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An Experimental Study of the Stranding of Juvenile Coho Salmon and Rainbow Trout during Rapid Flow Decreases under Winter Conditions

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Abstract.—The stranding of juvenile coho salmon *Oncorhynchus kisutch* and rainbow trout *O. mykiss* on river bars caused by rapid decreases in river flow during the operation of hydroelectric facilities was investigated in an artificial stream channel. We conducted experiments with winter water temperatures (<4°C) and a gravel substrate. In daytime trials, many fish became stranded because they were concealed in the interstitial areas of the substrate and were reluctant to leave when water levels receded. Coho salmon were more likely to be stranded than rainbow trout. At night, instead of using the substrate as cover, fish were active in the water column and the incidence of stranding during flow reductions was greatly diminished. Stranding was less frequent at slow rates of dewatering. The addition of shallow, covered pools to the substrate did not alter the principal results. Our findings suggest that during winter months, fish losses from stranding will be minimized if flow reductions occur at night and at slow rates of change.

In rivers regulated for electricity generation, flows can fluctuate suddenly because of power plant operations. Rapid decreases in flow may strand rearing fishes and other organisms that cannot respond to receding water levels (Cushman 1985; Hunter 1992). Stranding can occur on gently sloping river bars, and in potholes and backchannels that become isolated as water levels decrease (Bauersfeld 1978). Although stranding has been observed in a number of field studies (e.g., Hamilton and Buell 1976; Bauersfeld 1978; Olson and Metzgar 1987), with the exception of Monk (1989) there are no experimental data available on the stranding of rearing fish during controlled flow decreases (referred to here as "downramping").

Flow decreases during the winter months may pose special problems in salmonid streams because the behaviour of rearing juvenile salmon is different in winter than during the summer. Field and laboratory observations indicate that juvenile salmonids associate closely with either cover or substrate when water temperatures drop below 4–8°C (Hartman 1963; Chapman and Bjornn 1969; Taylor 1988; Hillman et al. 1992). In some cases, fish may occupy interstitial spaces in rock and cobble substrates (Hartman 1965; Hillman et al. 1987). Griffith and Smith (1993) found that all concealed juveniles were located within 1 m of the river margin in water depths of less than 0.5 m. These fish may be extremely susceptible to stranding during flow reductions because they may not be able to detect changes in flow and water levels while occupying interstitial spaces in the substrate. At night, however, juvenile salmonids leave the substrate and swim in the water column (Campbell and Neuner 1985; Heggenes et al. 1993; Contor and Griffith, in press), which may make them less susceptible to being stranded during rapid flow decreases.

We tested the hypothesis that the incidence of stranding of juvenile salmonids during the winter would be minimized if downramping is conducted at night, when fish are occupying the water column rather than interstitial spaces in the substrate. Hvidsten (1985) observed that parr of Atlantic salmon *Salmo salar* became stranded during daytime flow decreases in a Norwegian river during winter months because they were hiding among river cobbles. Stranded juvenile rainbow trout *Oncorhynchus mykiss* and Pacific salmon *Oncorhynchus* spp. were also observed after the daytime downramping of the Seton River, British Columbia, on January 17, 1993 (average rate of stage change, 12 cm/h). Visual surveys of exposed unimbedded gravel and cobble bars produced an estimate of 1 fish stranded per 20 m^2 of substrate; most stranded fish were found in the interstitial spaces of the substrate and were not visible from

