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## Use of Electromyogram Telemetry to Assess Swimming Activity of Adult Spring Chinook Salmon Migrating Past a Columbia River Dam

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**Abstract.**—Electromyogram (EMG) radiotelemetry was used to estimate the swim speeds of spring Chinook salmon *Oncorhynchus tshawytscha* migrating upstream past a Columbia River dam. Electrodes from EMG transmitters were surgically implanted in the red muscle of fish captured at Bonneville Dam, and output from the tags was calibrated to defined swim speeds for each fish in a tunnel respirometer. The fish were then released below Bonneville Dam and radio-tracked as they migrated through the tailraces, fishways, and forebays of the dam. On average, swim speed was significantly higher when tagged salmon were moving through tailraces than when they were moving through other parts of the dam. Specifically, swim speeds for fish in tailraces (106.4 cm/s) were 23% higher than those of fish in fishways (84.9 cm/s) and 32% higher than those of fish in forebays (80.2 cm/s). Swim speeds were higher in fishways during the day than during the night, but there were no diel differences in swim speeds in tailraces and forebays. During dam passage, Chinook salmon spent the most time in tailraces, followed by fishways and forebays.

Pacific salmon *Oncorhynchus* spp. are known for their long spawning migrations. The freshwater stage of this upstream migration marks a change in the intake and allocation of energy. Instead of actively feeding and growing as they did during their oceanic phase, the salmon cease feeding once in freshwater and mobilize some of their energy reserves to gonad development. They use a substantial amount of their remaining energy reserves to fuel locomotory processes required for upstream migration (Greene 1926; Brett 1995).

Much research on the behavior of adult Pacific salmon during their spawning migrations has been conducted (see reviews by Dauble and Mueller 2000 and Lucas and Baras 2001). Within the Columbia River basin, where hydroelectric development has significantly altered the migration corridor, thousands of adult salmon are implanted with radio transmitters during most years and their locations are tracked during their spawning migration (Boggs et al. 2004; Keefer et al. 2004a). These studies have shown that fish can be delayed at or fall back over dams and can have difficulty finding entrances to fishways. Delay of adult salmonids at dams can last for hours or days and can expose fish to increased predation by marine mammals,

harvest by anglers, or mortality due to other sources (Dauble and Mueller 2000). The inability of fish to locate fishway entrances is a type of delay and results from the numerous sources of water discharge in the dam tailraces that act as attraction flow and confuse salmon (Bjornn et al. 1995). Fallback occurs when salmon ascend dams successfully but later end up downstream of the dam, requiring a repeat ascent (Liscom et al. 1985; Swan et al. 1994; Boggs et al. 2004). For example, from 1996 to 2001, at least 22% of radio-tagged spring and summer Chinook salmon *O. tshawytscha* that passed a dam fell back over at least one dam while migrating up the Columbia and Snake rivers (Boggs et al. 2004).

Delay and fallback at dams may deplete the limited energy reserves of upstream-migrating adult salmonids, perhaps leaving them with insufficient reserves for gonad development and successful spawning. However, little is known about the behavior associated with dam passage in adult salmonids. Thus, to address this information gap, we conducted a 1-year study based on the use of electromyogram (EMG) radiotelemetry to estimate the swim speed of Chinook salmon passing Bonneville Dam, the lowermost dam on the Columbia River. Although EMG telemetry has been used to examine the behavior and energy use of Pacific salmon in free-flowing rivers (Hinch et al. 1996; Hinch and Rand 1998; Rand and Hinch 1998; Hinch and Bratty 2000; Brown and Geist 2002), this technology has not

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been used to estimate salmon swimming behavior associated with dam passage. Specifically, our objectives were to (1) describe the movements and behavior of adult spring Chinook salmon as they approached and passed the dam and (2) estimate the swim speed of spring Chinook salmon as they passed through the tailraces, fishways, and forebays of the dam. Information on the activity of salmon as they migrate through a dam should aid managers in modifying or deriving new fish protection measures to improve recovery of populations listed under the federal Endangered Species Act.

