these screens on fishes besides salmonids—such as juvenile lampreys—would be informative.

We evaluated the hydraulic and biological performance of a new, off-stream channel horizontal flat plate fish screen, a.k.a. the Farmers Screen. These screens, designed over a 10-year period by personnel from the Farmers Irrigation District in Hood River, Oregon, have a higher rate of horizontal movement of water across the screen (sweeping velocity; SV) relative to the rate of movement of water through the screen (approach velocity; AV), good self-cleaning characteristics, the potential for reduced impingement, injury, and entrainment of fish, and may provide lower installation and maintenance costs. The screens come in various sizes and a large, 2.3 m^3/s (80 cfs) version has been subjected to hydraulic, debris-loading, and biological tests to evaluate injury and mortality to juvenile and kelt salmonids, including Chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss*. The results showed that the large Farmers Screen did not cause injury or mortality to fish when operated in accordance with its design parameters (FID, 2003). However, smaller versions of this screen have not been tested. Evaluations of smaller versions of the Farmers Screen would help to more fully evaluate the performance of these alternative technology screens. Specifically, our objectives were to assess:

(1) the hydraulic performance of a small version of the Farmers Screen under different environmental conditions; and (2) the effects of passage over the screen on fish injury and delayed mortality.

Methods

The screen we evaluated was located at the Oxbow National Fish Hatchery in Cascade Locks, Oregon. The screen is on a side-channel of Herman Creek, a tributary of the Columbia River, and is designed to divert 0.28 m^3/s (10 cfs) of water. The installation is representative of other Farmers Screens that have already been installed in the Pacific Northwest. For a complete description of this screen and of the Farmers Screen in general, see http://www.farmerscreen.org/. For purposes of this report, we refer to the screen as the Herman Creek screen.

To assess the hydraulic performance of the Herman Creek screen, we adjusted the inflow entering the screen, measured it and water depth (Z), diversion discharge, and bypass discharge, and calculated mean SV, AV, and normal velocity (NV, which is the AV multiplied by the percent open area of the screen, or AV × 0.5) under different weir wall heights. After most of these measurements, we experimentally released fish over the screen (see below), but for some, we did not release fish. We evaluated the screen under four weir wall heights (i.e., 4, 11, 13, and 20 cm; or 1.6, 4.3, 5.1, and 7.8 inches) and at inflows ranging from 0.02 – 0.42 m^3/s (0.71 – 14.8 cfs).

To assess the biological performance of the Herman Creek screen, we experimentally released groups of juvenile coho salmon *O. kistuch* over the screen under different hydraulic conditions and quantified injuries to the integument and documented short-term delayed mortality. Our test fish were from the Oxbow Hatchery and we evaluated two size groups, large (85 – 145 mm FL) and small (54 – 78 mm), in two separate sets of trials. Fish that passed over the screen (treatment fish) were released in groups of 10, 1-2 m above the upper edge of the screen and recaptured in a net below the bypass outfall. Control fish were released into the bypass outfall and captured in a net and held for several minutes to simulate the time it took most treatment fish to pass over the screen. We used a fluorescein dye method described by Noga and Udomkusonsri (2002) to determine the extent of ulceration on the skin, eyes, and fins of each fish. After capture, both groups were euthanatized in a lethal dose of MS-222 (200mg/L), rinsed in a fresh water bath for 1 min, and then placed in a solution of fluorescein dye (fluorescein disodium salt at 20mg/L). After 6 minutes, fish were removed from the dye and rinsed in three separate fresh water baths over 3 min to remove excess dye. Images were taken of both sides of each fish in a dark box under ultraviolet (UV) light using a digital camera with a 200-mm macro lens. The UV lights were placed at 45° angles to the side of the fish and we used a yellow barrier filter to eliminate the blue auto-fluorescence. Images were imported into Photoshop CS3 and we measured the body surface area and area of fluorescence for each side of a fish. The percent body surface area of a fish that was injured was derived by dividing the total area of fluorescence by the total body surface area. We calculated the mean (and SD) body surface area that was injured for each release group and compared control and treatment fish using two-sample, one-tailed *t*-tests. We were interested in whether the mean level of injury in treatment fish was significantly higher than background levels of control fish. The level of significance was set at $P < 0.05$. To assess delayed mortality after passage, fish were released in the same manner as described above but were transported to holding tanks after being collected in the bypass outfall. Fish were monitored for 24 – 48 h after passage and handling and the number of fish that died was compared between treatment and control groups. Mortality tests were conducted for most, but not all, of the same hydraulic conditions as injury tests.