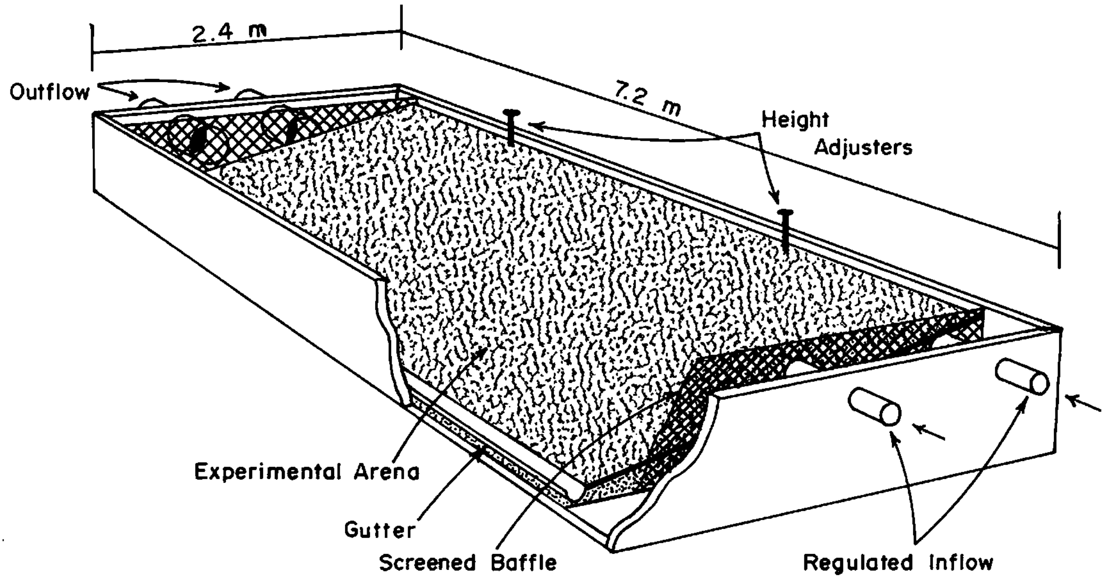

FIGURE 1.—Diagram of the artificial stream channel used for stranding experiments, showing the sloped substrate and refuge gutter on the deep side.

the surface (Bradford, Taylor, and Allan, unpublished data).

We report an experimental study of the stranding of juvenile coho salmon *O. kisutch* and rainbow trout under simulated winter conditions. In addition to time of day, we varied the downramping rate, gravel bar angle, and presence of cover to identify the factors that lead to stranding during controlled flow reductions. Our results, the first experimental data on winter stranding, may help in the development of operating guidelines for hydroelectric facilities.

Methods

We conducted experiments during February and March 1993 in an artificial stream channel located at the Canada Department of Fisheries and Oceans' Cultus Lake Laboratory, 100 km east of Vancouver, British Columbia. The channel was 2.4 m wide, 7.2 m long, and 0.6 m deep (Figure 1). Screened baffles separated the channel into the experimental arena, and head and tail tanks (0.4 m long). Mounted in the experimental arena was a wood and metal frame with chain-link fencing stretched over the top. A polyethylene sheet was placed over the fencing; this formed the base substrate for the simulated river bar. On one side of the channel, 11-mm steel nuts were mounted in the frame; threaded rods extended from the nuts to the bottom of the channel so that the angle of the simulated bar could be manipulated by screwing the rods up or down. At the lower side of the bar we hung a plastic rain gutter below the screen to serve as a refuge for fish during experimental dewaterings.

Most of the trials used a gravel substrate consisting of a single layer of river stones (mean diameter, 6.5 cm; SD, 1.7 cm) on the wire and plastic frame. We also evaluated the effect of increased habitat complexity on stranding behaviour. We created three shallow pools (≈80 cm in diameter) in the substrate by removing some of the supports under the chain-link fence panels. When the channel was completely dewatered, about 5 cm of water remained in the pools. We placed sandbags at the upstream edge of each pool to deflect the current, and additional sandbags were placed at the downstream side. A piece of plywood (80 × 100 cm) was positioned over the pool to create shade, and a mass of tree branches was added to the pool to create the habitat complexity that has been found to attract overwintering juveniles (McMahon and Hartman 1989). Pea gravel and sand were used as substrate in the pools.

Water for the channel was pumped from Cultus Lake at a depth of 150 m and remained between 3.5 and 4°C throughout the experiments. Two pipes (10 cm diameter) supplied water to the head tank, and hand-operated valves controlled the flow. The maximum flow rate was about 50 L/s. We were able to develop a schedule of valve handle turns that allowed the water depth in the stream channel to be regulated at 5-mm intervals. When the bar was set to a slope of 2%, the maximum water depths ranged from 4 cm on the shallow edge of the bar to 15 cm at the deep side; maximum water velocities, measured with a Marsh–McBirney flowmeter, ranged from 10 cm/s to 25 cm/s from the shallow to the deep sides. With the bar set to a slope of 6%, water depths ranged from 4 to 18 cm and velocities from 8 to 18 cm/s.

Coho salmon used in most of the experiments were the offspring of adults collected in fall 1991 from the Chilliwack River, British Columbia. The mean fork length (±SD) of these subyearlings was 88.4 ± 10.0 mm. Additional trials were conducted with wild coho salmon juveniles collected by minnow trap in mid-February from Post Creek, a tributary of the Chilliwack River. These fish were smaller than the hatchery fish (58.3 ± 5.6 mm). Rainbow trout underyearlings from the Blackwater River (1992 brood, 89.8 ± 11.0 mm), supplied by the British Columbia Ministry of Environment's Fisheries Branch hatchery at Abbotsford, were also used. About 350 fish of each species were kept in fiberglass troughs at the Cultus Lake Laboratory in the same water used for the experiments; fish were fed standard pellet food at approximately maintenance level ration.