### Methods

*Study site.*—This study was conducted from 12 April to 1 July 2001 at Bonneville Dam on the Columbia River. Bonneville Dam was constructed in 1938 and is located at river kilometer 235 above the Pacific Ocean. During the study, mean daily discharge was 3,784 m<sup>3</sup>/s (SD = 562) and daily averages ranged from approximately 2,500 to 5,000 m<sup>3</sup>/s. The Pacific Northwest was experiencing a drought in 2001, and these flows were much lower than the 10-year average of 8,141 m<sup>3</sup>/s. The majority of water discharged past Bonneville Dam is directed through two powerhouses and one central spillway. Flow in these areas varies depending on operation of the dam. In 2001, mean daily flows were much higher through powerhouse 2 (2,728 m<sup>3</sup>/s; SD = 395) than through powerhouse 1 (277 m<sup>3</sup>/s; SD = 278) or over the spillway (595 m<sup>3</sup>/s; SD = 644). Spillway flows were between 1,382 and 1,416 m<sup>3</sup>/s during 36% of the study period and were between 48 and 68 m<sup>3</sup>/s during 58% of the study period. During the remaining 4 d of the study period, flows over the spillway were between 400 and 1,416 m<sup>3</sup>/s. Water temperatures increased almost linearly over the study period, from about 9°C in April to 18°C in July.

*Fish capture and tagging.*—Adult spring Chinook salmon were captured at Bonneville Dam between 12 April and 8 June 2001. These fish had a mean weight of 6.0 kg (range = 4.0–8.8 kg; SD = 0.9) and a mean fork length of 76 cm (range = 68.0–85.5 cm; SD = 3.1). Fish were captured in a trap that was located in the lower portion of the Washington-shore fishway. While the trap was in operation, all fish swimming up this fishway were diverted into sampling facilities located in an adjacent building. Fish entering the sampling facilities could be diverted into a large, aerated holding tank containing anesthetic (clove oil, 25 mg/L; Keefer et al. 2004b). After a fish was anesthetized, it was gastrically implanted with a coded positional radio transmitter by personnel from the University of Idaho (see Keefer et al. 2004b for methods). These coded transmitters were 16 mm in diameter and 83 mm long,

weighed 29 g in air, and had an estimated lifetime of 1,013 d (Lotek Engineering, Inc., Ontario, Canada; Model MCFT 7A). These transmitters allowed us to use the existing and extensive arrays of antennas and receivers to track our fish throughout the Columbia River basin. After insertion of the coded transmitter, fish were carried in a wet sling to holding facilities in an adjacent building. The fish were out of the water for only about 20–30 s. Since fish were allowed to recover for several days afterward, it is unlikely that this brief transportation period influenced our results. Three fish were placed in each of four covered circular tanks receiving fresh river water. The tanks were 1.5 m in diameter and had flow rates of about 6–7 L/min and a water depth of about 50 cm.

Shortly after capture, these same fish were surgically implanted with EMG transmitters (in addition to the coded transmitter) by means of methods similar to those of Hinch et al. (1996); see Cooke et al. (2004) for a review of EMG telemetry. Briefly, EMG transmitters detect and quantify electrical activity of the swimming musculature. The electrical impulses emitted by the muscle are detected and stored, and when a factory-set threshold ( $\mu$ V) is reached a radio pulse is transmitted. Therefore, increasing muscle activity results in an increase in the pulse rate of transmitted radio signals (i.e., the time between the radio transmissions decreases; see Kaseloo et al. 1992). Electromyogram signals can then be correlated with swim speed. Following implantation of EMG transmitters, fish were allowed 48 h for recovery prior to the calibration of EMG signals to swim speed.