We also videotaped the passage of treatment fish over the screen using three underwater cameras mounted to one edge of the screen. Each camera provided only a partial, upstream view of the screen and the system was not designed to cover the entire screen area. Video files were reviewed in slow motion and the approximate number of times fish contacted the screen, their orientation to the current during passage, and their general depth of passage were recorded. Control fish were not videotaped.

Results

A summary of hydraulic conditions measured at the Herman Creek screen and the numbers of coho salmon released for injury and delayed mortality assessments is shown in Table 1. Diversion discharges (the volume of water collected from the screen and sent to the hatchery) comprised from 65% to 100% of the inflow rates. Mean AVs estimated for the entire screen ranged from 0 to 5 cm/s (0 – 0.16 ft/s) and for individual sections of the screen never exceeded 6 cm/s (0.20 ft/s). Mean NVs ranged from 0 – 10 cm/s (0 – 0.33 ft/s) and varied along the length of the screen (Figure 1).. Mean SVs ranged from 36 to 178 cm/s (1.2 – 5.8 ft/s) and were generally faster at the upstream edge and slower at the downstream edge of the screening panels.

Mean SVs were usually at least 32 times higher than AVs for all conditions tested. The mean Z ranged from 1 to 25 cm (0.39 – 9.8 inches) and was generally deeper at the upstream than at the downstream end of the screen. Mean depths were directly related to weir wall height and inflow and were inversely related to diversion discharge, mean SVs were inversely related to weir wall height and diversion discharge and were directly related to inflow, and diversion discharge was related to several variables (Table 2). "Hot spots", or localized areas of high AV with spiraling flow, were not observed during any of our tests.

Overall, the injury rates of fish after passage over the Herman Creek screen were low and severe injuries to the skin, eyes, and fins of both size cohorts were not observed. For large fish, the mean percentage of body surface area that was injured varied by release group and ranged from about 0.5 – 2.5% (Figure 2). The mean percentage of body surface area that was injured in treatment fish was significantly higher than control fish for two test conditions (*t*-tests, $P<0.05$; Figure 2), but the magnitude of these differences was small (< 1%). For small fish, the mean percentage of body surface area that was injured ranged from about 0.4 – 3.0% (Figure 3). The mean percentage of body surface area that was injured in treatment fish was significantly higher than control fish for one test conditions (Figure 3), but again, the magnitude of this difference was small. One small fish, shown as an outlier in Figure 3 with about 60% of its body surface area injured, was probably injured by something other than passage over the screen. Individual injury rates for every fish in our tests are presented in Appendix A. For delayed mortality after passage, we tested 849 fish in total and none died within 24 – 48 h of passage or handling and only one control fish died.

For large fish, the mean number of times fish contacted the screen surface ranged from 0.15 – 0.72 per fish observed (Table 3). During passage, most fish remained low in the water column near the screen surface (Table 3). Fish were oriented up and downstream during passage, with no clear relation to the hydraulic conditions (Table 3). For small fish, the mean number of times fish contacted the screen surface ranged from 0.26 – 0.62 per fish observed (Table 4). Again, most fish remained low in the water column and near the screen surface during passage (Table 4). Most fish were oriented upstream during passage (Table 4).

Discussion

Our results indicate that passage of juvenile coho salmon over the Herman Creek screen under a variety of hydraulic conditions did not severely injure them or cause delayed mortality.

This occurred even though most fish passed over the screen near the screen surface, many contacted the screen during passage, and they were oriented to the current in a variety of directions. However, we never observed fish becoming impinged on the screen surface (i.e., >1 s contact with the screen). The screen showed good self-cleaning performance and never had problems with debris loading. Our results are similar to those of Rose and Mesa (2008), who reported minimal injuries to and low mortality of rainbow trout after passage over backwatered and inverted-weir horizontal flat plate screens in Oregon. Other studies evaluated various designs of vertically-oriented screens and reported results similar to ours (e.g., Danley et al. 2002; Zydlewski and Johnson 2002; Nobriga et al. 2004).

