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Response of Bull Trout Fry to Four Types of Water Diversion Screens

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Abstract.—Bull trout *Salvelinus confluentus* are currently listed as a threatened species in the western United States. Entrainment (the passage through screens of water diversion structures) has been identified as one cause of bull trout population decline. The objective of this study was to evaluate whether existing fish screen criteria developed for the Pacific Northwest are adequate to prevent bull trout fry from being impinged (having extended whole-body contact with a screen) or entrained by screened water intakes. Bull trout were exposed to four types of screens in an artificial stream. Recently emerged bull trout (median total length = 25.0 mm) were tested in groups of 25 at 6–7°C for approximately 16 h. Only one bull trout was entrained during all the experiments. Bull trout were regularly impinged on the screens but, in most cases, escaped impingement and survived for at least 24 h. This implies that the currently specified screen regulations for salmonid fry might not need to be modified for bull trout fry.

If not properly screened, water diversion structures can negatively impact fish populations by allowing fish to be injured or killed by pumps for irrigation, turbines for electrical generation, or dewatering. The effectiveness of screens depends on several biological and physical factors, among them the swimming ability of the fish. Fish swimming ability is dependent on species, size, stamina, developmental stage, and migrational stage. Dissolved oxygen concentration, water temperature, and lighting also influence swimming ability and therefore the fate of fish at diversion screens. Two of the more important factors to be considered are (1) the time of emergence of the smallest life stage, and (2) low water temperatures. The smallest life stages will have the highest probability of entrainment based on size; low water temperatures result in lower metabolic activity that may, in turn, result in poor swimming performance and slower escape responses at intake screens. Together these factors increase the probability of impingement on and entrainment through diversion screening. Impingement and entrainment are defined as the processes by which aquatic organisms make contact with or are pulled through water diversion or other structures at dams, fish hatcheries, and irrigation facilities.

Currently established screen criteria are based on excluding fish and minimizing the effects on those encountering the screen. Generally, state and federal laws in the Pacific Northwest require any diversion of water from streams, rivers, lakes, reservoirs, and tidal areas to be screened to protect fish. The Washington Department of Fish and Wildlife (WDFW; State Laws RCW 77.16.220, RCW 75.20.040, and RCW 75.20.061) and the National Marine Fisheries Service (NMFS 1995) have adopted screen criteria based on experimental trials using 30–37 mm TL fall chinook salmon *Oncorhynchus tshawytscha*, sockeye salmon *O. nerka*, and chum salmon *O. keta* fry (Bates and Fuller 1992).

Washington State requirements for water diversion screens specify that the approach velocity for salmonid fry less than 60.0 mm (fork length) shall not exceed 0.12 m/s. Approach velocity is defined as the water velocity component perpendicular to and approximately 7.6 cm in front of the screen face, where juveniles must be able to swim at speeds equal to or greater than the approach velocity for an extended length of time to avoid impingement. The screen face material (the size and shape of the screen) for salmonid fry must provide a minimum of 27% open area. Screen materials include a perforated plate with openings not exceeding 2.4 mm, a profile bar with its narrowest

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dimension not exceeding 1.75 mm, and woven wire with its widest opening not exceeding 2.4 mm.

Additional data are needed to describe the relationship of other species and environmental variables to screen criteria (NMFS 1995). For example, the interaction of bull trout *Salvelinus confluentus* with screens is a concern because the bull trout may only measure 25 mm (McPhail and Murray 1979) when they emerge as fry. The basic preferences and biological differences (Fraley and Shepard 1989; Rieman and McIntyre 1993) between bull trout and other salmonid species may influence the effects of screens on bull trout. Bull trout are believed to remain in spawning gravel for up to several weeks after yolk sac absorption. During this period of time fry begin to feed, fill their swim bladders, and become neutrally buoyant at approximately 25 mm (McPhail and Murray 1979).

Although bull trout have historically ranged from southeast Alaska to California and Nevada, the species is now listed as threatened under the Endangered Species Act. Bull trout populations have declined due to habitat degradation, competition with and predation from introduced nonnative species, fish passage issues caused by dams and diversion structures, incidental harvest, and impingement and entrainment at water diversion structures (USFWS 1998). The objective of this study was to evaluate whether existing screen criteria—specifically the approach velocity and screen type—are adequate in preventing juvenile bull trout fry from being impinged or entrained by screened water intakes at diversion structures.