To establish the relation between EMG signals and swim speed, each fish was made to swim at defined speeds in a 500-L Blazka respirometer by means of methods similar to those of Geist et al. (2003). First, a single fish was netted from a holding tank and placed in a large cooler with water and clove oil at a concentration of 50 mg/L. To facilitate removal of fish from the large holding tanks, a light dose (30 mg/L) of clove oil was added to the tank prior to netting. When the fish in the cooler was quiescent, we logged at least 30 signals from the EMG tag by use of a telemetry receiver. These signals were assumed to represent muscle activity of a fish at rest. Immediately after these signals were collected, we transferred the fish to the partially filled swim tunnel. The tunnel was closed and filled completely with water, and the fish were allowed to acclimate for 1 h at a velocity of 30 cm/s. After acclimation, fish were forced to swim at velocities ranging from 30 to 230 cm/s in 20-cm/s increments while we simultaneously logged the EMG signals. Typically, fish swam for only a few minutes at each velocity to allow collection of valid signals, and not all

fish swam at each velocity. A simple linear regression model was used to describe the relation between swim speed and mean EMG pulse interval for each individual. All of the models we derived had coefficient of determination ( $r^2$ ) values of over 0.90. These models were then used to estimate the swim speeds of the same individual after its release. Subsequent to this calibration of the EMG tag, fish were released from 9.5 to 11.0 km downstream from Bonneville Dam on either the Washington or Oregon shoreline. Fish were released during daylight between 18 April and 10 June 2001.

*Electromyogram radiotelemetry.*—After release, as fish approached and passed Bonneville Dam, EMG signals from individual fish were logged on up to 19 telemetry receivers (Lotek Engineering) and antenna arrays located around the dam. Arrays of up to eight antennas were used to receive signals from fish that were located in the tailraces, fishways, or forebays. We designed, set up, and tested our antenna arrays to maximize signal reception in the local area in which they were placed and to minimize logging of signals from other areas of the dam. In one specific area of the dam forebay, we used an array of underwater antennas connected to a computer to log EMG signals (Grant System Engineering, Ontario, Canada; Multiprotocol Integrated Telemetry Acquisition System). Eighteen underwater dipole antennas were placed along the front of the spillway, and 32 balanced loop vee underwater antennas (dB Laboratories, Gretna, Nebraska; Model LVB-150-B) were placed just offshore of Cascade and Bradford islands. In addition to all of our fixed antenna arrays, personnel on foot and in trucks monitored EMG signals from fish as they approached and passed the dam. By using a combination of fixed and mobile radio-tracking, we collected EMG signals 24 h/d during our study.

In addition to the receivers that monitored EMG signals, several other receivers monitored signals from coded positional radio transmitters. Data from these transmitters indicated when fish entered and exited the fishways.

*Data analysis.*—Individual fish EMG data stored in the receivers was downloaded to a portable computer on a regular schedule, transferred to compact disc, and taken back to the laboratory, where the data were imported to spreadsheets. After data were proofed to remove signals associated with noise or other anomalies, a swim speed was estimated from each EMG signal by use of the regression models derived from the prerelease calibrations. When EMG signals indicated swim speeds higher than those used during calibrations, the speeds were designated as the highest

calibrated swim speed. Therefore, swim speeds may be slightly underestimated.

Because data on swim speeds were normally distributed and variances did not differ, we used a two-factor analysis of variance (ANOVA) to determine whether mean swim speed differed among fish in the three areas (tailrace, fishway, and forebay) of the dam and between genders (male and female). For data that were not normally distributed, such as the time fish spent in each area, we used Kruskal–Wallis tests to assess differences in medians among fish in each area.

We compared mean swim speeds from fish migrating during the day and the night in tailraces and forebays using a two-factor ANOVA. For this analysis, data from twilight periods were excluded because they represented a small proportion of the diel period and because they might dilute the contrast effects of maximum darkness versus full daylight. Within each general area (i.e., tailraces or forebays), one factor controlled for specific location (powerhouse 1, powerhouse 2, or spillway) and a second factor controlled for day and night. Unless otherwise stated, the significance level  $\alpha$  for all tests was 0.05.