The injuries observed in our fish—both treatment and control groups—were minor and indicate that fish had some trauma to the integument prior to testing and that our holding and handling procedures probably caused more trauma. The fluoroscein dye method was effective for detecting injuries to the integument and essentially resulted in all of our fish having some level of injury. However, as we stated previously, all injuries were minor and any differences in mean injury rates between treatment and control groups were small, which makes it difficult to ascribe any biological significance to the injuries we observed. Further, and perhaps more importantly, all of our fish would have far exceeded the performance standards for safe passage of fish over conventional screen systems as established by NOAA-Fisheries. For example, performance standards set by NOAA-Fisheries include less than 0.5% mortality and ≤ 2% injury rate (i.e., the percent of a sample that is injured) for salmonid smolts. The agency defines injury as visual trauma (including but not limited to hemorrhaging, open wounds without fungus growth, gill damage, bruising greater than 0.5 cm in diameter, etc.), loss of equilibrium, or greater than 20% descaling on one side (Bryan Nordlund, NOAA-Fisheries, personal communication).. Because none of our fish showed such injuries and mortality was lower than 0.5%, the Herman Creek screen would surpass these NOAA-Fisheries standards. Although the performance standards discussed here are for other types of screens, they do indicate that screens like the one at Herman Creek would probably, at a minimum, meet federal regulatory standards.

The ability of the Herman Creek screen to safely pass fish—at water depths ranging from 7 – 25 cm (3 – 10 inches)—was largely due to achieving a high ratio of SV to AV under a variety of diversion scenarios. The ratios of SV to AV in our study ranged from about 30 – 60, which are substantially higher than the 2:1 SV: AV criteria established by NOAA-Fisheries for passive screens. The combination of high SVs and low AVs facilitated quick fish passage, eliminated impingements, and resulted in good self-cleaning. That most fish passed over the screen near the screen surface—regardless of water depth—suggests that water depth criteria previously established for larger versions of the Farmers Screen (i.e., 30 cm or 12 inches) could be relaxed for smaller screens like the one at Herman Creek. Although we safely passed fish over the screen at a depth of only 7 cm (2.8 inches), the number of screen contacts per fish was higher at this shallow depth for large, but not small, fish. Even though the screen contact rate was not related to the extent or severity of injuries, operating the screen at water depths near 7 cm seems too shallow, particularly under high flow conditions. Thus, although our results suggest that the Herman Creek screen can be operated effectively at water depths less than 30 cm (12 inches), we cannot unequivocally recommend a single, specific minimum depth for this screen. Rather, a range of minimum depths, perhaps from 15 – 20 cm (6 – 8 inches), would probably provide safe passage of fish under most circumstances.

Despite the advantages of the Herman Creek screen for protecting fish populations, there are some things to consider when interpreting our results. First, we were unable to evaluate all possible hydraulic conditions on screen performance, fish injury, and mortality. Although we believe our evaluations were realistic because they encompassed typical diversion scenarios, there may be other flow conditions we missed that are relevant to fish passage and safety. Second, only one species of fish was tested for the screen evaluations and our results may not be applicable to other species. The two size groups of juvenile coho salmon we used were probably good surrogates for other salmonids of similar size. Extrapolation of our results to other fishes, such as juvenile lampreys, seems inappropriate and would require further testing. Finally, our video analyses were not rigorous and our camera installation was meant to provide qualitative information on the behavior of fish as they passed over the screen. Even though we used three cameras, we had limited fields of view and it was often difficult to see because of water turbidity, sunlight, or other factors. Although we are confident that the data we did collect were representative of fish behavior during passage, more detailed analyses will require further work.

In summary, when operated within its design criteria (i.e., diversion flows of about 0.28 m^3/s or 10 cfs), the Herman Creek screen provided safe and effective passage of juvenile salmonids under a variety of hydraulic conditions. We do not recommend operating the Herman Creek screen at inflows lower than 5 cfs because water depth can get quite shallow and the screen can completely dewater, particularly at very low flows. If the screen is operated at inflows lower than 5 cfs, caution must be used to avoid diverting an excessive amount of water, which can lead to shallow depths, insufficient bypass flow, and perhaps screen dewatering. Our research only provided crude estimates of the time it takes for fish pass over the screen under various hydraulic conditions. Future work, if necessary, should address this issue using more appropriate techniques (e.g., PIT tag studies). Finally, we do not know the fate of fish that pass over the screen, enter the bypass channel, and are diverted back to Herman Creek. It is possible that passage through these areas is a stressful and disorienting event for fish, which could make them vulnerable to hazards that exist downstream, such as predation by fish or birds. This is not an idea unique to the Herman Creek screen, but is relevant for many types of diversions and obstacles fish may encounter in the wild. Further research would be necessary to address this issue.