Methods

Bull trout fry were exposed to different screen conditions in a standard test apparatus. Groups of individuals were introduced to a test chamber where the downstream division consisted of a removable test screen. Challenges were run and videotaped for approximately 16 h at which time fish were removed and monitored for 24 h.

The bull trout originated from an experimental broodstock cultured at the U.S. Fish and Wildlife Service's Creston National Fish Hatchery (Creston NFH) in Kalispell, Montana. These fish were transferred to the Abernathy Fish Technology Center (AFTC) in Longview, Washington. The Creston NFH bull trout broodstock is from the Swan River drainage in northwestern Montana. Bull trout eggs were cultured at 6°C before shipping. Eyed bull trout eggs were received at the AFTC on 5 November 1999.

The eyed eggs were incubated in Heath trays at the AFTC. The water source for the eggs was maintained between 5°C and 6°C (cf. Fredenberg et al. 1995). On 20 January 2000, the majority of fish absorbed most of their yolk and were released from the Heath trays into two 76.2-cm-diameter tanks. A dim light was placed over each tank to simulate dusk and dawn when overhead lights in the hatchery turned off and on via a photocell. On 24 January 2000, fish had absorbed most of their yolk sacs and a daily ration of Biodiet starter (Bio-Oregon, Warrenton, Oregon) was provided. Experiments were initiated once most individuals had completely absorbed their yolk sacs as assessed under a dissecting microscope (mean TL = 24.8 mm; SD = 0.11 mm). The bull trout were incubated, reared, and experimentally challenged in incubators and tanks with safety-screened outflow to prevent any escape. Following the tests, all remaining bull trout were euthanatized.

Fry were tested in an oval-shaped fish tank (Figure 1A) designed by Smith–Root, Inc., Vancouver, Washington. The water depth was maintained at 35.6 cm, and the tank had a flow-inducing propeller system with an adjustable control for setting precise velocities. The test area was located on the opposite side of the tank from the propeller system. The test chamber was 102 cm long (Figure 1B). At each end of the test chamber a barrier screen constructed of nylon mesh (0.159-cm stretch mesh) retained fish in the chamber. Experimental test screens were positioned in the center of the test chamber (66 cm downstream of the upper barrier screen) for testing the impingement and entrainment of fish. Downstream of the experimental screen was a 35.6-cm capture area where entrained fish were collected. The test chamber was constructed of etched aluminum, resulting in a gray color throughout the chamber (including the test screens). This uniform coloration prevented refuge areas based on coloration and allowed us to see the fish.

Before the experiments were initiated, water velocities were measured in four areas of the test chamber at six positions in each area. The six positions included three measurements horizontally across the chamber at two water depths (three positions at 7.6 cm above the chamber bottom and three positions at 10.2 cm below the water surface). The four areas were (1) 7.6 cm downstream of the upper barrier screen, (2) midway between the upper barrier screen and the experimental