For comparisons of swim speed to the estimated critical swim speed ( $U_{crit}$ , i.e., a measure of prolonged swimming performance) of fish, a mean  $U_{crit}$  of 154.7 cm/s was used (Geist et al. 2003). This value was derived from the  $U_{crit}$  of 22 adult spring Chinook salmon tested during 2000 as a different aspect of this study. The mean size of these fish was 75.5 cm (range = 69–82 cm), and fish were tested in 12.5°C water. Fish were allowed to acclimate at a water velocity of 30–50 cm/s and then swam at 75 cm/s for 30 min; thereafter, water velocity was increased by 25 cm/s every 30 min until fish became fatigued.

## Results

In total, 96 adult spring Chinook salmon were implanted with EMG transmitters and released below Bonneville Dam. Electromyogram signals were logged from 85 fish (89% of the total released); 76, 81, and 45 of these fish were detected in the tailraces, fishways, and forebay, respectively. Most fish ( $N = 79$ , or 82% of the total) passed through the fishways and the dam successfully. Two fish entered fishways but did not successfully pass the dam. Two fish passed the dam but were not detected in the fishways; however, they were detected in the navigation lock and probably passed the dam via this route. A mean of 8,858 (range = 59–78,072) EMG signals was received from each implanted spring Chinook salmon as the fish migrated past Bonneville Dam. A mean of about 2,578 (range = 59–22,391) EMG signals was received from fish moving through the tailraces; 6,142 (range = 168–

73,146) signals were received from fish swimming in the fishways, and 1,346 (range = 35–48,490) signals were logged from fish passing through the forebays.

The mean swim speed of fish moving through tailrace areas was significantly higher than the swim speed of fish moving through fishways or forebays (Table 1; Figure 1). The mean ( $\pm$  SE) swim speed of spring Chinook salmon located in the tailraces ( $106.4 \pm 4.2$  cm/s) was 23% faster than that of fish moving through fishways ( $84.9 \pm 4.2$  cm/s) and 32% faster than that of fish migrating through forebays ( $80.2 \pm 6.2$  cm/s). Although the mean swim speed of fish moving through fishways was slightly higher than that of fish in the forebays, this difference was not significant. Overall, swim speed exceeded the  $U_{crit}$  of spring Chinook salmon (Geist et al. 2003) 26, 17, and 13% of the time for fish moving through tailraces, fishways, and forebays, respectively.

On average, the amount of time spring Chinook salmon spent in the tailraces was significantly longer than the times spent in other areas (Table 1). The median residence time for fish in the tailraces (21.1 h) was almost four times higher than that for fish moving through fishways (5.0 h) and over 30 times higher than the time spent in forebays (0.7 h). In addition, the median amount of time fish spent in fishways was significantly longer than the residence time of fish in forebays.

There were differences in swim speeds among fish in the three tailraces, but not among fish in the three forebays (Table 1). Within the tailraces, the highest swim

TABLE 1.—Mean swim speed (SE) of spring Chinook salmon as they passed tailraces, fishways, and forebays of Bonneville Dam, April–June 2001. The median amount of time spent in the three main areas is also shown. Abbreviations are as follows: *N* = number of fish; BL = body length. Variables in the same column with a capital letter in common showed no significant ( $P > 0.05$ ) differences among major areas (tailraces, fishways, and forebays). Variables in the same column with a lowercase letter in common showed no significant differences among particular tailraces or forebays.