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Table 1.—Summary of hydraulic conditions at the Herman Creek screen and the numbers of two size groups of juvenile coho salmon used during injury assessments (and delayed mortality tests). Trials were conducted on different days during February through May, 2009. *Q* = discharge, SV = sweeping velocity, AV = approach velocity, *Z* = water depth over the screen, T = treatment fish, C = control fish.

Inflow *Q* (m^3/s)	Diversion *Q* (m^3/s)	Bypass *Q* (m^3/s)	SV (cm/s; mean [SD])	AV (cm/s)	*Z* (cm; mean [SD])	Large Fish T	Large Fish C	Small Fish T	Small Fish C
4-cm weir wall height									
0.10	0.10	0.00	67 (34)	1	7 (1)				
0.14	0.13	0.01	87 (41)	2	7 (1)	37	17		
0.15	0.14	0.01	120 (50)	2	9 (1)			40 (44)	19 (15)
0.26	0.23	0.03	166 (52)	3	12 (1)				
0.27	0.25	0.02	137 (49)	4	11 (3)	38 (65)	20		
0.29	0.26	0.02	138 (73)	4	10 (1)				
0.31	0.28	0.02	130 (46)	4	12 (2)				
0.34	0.31	0.03	173 (45)	5	12 (1)			39 (51)	19 (17)
0.36	0.33	0.03	171 (41)	5	12 (1)	41 (60)	15 (30)		
11-cm weir wall height									
0.14	0.11	0.03	101 (30)	2	14 (1)	39	20		
0.15	0.12	0.03	106 (30)	2	14 (1)			40 (45)	20 (18)
0.29	0.23	0.05	161 (23)	3	16 (2)	40	20		
0.29	0.23	0.06	143 (30)	3	16 (1)			40 (45)	14 (15)
0.34	0.26	0.08	178 (32)	4	19 (1)			41 (36)	20 (15)
0.42	0.34	0.07	161 (30)	5	18 (1)	38 (61)	15 (42)		
13-cm weir wall height									
0.10	0.09	0.02	61 (20)	1	14 (0)				
0.20	0.13	0.07	170 (36)	2	16 (2)				
0.31	0.24	0.06	127 (25)	4	20 (1)				
20-cm weir wall height									
0.02	0.02	0.00	na	0	1 (1)				
0.04	0.03	0.01	36 (15)	0	8 (0[a])				
0.15	0.10	0.05	72 (12)	2	22 (1)	38	14		
0.15	0.10	0.05	73 (12)	2	23 (0[a])			40 (44)	20 (15)
0.27	0.20	0.07	100 (15)	3	25 (1)			40 (45)	20 (15)
0.28	0.22	0.06	115 (17)	3	24 (1)	39 (60)	15 (52)		
0.29	0.21	0.08	101 (25)	3	25 (1)				

Table 2.—General linear models describing the relation between hydraulic variables measured at the Herman Creek screen, 2009. All coefficients are significant ($P < 0.05$) unless noted. *AV* = approach velocity (cm/s); *SV* = sweeping velocity (cm/s); *Z* = depth of water over screen (cm); *SQ* = inflow discharge (m^3/s); *DQ* = diversion discharge (m^3/s); *WW* = weir wall height (cm); *SEE* = standard error of estimate.

Dependent variable	Equation
Depth	*Z* = 2.592[a] + 0.572 (*WW*) + 89.673 (*SQ*) – 75.712 (*DQ*)
	N = 24, R^2 = 0.84, *SEE* = 2.27
Diversion discharge	*WQ* = 0.056 – 0.003 (*WW*) + 0.902 (*SQ*) + 0.000 (*SV*)
	N = 24, R^2 = 0.99, *SEE* = 0.01
Sweeping velocity	*SV* = 105.007 – 4.863 (*WW)* + 1,166.178 (*SQ*) - 1,063.394 (DQ)
	N = 24 R^2 = 0.81, *SEE* = 17.82

[a]*P*=0.25

Table 3.—Mean number of fish contacts with the screen, their relative depth of travel during passage, and their general orientation to the water flow during passage for large juvenile coho salmon experimentally released over the Herman Creek screen, 2009. AV = approach velocity, SV = sweeping velocity.