For each trial we set the flow to the maximum level and added 50 fish of one species to the channel. The fish were left undisturbed for a 1–1.5-h acclimation period. Netting was strung over the stream to diffuse bright sunlight during the daytime trials. After the acclimation period, downramping began; we defined ramping rate as the rate change in water depth (cm/h) measured at the deep side of the gravel bar. As the water reached its lowest levels the cobbles were searched for stranded fish, starting from the high side of the bar. The search of the cobble area was completed within 5–10 min, so few fish died from suffocation. Fish found in the refuge gutter were counted as having survived, and were removed. At the end of each trial a second group of 50 fish was removed from the stock group for the next trial, and the first group was returned to the holding tank. Because of their limited availability, fish were reused during the experiment; however, they were chosen randomly for any individual trial. We ran night trials from 1800 to 0100 hours. Overhead fluorescent lighting in the laboratory compound illuminated the stream channel to the approximate level of moonlight. Lights used for the operation of the valves were shielded from the channel during the experiments,

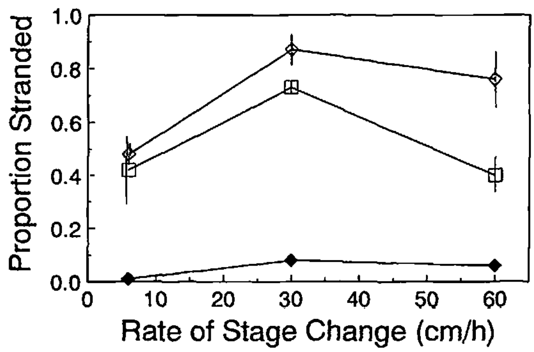

FIGURE 2.—Proportion of juvenile coho salmon stranded on a gravel substrate during day (◇) and night (◆) dewatering trials as a function of the ramping rate (2% bar slope). Also plotted are results for daytime trials conducted on a 6% bar slope (□). Data are means ± 1 SE; N = 3 for daytime trials and 2 for nighttime trials.

and portable lights and flashlights were used to search for stranded fish at the end of each trial.

The experimental design was in part limited by time and the availability of fish. First, we ran trials with hatchery-reared coho salmon and rainbow trout on a 2% slope at ramping rates of 6, 30, and 60 cm/h during the day and night. Some additional trials were run during the daytime over a 6% slope with hatchery-reared coho salmon. Trials with wild coho salmon were conducted at the 30 cm/h rate because of a limited supply of fish. The stream substrate was then modified to include pools, and trials were run at 6 and 30 cm/h (day and night) with hatchery-reared coho salmon and rainbow trout. We ran two or three replicates at each factor level; the sequence of replicates was randomized among the ramping rates.

The proportion of fish stranded was transformed as $\sin^{-1}\sqrt{p}$ before analysis. Analysis of variance (ANOVA), as implemented by the GLM procedure of SAS (SAS Institute 1988), with all factors treated as fixed, was used to test for differences between factor levels.

Results

Hatchery-Reared Coho Salmon

On the plain cobble substrate (2% slope), significantly more juvenile coho salmon were stranded during the day than at night (ANOVA: F = 34.6; df = 2, 14; $P < 0.001$; Figure 2). Fewer fish were stranded at the slowest ramping rate (6 cm/h versus 30 and 60 cm/h, P = 0.014). Stranding was less frequent on the 6% than the 2% bar slope during the daytime ($P < 0.05$, Figure 2).

Stranding rates were much lower for the night-

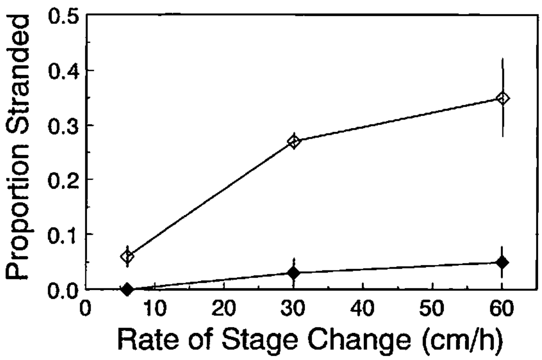

FIGURE 3.—Proportion of juvenile rainbow trout stranded on a gravel substrate during day (◇) and night (◆) dewatering trials as a function of the ramping rate (2% bar slope). Data are means ± 1 SE; N = 3 for daytime trials and 2 for nighttime trials.