Area	<i>N</i>	Swim speed		Time (h)
		cm/s	BL/s	
<b>Tailraces</b>				
Powerhouse 1	22	108.0 (9.1) yx	1.43 (0.1)yx	
Spillway	41	91.5 (4.1) y	1.21 (0.1) y	
Powerhouse 2	49	119.2 (6.5) zx	1.58 (0.1) zx	
Combined	76	106.4 (4.2) Z	1.40 (0.1) Z	21.1 Z
<b>Fishways</b>				
Combined	79	84.9 (4.2) Y	1.13 (0.1) Y	5.0 Y
<b>Forebays</b>				
Powerhouse 1	35	82.3 (7.4) z	1.09 (0.1) z	
Spillway	10	89.3 (13.9) z	1.17 (0.2) z	
Powerhouse 2	13	70.6 (10.8) z	0.96 (0.2) z	
Combined	45	80.2 (6.2) Y	1.06 (0.1) Y	0.7 X

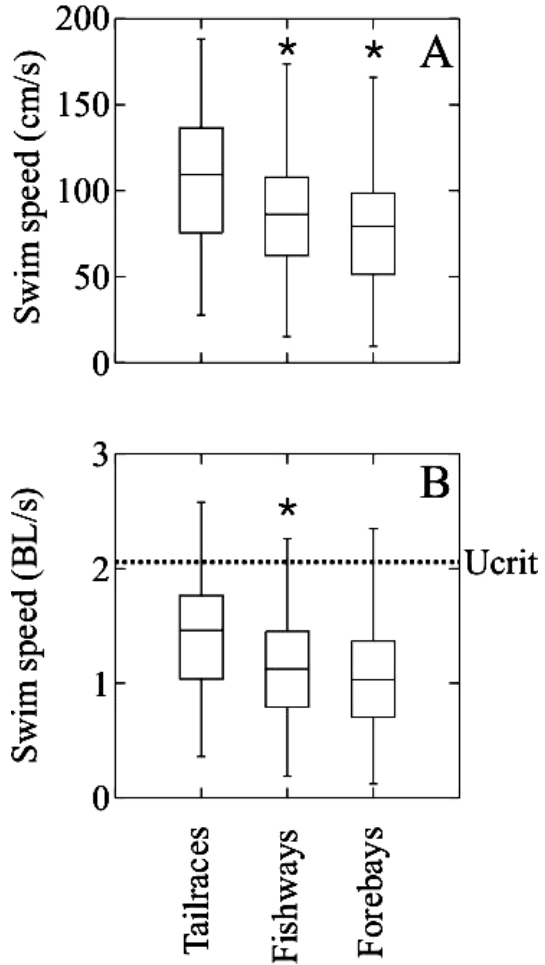


FIGURE 1.—Box plots of mean swim speed in (A) centimeters per second and (B) body lengths (BL) per second for 85 radio-tagged spring Chinook salmon in Bonneville Dam tailraces, fishways, and forebays during April–June 2001. The lower and upper boundaries of the boxes indicate the 25th and 75th percentiles of the data, respectively, while the lines inside the boxes indicate the medians; outliers (asterisks) are also shown. Whiskers indicate 1.5 $\times$  the interquartile range beyond the box. The critical swim speed ( $U_{crit}$ ) measured on Columbia River spring Chinook salmon in 2000 (Geist et al. 2003) is shown for reference.

speed was observed in the tailrace of powerhouse 2. Mean swim speed ( $\pm$  SE) there ( $119.2 \pm 6.5$  cm/s) was 31% faster than that recorded in the tailrace of the spillway ( $91.5 \pm 4.1$  cm/s; significantly different) and 10% faster than values in the tailrace of powerhouse 1 ( $108.0 \pm 9.1$  cm/s; not significantly different). There was no significant difference in the swimming speeds through the tailraces of powerhouse 1 and the spillway. Interestingly, the daily average discharge through

powerhouse 2 was consistently higher than those through powerhouse 1 and over the spillway at all times during the study. There was no significant difference in the swim speed of Chinook salmon among the three forebays (Table 1).

The influence of diel period on swim speed depended on area (Figure 2). The mean  $\pm$  SE swim speed of spring Chinook salmon passing through fishways was 30% (and significantly) higher during the day ( $84.9 \pm 3.8$  cm/s) than during the night ( $65.4 \pm 11.8$  cm/s). There was no significant difference between mean swim speed in tailraces between day ( $109.0 \pm 4.5$  cm/s) and night ( $87.6 \pm 7.1$  cm/s). In the

forebays, there was also no significant difference in swim speed between day ( $88.0 \pm 6.5$  cm/s) and night ( $62.4 \pm 32.0$  cm/s).