Date	AV (cm/s)	SV (cm/s; mean [SD])	Water Depth (cm)	Mean (SD) number of screen contacts per fish	Depth in water column (% of observed)			Orientation (% of observed)		
					low	mid	high	up stream	down stream	other
2/27	2	87 (41)	7	0.72 (0.58)	50	23	4	41	59	0
2/17	4	137 (49)	11	0.45 (0.23)	41	54	5	36	60	4
3/4	5	171 (41)	12	0.47(0.24)	41	21	4	59	41	0
3/2	2	101 (30)	14	0.26 (0.18)	50	23	2	37	63	0
2/18	3	161 (23)	16	0.41(0.23)	35	34	13	60	40	0
3/3	5	161 (30)	18	0.15(0.18)	49	23	2	27	73	0
2/24	2	72 (12)	22	0.41 (0.34)	49	19	5	56	44	0
2/19	3	115 (17)	24	0.41 (0.33)	42	19	5	39	61	0

Table 4.—Mean number of fish contacts with the screen, their relative depth of travel during passage, and their general orientation to the water flow during passage for small juvenile coho salmon experimentally released over the Herman Creek screen, 2009. AV = approach velocity, SV = sweeping velocity.

Date	AV (cm/s)	SV (cm/s; mean [SD])	Water Depth (cm)	Mean (SD) number of contact per fish	Depth in water column (% of observed)			Orientation (% of observed)		
					low	mid	high	up stream	down stream	other
5/19	2	120 (50)	9 (1)	0.32 (0.14)	57	40	3	56	40	4
5/20	5	173 (45)	12 (1)	0.50 (0.30)	63	33	4	61	15	24
5/15	2	106 (30)	14 (1)	0.56 (0.26)	58	32	10	55	41	4
5/13	3	143 (30)	16 (1)	0.42 (0.25)	49	37	14	44	38	18
5/14	4	178 (32)	19 (1)	0.62 (0.35)	65	23	12	53	35	12
5/8	2	73 (12)	23 (0)	0.26 (0.22)	69	23	7	70	30	0
5/12	3	100 (15)	25 (1)	0.35 (0.21)	55	29	20	61	36	2