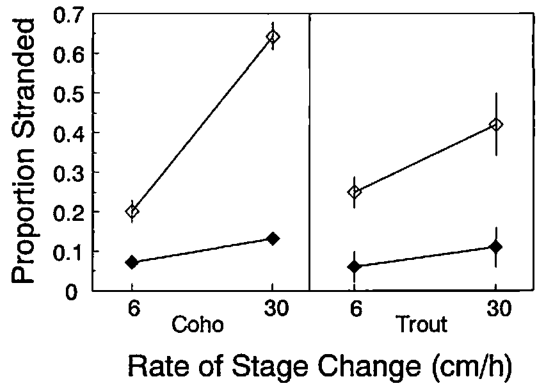

FIGURE 4.—Stranding of juvenile coho salmon and rainbow trout during day (◇) and night (◆) trials when pools and cover were added to the stream channel (2% slope). Data are means ± 1 SE; N = 3 for daytime trials and 2 for nighttime trials.

time trials, averaging less than 10% across all ramping rates. During the day, nearly all juvenile coho salmon sought cover in the substrate by burrowing down to the plastic sheet below the rocks. Fish concealed in the substrate did not respond to decreasing water levels and velocities until their backs or tails became exposed to the air. By then it was difficult for them to swim up and escape, and their success in avoiding stranding depended on the ability of an individual to move among the cobbles to deeper water. Cover-seeking behaviour during daytime was not a function of the length of the acclimation period, because in some cases we introduced fish on the previous night and found that nearly all fish were concealed in the substrate after the sun rose the following morning. At night most fish swam freely in the water column and did not seek cover among the cobbles. Fish were usually able to escape from very shallow water, moving to the deepest part of the channel as water levels receded.

Wild Coho Salmon

The difference in day and night behaviour for wild coho salmon was similar to that found for the hatchery-reared fish. At a ramping rate of 30 cm/h (2% bar slope, cobble substrate), an average of 83% and 25% of wild coho salmon were stranded during the day and night, respectively; these results were not significantly different from those for hatchery fish (F = 0.72; df = 1, 5; P = 0.44).

Rainbow Trout

Similar to our results for coho salmon, significantly fewer rainbow trout were stranded at night than during the day (F = 44.2, df = 1, 8; P = 0.0002; Figure 3), and the incidence of stranding was lower at ramping rates of 6 cm/h compared with 30 or 60 cm/h (F = 10.3; df = 2, 8; P = 0.006). During the day, rainbow trout were less likely to be stranded than coho salmon (F = 35.1; df = 1, 10; P < 0.001), however, there was no significant difference between the two species at night (F = 2.75; df = 1, 6; P = 0.14).

Our observations of rainbow trout during the stranding trials indicated that although they were closely associated with the substrate during the day, they were better able to sense retreating water levels and extricated themselves from the substrate earlier than coho salmon. As a result, rainbow trout were more likely than coho salmon to successfully move to deeper water and avoid stranding.

Effect of Cover

When habitat complexity in the form of small covered pools was added to the stream channel, the incidence of stranding for juvenile coho salmon during the day was reduced from that with the substrate without pools (F = 19.3; df = 1, 7; P = 0.003; Figures 2, 4). The incidence of stranding with the pools was significantly lower at 6 cm/h than at 30 cm/h (F = 68; df = 1, 6; P = 0.0002; Figure 4). During the day, we observed that when the fish were added to the channel some hid in the cobble, but most sought refuge in the covered pools. At the faster dewatering rate (30 cm/h), 59% of the fish that were stranded were found in the pools, but when dewatering occurred at 6 cm/h, most fish left the pools and swam directly to deeper water and the refuge gutter. Of the fish that were stranded, only 27% were found in the pools. At night, fish were swimming freely throughout the channel, and the incidence of stranding was much lower than during the day (F = 118; df = 1, 6; $P < 0.0001$).

The addition of pools increased the likelihood of stranding for rainbow trout (Figures 3 and 4; F = 20.8; df = 1, 15; P = 0.0004), and the overall incidence of stranding with the pools was similar to that of coho salmon (F = 2.98; df = 1, 8; P = 0.12). Stranding was more prevalent during the day than at night (F = 19.4; df = 1, 7; P = 0.003; Figure 4), and there was a small increase in stranding at the faster dewatering rate (F = 4.21; df = 1, 7; P = 0.08).

Discussion

Our results suggest that losses of juvenile coho salmon and rainbow trout from stranding in winter months will be reduced if downramping is conducted at night. A slower rate of stage change will reduce the incidence of stranding, but even at the slowest rates, stranding will still be greater during the day than at night. This was true for both the gravel substrate and the combination of gravel and covered pools.