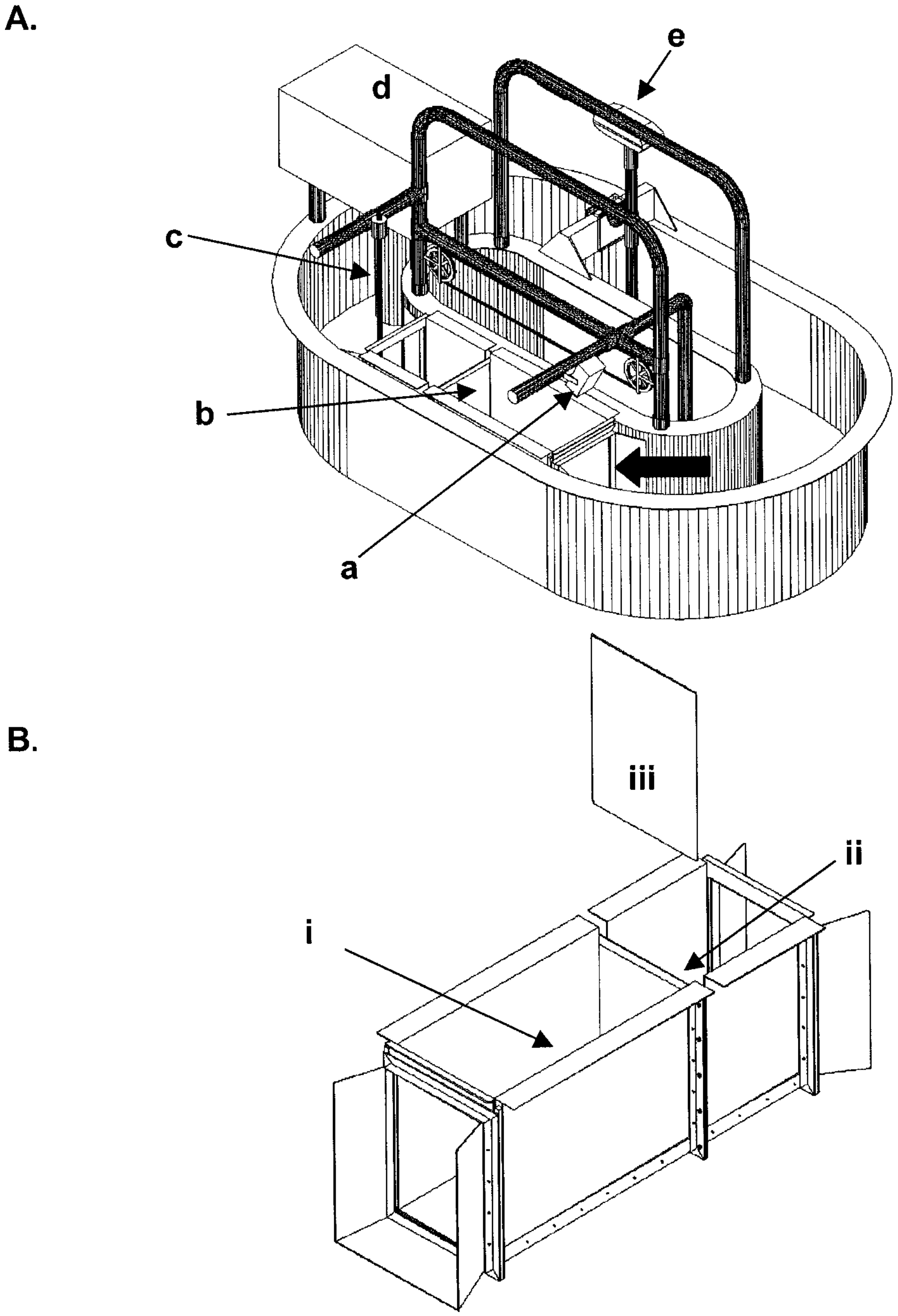

FIGURE 1.—Schematic of test tank and insert for bull trout screening study; **(A)** Test tank, showing the (a) video camera, (b) test chamber, (c) velocity meter, (d) cooling unit, and (e) propeller system. The thick black arrow indicates the direction of water flow. **(B)** Test chamber, showing the (i) release area, (ii) capture area, and (iii) position of removable test screens.

screen, (3) 7.6 cm upstream of the experimental screen, and (4) 7.6 cm upstream of the lower barrier screen. Water velocity was measured with a Swoffer velocity meter (Seattle, Washington) calibrated for low velocities. Water velocities were adjusted before each experiment to achieve laminar flow (horizontal and vertical uniformity) in the test chamber (Zydlewski et al. 2000). During the experiments, the average velocities measured 7.6 cm in front of the screen ranged from 0.114 to 0.129 m/s for individual locations. The average velocity across the entire screen ranged from 0.118 m/s (SE = 0.001) to 0.123 m/s (SE = 0.001) for the different experiments.

Once the velocity characteristics of the test chamber were determined, the velocity meter was placed 17.3 cm above the bottom, behind the lower barrier screen as a reference to monitor velocity throughout the experiments. During the experiments, water velocity behind the barrier screen was maintained within 0.01 SDs of the established velocity at the beginning of the experiment.