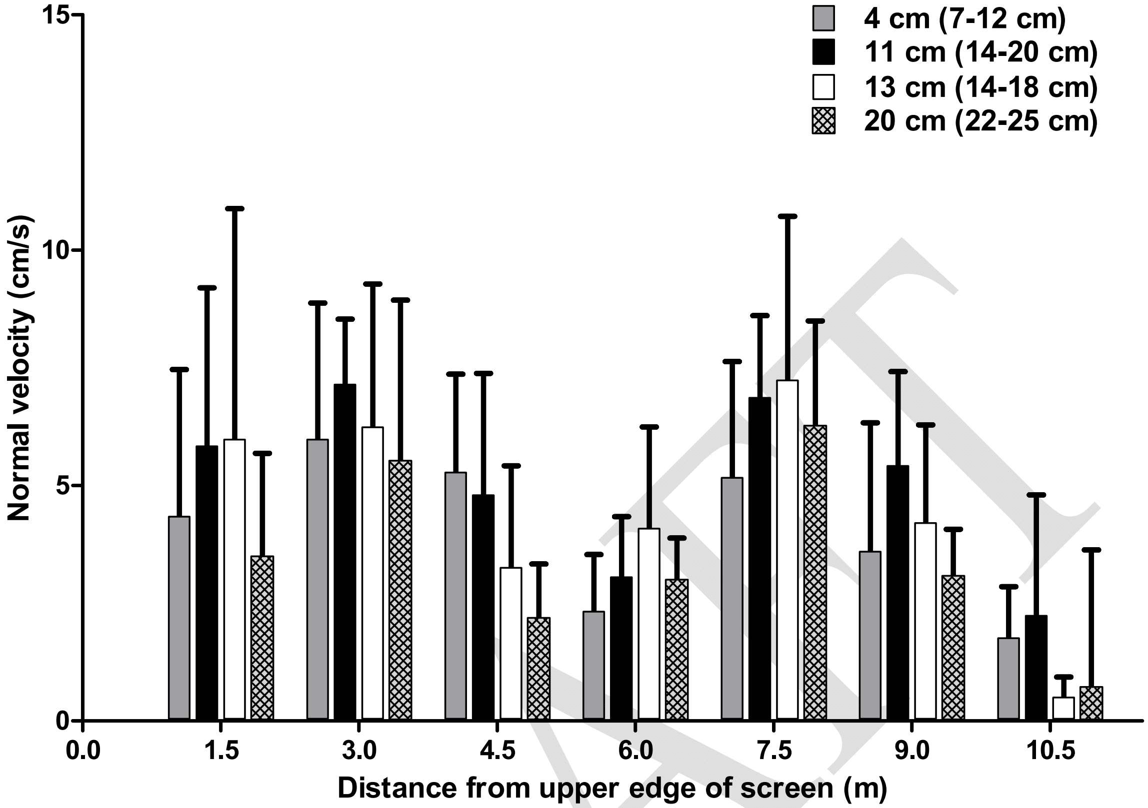

Figure 1.—Mean (and SD) normal velocities (approach velocities corrected for the net open area of the screen) estimated for different sections of the Herman Creek screen relative to weir wall height and water depth (in parentheses), 2009.

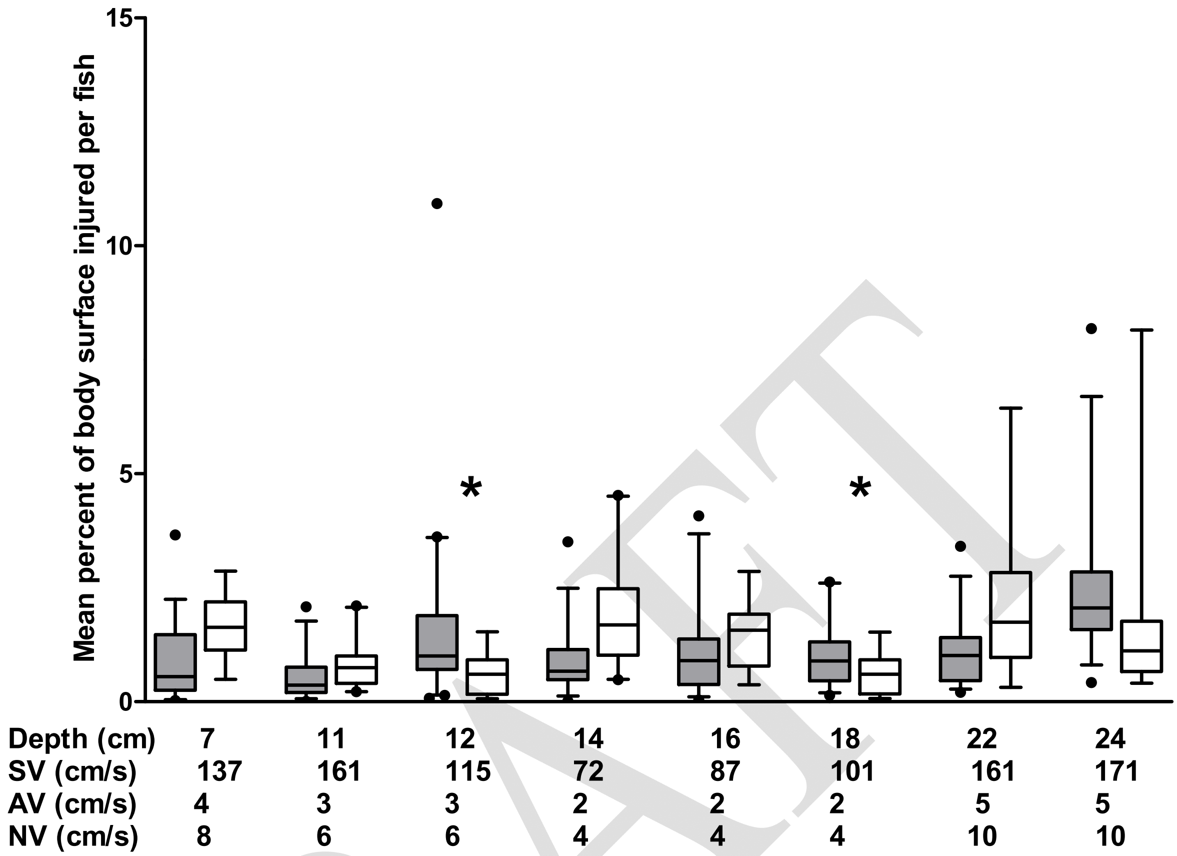

Figure 2.—Box and whisker plots of the percent body surface area injured in large juvenile coho salmon released over the Herman Creek screen (grey boxes) under different hydraulic conditions relative to control fish (white boxes). The upper and lower boundaries of the box represent the 25^{th} and 75^{th} quartiles, the line inside the box is the mean, the whiskers represent the 5% and 95% confidence intervals, and outliers are shown by solid points. The X-axis shows the water depth over the screen, the mean sweeping velocity (SV), the approach velocity (AV), and the normal velocity (NV) during each trial. Asterisks denote a significant difference between means within a group (one-tailed *t*-test, $P < 0.05$).