The proportion of fish stranded in our experiments may not be directly applicable to the field because of limitations of our experiments. First, the presence of low levels of illumination near our stream channel may have prompted more fish to remain concealed during the night (Contor and Griffith, in press), which potentially increased the rate of stranding during the nighttime trials. Second, the use of a single layer of relatively small stones as the substrate in our trials may have resulted in concealed fish being located closer to the surface of the substrate than in natural streambeds, where fish have been observed below the first layer of cobbles, 10–15 cm from the substrate surface (Edmundson et al. 1968, Heggenes et al. 1993). The incidence of stranding in the field may be higher if fish are located well below the surface and if the lack of response to decreasing flows that we observed can be extrapolated to the field.

We cannot distinguish whether the difference in stranding propensity between the rainbow trout and coho salmon used in our experiments was a real difference between the species because the fish we used were from different rivers, and were raised in different hatcheries (Taylor 1988). Our results might also be biased because we used hatchery-reared fish in most of the trials. However, the general behaviour of hatchery-reared fish in our stream channel was consistent with observations of wild salmonids in the field (e.g., Campbell and Neuner 1985; Hillman et al. 1987; Heggenes et al. 1993). Furthermore, the few data we obtained from wild coho juveniles were similar to those collected from the hatchery-reared fish.

The effect of time of day on the susceptibility of juvenile salmonids to stranding is much clearer in our results than in experimental and field observations made on newly emerged fry in the spring and summer. For example, Bauersfeld (1978) documented considerable stranding of chinook salmon fry during night downramping on the Cowlitz River, Washington, in April, and Hamilton and Buell (1976) suggested that night ramping should be avoided because fry are often in shallow waters. In contrast, Woodin (1984) and Olson and Metzgar (1987) found fewer stranded salmon fry during night ramping trials conducted in March and April, however, the latter authors noted that fry of steelhead (anadromous rainbow trout) were more likely to be stranded at night than during the day. Finally, Monk (1989) was unable to detect an effect of time of day in her laboratory experiments with fry of chinook salmon *Oncorhynchus tshawytscha* and steelhead during the summer. The striking differences we found are likely due to much greater diel shift in winter behaviour of juvenile salmonids compared with their behavior in spring or summer.

The stranding of juvenile coho salmon was reduced when the slope of the bar was increased. Once a fish decided to move from its hiding place in the gravel, it was more likely to move to the deeper part of the channel on the steeper bar than on the 2% bar, where there was less contrast in water depth in the vicinity of the hiding area. Monk (1989) and Bauersfeld (1978) also found stranding was reduced on gravel bars with slopes greater than 4%. Stranding will probably also be less frequent in streams with very embedded substrates because fewer fish will be able to find daytime hiding locations (Chapman and Bjornn 1969; Hillman et al. 1987).

We found the incidence of stranding was greater at ramping rates of 30 cm/h than at 6 cm/h. Similar rates of stranding were observed at 60 cm/h and at 30 cm/h, with the exception of the daytime trials conducted with a 6% bar slope, where the incidence of stranding decreased at the highest ramping rate. We have no explanation for this result, and suggest that the combination of steep bar slope and fast rate of dewatering may have elicited a stronger escape response for fish hiding in the substrate. Monk (1989) also found no effect of stage change on stranding at rates of 30 cm/h or higher (Monk's rates were 42–240 cm/h). The only published field data on winter stranding are provided by Olson and Metzgar (1987), who found few juveniles stranded during trials at rates of 10–15 cm/h in the Sultan River, Washington. They may have underestimated the incidence of stranding by searching only the surface of the dewatered areas.

The strong association between juvenile coho salmon and pools with cover provided by rootwads or logs during winter is well documented (Bustard and Narver 1975; McMahon and Hartman 1989; Nickelson et al. 1992). A critical concern for flow ramping is whether juveniles will remain in these pools as water levels recede. We found that during daytime trials when the rate of dewatering was slow, fish left the pools and moved towards the deeper part of the channel and were therefore less likely to be trapped in the pool. Stranding may be more of a problem in deeper pools or side channels, where fish might not be stimulated to leave cover by receding water levels; this is a subject for further research.

Our results support the hypothesis that juvenile salmonids may be extremely vulnerable to stranding during daytime flow reductions when water temperatures are low enough to initiate daytime concealment behavior. These findings should be verified in the field by controlled trials that include the careful visual examination of interstitial areas of the substrate for stranded fish.

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