A temperature probe was placed in the portion of the tank away from the test chamber for the continuous monitoring of water temperature throughout the trials. The water temperature was maintained between 6°C and 7°C throughout the experiments.

The test screens used in this study were those currently approved by the National Marine Fisheries Service (NMFS) and WDFW for salmonid fry. Screen criteria specify that the screen material provide a minimum of 27% open area. The screens were plates of metal with the following types of openings: 2.4-mm, evenly-spaced round openings (perforated plate, PP); 1.75-mm openings created by evenly-spaced vertical bars (profile bar with vertical orientation, VPB); 1.75-mm openings created by evenly-spaced horizontal bars (profile bar with horizontal orientation, HPB); and 14-gauge metal wire woven to have maximum openings of 2.4 mm (woven wire, WW). One additional test was run as a control (CL): no screen was placed in the central slot for the experimental screens. The control provided baseline information of fish distribution throughout the chamber under the artificial test conditions of the simulated stream.

Initial testing was done to determine the number of fish to introduce per experiment while retaining the ability to count individual fish. For bull trout fry, we determined that 25 individuals could be counted accurately in all sections of the test chamber. We used fish 22.5–31.0 mm TL (median = 25.0 mm) that had been feeding for at least one week.

The experimental screens and the control were tested in random order (chosen with a computer random number generator): CL, VPB, PP, HPB, and WW. Each screen condition was considered an experiment. Experiments were run from 29 February 2000–4 March 2000.

Groups of fish were introduced into the release area (Figure 1B) of the test chamber with the experimental screen or no screen (CL) in place. Fish were allowed to acclimate to static-water tank conditions for 15 min, after which time the motorized propeller was turned on at the lowest setting to generate a velocity of approximately 0.03 m/s. At 15-min intervals over 1 h, velocity was increased to 0.12 m/s at 7.6 cm in front of the experimental screen, which is the approach velocity of the current screen criteria. The water velocity was maintained at 0.12 m/s throughout the remainder of the experiment.

Experiments were run from 1545 to 0800 hours (16.25 h) in order to observe those behaviors associated with dusk and dawn periods that have shown to be important in other screen retention studies (Stelfox 1997). Dim lights were installed above the test chamber to simulate the same dawn and dusk conditions fish experienced during rearing. Fish behavior was videotaped from above the tank; infrared light allowed video observation under dark conditions. Once water velocity reached 0.12 m/s, fish were continuously observed for 1 h and then checked at 30-min intervals until 2200 hours and from 0400 hours to 0800 hours ($n = 23$ observations). The number of fish impinged on the experimental screen and the number of fish passing through or entrained by the experimental screen (in the lower section of the test chamber) were recorded. Individual time to impingement and time to pass through the experimental screen were subsequently observed from the videotapes.

For experiments 2–5, impingement was defined as extended contact (>1 s) with the test screen, entrainment as passing through the test screen and being observed in the capture area, and free as being observed in the release area not in contact with the test screen. For the control experiment (no screen), impingement was defined as extended contact (>1 s) with the lower barrier screen (different from experiments 2–5), entrainment as being present in the area below where the test screen would be placed (i.e., in the capture area), and free as above where the test screen would be placed (i.e., in the release area). The average number of