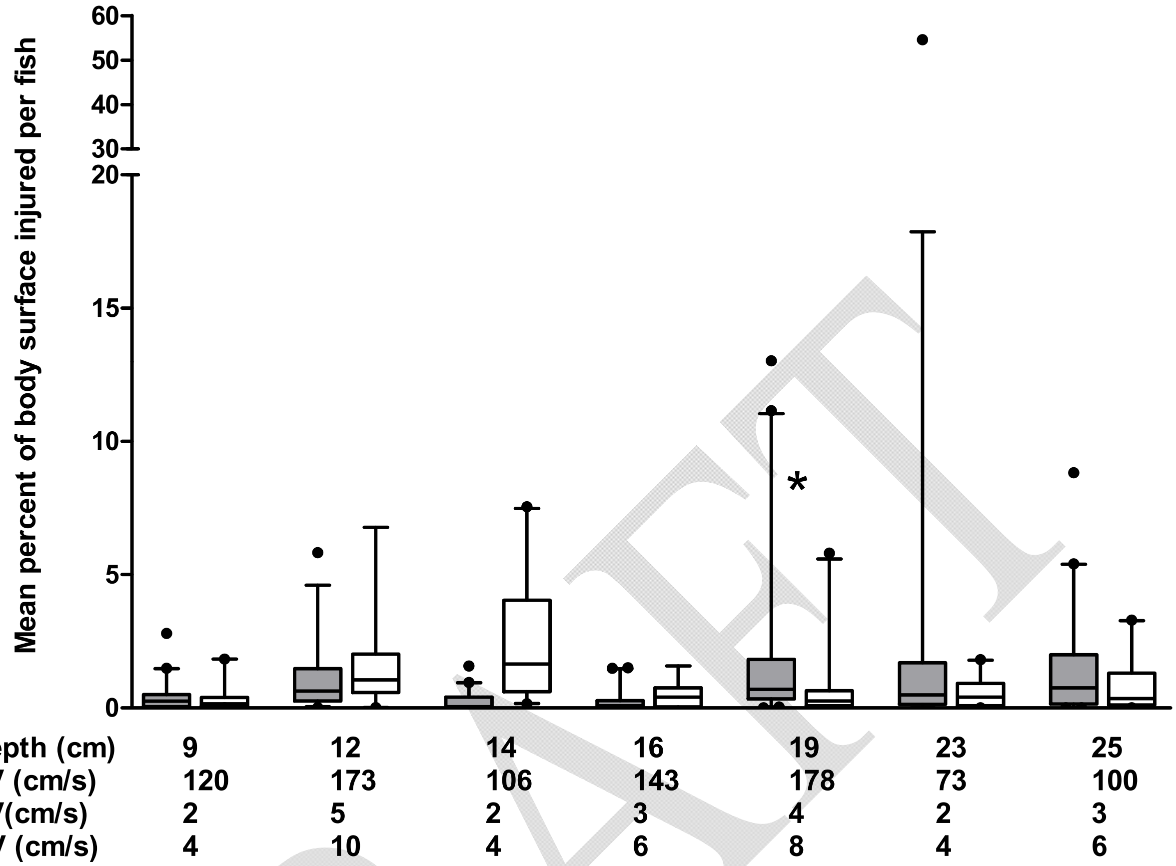

Figure 3.—Box and whisker plots of the percent body surface area injured in small juvenile coho salmon released over the Herman Creek screen (grey boxes) under different hydraulic conditions relative to control fish (white boxes). The upper and lower boundaries of the box represent the 25th and 75th quartiles, the line inside the box is the mean, the whiskers represent the 5% and 95% confidence intervals, and outliers are shown by solid points. The X-axis shows the water depth over the screen, the mean sweeping velocity (SV), the approach velocity (AV), and the normal velocity (NV) during each trial. Asterisks denote a significant difference between means within a group (one-tailed t-test, $P < 0.05$).