The sex of the fish did not make a significant contribution to the differences in swim speed in any of the three main parts of the dam (tailraces, fishways, or forebays).

### Discussion

This study showed that adult spring Chinook salmon passing Bonneville Dam in 2001 spent more time and swam harder in the tailrace areas than in fishways or forebays. However, mean swim speed did not differ between fishways and forebays. The main difference between fishways and forebays was that it took much longer (7.14 times longer) for fish to pass fishways than forebays.

This is the first study examining the swim speeds of salmon passing a large hydroelectric dam. Consequently, comparative data at hydroelectric facilities do not exist. The higher swim speed in tailraces is probably the result of higher water velocities present in tailraces than in other areas. The high swim speeds in tailraces may be partially due to a lack of resting areas along the approach to the fishway entrances. In comparison, the fishways themselves are designed to allow fish to rest between encounters with high-velocity areas. Standen et al. (2002) found that energy use by pink salmon *O. gorbuscha* was higher in constricted reaches of the Fraser River, British Columbia, that had high current velocity and complex flow patterns. These sections may be similar to the tailraces, where we found swim speeds to be highest. These high swim speeds would be reflected in higher energy use in tailraces.

There was no difference in the swim speeds of Chinook salmon among the three forebays; however, fish behavior differed among the different tailraces. The only difference was between the tailraces of powerhouse 2 and the spillway: the swim speed of Chinook salmon was higher in the tailrace of powerhouse 2 than in the spillway tailrace. This behavior is not surprising, because the daily average discharge through powerhouse 2 was higher than that through powerhouse 1 or the spillway. In fact, there was very little discharge over the spillway for a majority of the study period. However, there was also no significant difference in fish swim speeds between the tailraces of the two powerhouses, despite the much higher water discharge through powerhouse 2.

Diel differences in swim speed of migrating spring Chinook salmon were seen in fishways but not in the tailraces or forebays. Other studies have also shown that activity in fishways decreases during the night. For example, some researchers have found that relatively

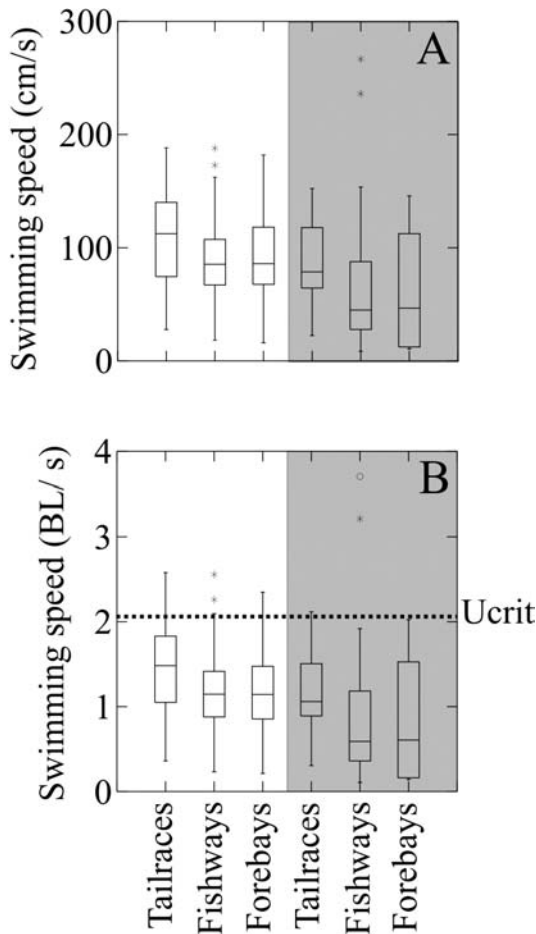


FIGURE 2.—Box plots of swim speed in (A) centimeters per second and (B) body lengths (BL) per second for radio-tagged spring Chinook salmon during the day (unshaded half of each figure) and the night (shaded half) at Bonneville Dam fishways, tailraces, and forebays during April–June 2001. Whiskers indicate 1.5 $\times$  the interquartile range beyond the box, and asterisks indicate outliers. See Figure 1 for additional details.

few migrating fish (e.g., Atlantic salmon *Salmo salar* and brown trout *S. trutta*) ascend fish ladders at dams or attempt to pass waterfalls during the night (Gowans et al. 1999).