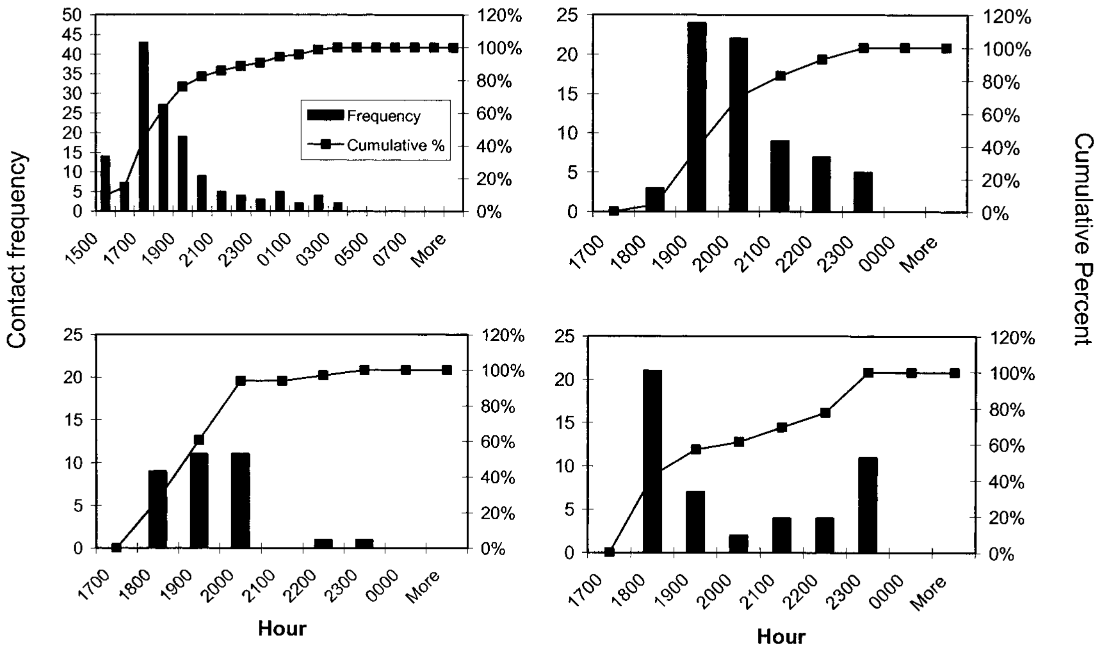

FIGURE 2.—Frequency distribution of the contact time for four experimental screen treatments used to evaluate fish screen criteria for bull trout (left scales) and the cumulative percent contact time (right scales). The screen treatments were as follows (from the upper left corner to the lower right corner): a vertical profile bar; a perforated plate; a horizontal profile bar; and a woven-wire screen; $N = 25$ fish per treatment.

fish entrained and impinged at the end of each 30-min observation were reported (mean ± SE).

Once each experiment was completed, live fish from the three sections of the test chamber (above the screen, below the screen, and impinged on the screen) were transferred to separate holding tanks for a 24-h survival test. After 24 h the number of fish surviving from each group was noted and each fish was measured for TL (mm) and wet weight (g).

Videotapes were analyzed to establish whether bull trout contacted test screens during the experiments. The most active period of the day was determined for one experiment before analyzing all videotapes. The frequency distribution of contacts over time for experiment 2 (VPB) revealed that 90% of the contacts were made between 1700 and 0000 hours (Figure 2, top left). Therefore, the remainder of the experimental tapes were examined from 1700 to 0000 hours. The videotapes were not analyzed for the control group since videos were used to ensure that fish were making contact with the test screens.

The videotapes from experiments 2–5 (VPB, PP, HPB, and WW) were examined for three variables: (1) the total number of contacts between 1700 and 0000 hours; (2) whether or not the fish escaped from the screen; and (3) the start and end time of the contacts with the screen. The mean time and SE of impingement (contact time) is reported for individual screens (decision probability for statistical comparisons, $P = 0.05$).

Results

For all screen types bull trout were distributed over the bottom of the release area (primarily near the edges) during experimentation. The bull trout tested under the control conditions were distributed similarly but over the entire test chamber rather than only in the release area. The control experiment provides evidence that bull trout tested in this experimental unit move throughout the entire chamber. The fish did not favor any particular lateral section of the experimental chamber based on water velocity gradients, lighting, or structural design.

Impingement and Contacts

Throughout the control trial individuals made contact with the lower barrier screen (impingement). According to videotape analysis, contacts were made with test screens between 1700 and 0000 hours for all four screen types. Detailed information concerning the location and orientation

TABLE 1.—Mean number (SEs in parentheses) of bull trout entrained and impinged on various types of screen and the number surviving the experiments. Data were used to evaluate the effectiveness of current Pacific Northwest fish screen criteria. Treatments were as follows: CL = control, VPB = vertical profile bar, PP = perforated plate, HPB = horizontal profile bar, and WW = woven-wire screen.