No relation was found between the sex of the fish and swim speed for the spring Chinook salmon as they passed Bonneville Dam. This is contrary to the findings of Hinch and Rand (1998), who suggested that female sockeye salmon *O. nerka* migrating in the Fraser and Nechako rivers, British Columbia, generally swam more slowly and used less energy per unit distance than did males. Hinch and Rand (1998) hypothesized that female sockeye salmon were more energetically efficient despite generally having the same sizes and shapes (i.e., had identical length–mass relationships) as males; they suggested, however, that males may experience more drag due to the development of a humped back and kype. In contrast, Standen et al. (2002) did not find a difference in energy use between male and female pink salmon migrating up the Fraser River; however, they did suggest that differences between the sexes may be more apparent in areas of difficult passage.

This study estimated the swimming speeds of spring Chinook salmon migrating past a hydroelectric dam. Some of our data indicated that fish swim at relatively high speeds and may therefore have recruited white muscle. White muscle uses energy through anaerobic pathways and is less efficient than aerobic red muscle. Salmon begin using anaerobic swimming at speeds around 59–80% of  $U_{crit}$  (Geist et al. 2003; Lee et al. 2003). When fish swim faster than this, anaerobic energy use may be considerable. Lee et al. (2003) suggested that when interior stocks of migrating wild salmon were swimming at  $U_{crit}$ , they used approximately 50% as much energy via anaerobic pathways as was used via aerobic pathways. Anaerobic energy use could be substantial for fish migrating up the Columbia River, since spring Chinook salmon passing Bonneville Dam swam at speeds greater than  $U_{crit}$  about 26, 17, and 13% of the time when moving through tailraces, fishways, and forebays, respectively. The fish examined during this study swam at speeds over  $U_{crit}$  for a greater percentage of time than the adult pink salmon and sockeye salmon studied by Hinch et al. (2002). Those authors estimated that pink salmon and sockeye salmon swam at burst speeds 5–10% of the time while migrating upstream in the Fraser River canyon.

Spring Chinook salmon probably used burst swimming more in the tailraces than in other parts of the dam. This is indicated by the high amount of swimming in excess of the  $U_{crit}$ . Burst swimming is used by salmon to pass high-velocity areas (Webb 1995). However, fish are unable to sustain burst swim

speeds for long periods of time. Brett (1995) stated that jumps or bursts of swimming at falls or obstacles in streams probably do not exceed 20–30 s. Similarly, Webb (1995) stated that burst swimming can be maintained for less than about 30 s. Brown and Geist (2002) found that fall Chinook salmon attempting to pass waterfalls used burst swimming for periods of only 20 s at a time on average. Thus, fish may use excess energy and may be delayed at dams if water velocities exceed  $U_{crit}$  for long distances without access to rest areas.

Many studies have examined fishways, but few studies have focused on the tailraces of large dams. Considering the high swim speeds observed and the large amount of time spent in tailraces, additional emphasis should be aimed toward aiding fish through these areas. Fish can spend long periods of time in tailraces searching for entrances to fishways. When attempting to pass hydroelectric dams, Chinook salmon can make up to 30 approaches before successfully entering fishways (Bjornn et al. 1995). Adding structures in tailraces that allow fish to rest as they approach the dam may decrease energy use and delay. Also, these structures could be placed to guide fish toward the entrances to fish ladders. This may be worthy of further study, and EMG telemetry provides a powerful tool for examining behavior of fish in these high-velocity areas.

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