	Condition at end of each 30-min interval		Condition at end of experiment			
Experimental condition	Number entrained	Number impinged	Number entrained	Number impinged	Number surviving	Number surviving 24 h after the experiment
CL	12.7 (1.3)	2.1 (0.3)	12	2[a]	25	24
VPB	0.05 (0.05)	2.75 (0.20)	1	3	25	25
PP	0	0.39 (0.10)	0	1	25	25
HPB	0	1.61 (0.31)	0	2	25	25
WW	0	1.26 (0.20)	0	1	25	25

[a] Two individuals were impinged on the rear barrier screen.

of impingement are reported in Zydlewski et al. (2000).

At the end of each 30-min observation period of the VPB trials approximately three fish were impinged on the test screen (Table 1). During all 30-min observation periods fish were found impinged on the screen. The duration of contact with the VPB screen averaged 12.9 min (SE = 3 min; $n = 69$); most contacts occurred between 1700 and 2000 hours (75%), and the number declined to 0 at 0400 hours (Figure 2).

For the PP trials, less than one fish (0.39; SE = 0.10) was impinged on the screen at the end of each 30-min observation period. No fish were impinged in 13 of the 23, 30-min observation periods. The duration of contact with the PP screen averaged 2.5 min (SE = 1.4 min; $n = 32$), with most contacts occurring between 1800 and 2100 hours (94%; Figure 2).

For the HPB trials, on average 1.61 fish (SE = 0.31) were impinged on the screen. No fish were impinged in 7 of the 23, 30-min observation periods. The duration of contact with the HPB screen averaged 7.1 min (SE = 1.8 min; $n = 69$), with most contacts occurring between 1900 and 2100 hours (83%; Figure 2).

For the WW trials, on average 1.26 fish (SE = 0.20) were impinged on the screen. No fish were impinged in 5 of the 23, 30-min observation periods. The duration of contact with the WW screen averaged 6.8 min (SE = 2.0 min; $n = 48$), with all contacts occurring by 2300 hours. There were two peaks of activity—1800 hours and 2300 hours (Figure 2).

Entrainment

Between 1700 and 1730 hours, one fish was entrained through the VPB screen. This fish was the smallest (23.0 mm) tested in the experiment. Once entrained the fish spent time on the bottom of the capture area and impinged on the barrier screen. Entrainment through the screen into the capture area never occurred with the three other screen types tested.

Survival

Although all individuals tested under the control condition survived the experiment, one individual was dead 24 h after the experiment. For all screen types all tested individuals survived the experiments and were alive 24 h later.

Discussion

Most water diversion structures have screens oriented at some angle to the water flow. Although the results from this study cannot be directly applied to angled screens, they represent the worst-case scenario: fish experiencing a vertically oriented structure with no sweep velocity. NMFS criteria explicitly state that the sweeping velocity, or the water velocity component parallel and adjacent to the screen face, shall be greater than the approach velocity. The sweeping velocity criterion (in combination with screen exposure time) and approach velocity criteria are considered to greatly reduce the potential for fish to be impinged on the screen mesh. This implies that the fish in our study were not given the opportunity of an alternative water flow for movement past the diversion screen. Future studies should examine the currently accepted screen criteria for different screen angles and various sweeping velocities.

This study was restricted to testing bull trout emerging at 24.8 mm at 6°C for their response to the currently imposed screen criteria for salmonid fry in the Pacific Northwest. However, there is little information about size and temperature at emergence for bull trout. Although 25 mm has been reported as the size at emergence for one population, more studies need to be conducted in different geographic regions with varying water temperatures to better identify the size(s) at emergence. These studies will provide better information for running further screen experiments on bull trout emerging at water temperatures relevant to specific watersheds.

Our experiments with bull trout fry suggest that existing screen criteria, particularly approach velocity and screen type, are appropriate for fry-sized bull trout. In particular, at 6–7°C temperatures (the typical temperatures for the distribution of bull trout; Ratliff 1992; Rieman and McIntyre 1995; Bonneau and Scarnecchia 1996) and at small emergent sizes, bull trout exposed to the currently accepted screens are unlikely to be entrained or killed when impinged on those screens. This implies that the currently specified juvenile fish screen criteria (NMFS 1995) may not require modification to safeguard bull trout fry. However, observations at field sites will be important to assure wild fish protection.

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