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[Article]

Defining Flow Windows for Upstream Passage of Adult Anadromous Salmonids at Cascades and Falls

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Abstract.—Variations in streamflow at falls and cascades can create transitory barriers to upstream passage of adult anadromous salmonids. In this study, we evaluated the ability of six anadromous salmonids (coho salmon *Oncorhynchus kisutch*, pink salmon *O. gorbuscha*, chum salmon *O. keta*, sockeye salmon *O. nerka*, Chinook salmon *O. tshawytscha*, and steelhead *O. mykiss*) to pass five sets of falls or cascades within Ward Creek, Alaska, a stream regulated by Connell Dam. The study focused on determining suitable instream flow releases to afford passage. Each set of falls was surveyed under three flow conditions (about 0.91, 1.34, and 3.0 m^3/s), and access portals were identified. Using computed stage–discharge relationships and published swimming and jumping criteria, we evaluated the falls barrier potential over a range (0.23–11.33 m^3/s) of flows. Analysis indicated pink salmon and chum salmon would be relegated to the area below the lower two falls. Flows affording passage over all five falls for the other species (excluding Chinook salmon) were defined as "flow windows" and ranged from 0.66 to 3.01 m^3/s. Flow windows varied by species; the narrowest range of acceptable passage flows was found for sockeye salmon, the widest was found for steelhead, and the range for coho salmon was intermediate. Escapement surveys generally confirmed our analysis; pink salmon and chum salmon were only found below the lowermost falls. The flow windows for passage were compatible with a set of instream flow recommendations derived via a PHABSIM-based study but were incompatible with the highest flow recommendation based on the method of Tennant (1976). Care must be taken when evaluating instream flow needs to ensure that all flow-sensitive factors are considered.

Upstream movements of adult salmonids can be spatially and temporally affected by variations in streamflow that can alter localized hydraulic and physical conditions at falls and cascades, rendering them transitory barriers to passage. Stuart (1964), Bjornn and Reiser (1991), and Heard (1991) have all reported the effects of varying flows in streams on the timing of upstream movements of adult salmonids. In natural systems, salmonid populations have evolved and adapted to seasonal patterns of flow that are specific to a watershed, so the timing of upstream migrations generally corresponds to periods when flow and water quality (primarily temperature) are biologically and bioenergetically advantageous (McKeown 1984; Burgner 1991; Quinn 2005). In these systems, when hydrological conditions conducive to fish passage do not coincide with the arrival of adult fish, short-duration migrational delays can occur until the return of suitable flow conditions.

In streams regulated by dams or other control structures, the amount of water allowed downstream is often the subject of intensive studies designed to define habitat–flow relationships for target fish species and life stages. These "instream flow" studies often employ PHABSIM assessment techniques as described by Bovee and Milhous (1978), Bovee (1982), and Stalnaker et al. (1995) or other methods (Instream Flow Council 2002). Such studies are typically focused on defining spatial habitat needs for adult, juvenile, fry, and spawning life history stages. For streams that have uniformly low to moderate gradients (up to about 2%) and that are dominated by pool and riffle habitats, the flow recommendations based on these techniques may provide hydraulic conditions that are conducive to the upstream passage of adult salmonids. A specific method for determining suitable passage flows through these types of systems has been described by Thompson (1972). The method focuses on defining flow conditions through a stream segment that meets a combination of minimum depth and maximum water velocity criteria; depth minima are defined by the body depth of adult fish, and velocity maxima are defined by swimming capabilities. Hydrologically based design flows for adult fish passage have been described by Bates (1992) and Powers and Saunders (2002). Bates (1992) defined the high passage design flow as the highest streamflow at which specified fish passage criteria are satisfied. Passage design flows have been defined as the 10% exceedance flow (for gauged streams) or the 2-year peak flood flow (for ungauged streams) (Powers and Saunders 2002) that occurs during the critical time periods of adult and juvenile upstream migration.

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However, none of the above methods are applicable for determining suitable flows for adult upstream passage in steep-gradient (>3%), nonuniform, spatially complex channels containing cascade and falls habitat types. In these systems, a fish's swimming and jumping capabilities and the site-specific channel morphology and hydraulics often determine successful upstream passage. In this paper, we describe a technical approach we used to evaluate upstream passage flow conditions at potential barriers for several species of anadromous fish in Ward Creek, a steep, regulated stream located near Ketchikan, Alaska. The study was conducted in parallel with a PHABSIM study that focused on defining habitat–flow relationships for the same species. An ancillary question addressed was whether the instream flows recommended for meeting species- and life-stage-specific habitat requirements would also afford suitable upstream passage conditions. The studies were conducted initially in support of potential hydroelectric licensing of Connell Dam by Ketchikan Public Utilities; later, when such plans were abandoned, the studies were used to support a water management assessment for the U.S. Forest Service, which administers the federal lands adjoining Ward Creek.

Study Area

The Ward Creek drainage is located in southeast Alaska along the western coast of Revillagigedo Island. The drainage has a watershed area of 7,575 ha and contains primarily coniferous forest composed of Sitka spruce *Picea sitchensis*, western hemlock *Tsuga heterophylla*, western red cedar *Thuja plicata*, and Alaska yellow cedar *Chamaecyparis nootkatensis*. Elevations within the watershed range from 672 m above mean sea level to sea level.

The anadromous fish species of interest consisted of coho salmon *Oncorhynchus kisutch*, sockeye salmon *O. nerka*, pink salmon *O. gorbuscha*, chum salmon *O. keta*, Chinook salmon *O. tshawytscha*, and steelhead *O. mykiss* (anadromous rainbow trout). Chinook salmon were included in our analysis even though they only infrequently use Ward Creek and are not considered a primary management species of that stream (S. Hoffman, Alaska Department of Fish and Game, personal communication). Connell Lake and several adjoining lakes contain resident populations of rainbow trout, cutthroat trout *O. clarkii*, brook trout *Salvelinus fontinalis*, and Dolly Varden *S. malma* (Hubartt 1990). Nongame fishes observed include sticklebacks *Gasterosteus* spp., sculpins *Cottus* spp. (Hubartt 1990), and lampreys *Lampetra* spp.

Connell Lake is a reservoir created by the construction of Connell Dam in 1952; it has a maximum pool surface area of 149 ha at an elevation of 77 m above mean sea level. Prior to dam construction, sockeye salmon, coho salmon, and steelhead were known to migrate into the upper 11 km of watershed beyond the dam (Alaska Game Commission 1952). Pink salmon and chum salmon presumably were prevented from reaching the upper watershed by a series of high-gradient falls within the reach. However, no studies have been conducted to determine the actual extent of upstream migration for these species. Moreover, passage conditions at falls and cascades can vary substantially with flow, and although sockeye salmon, coho salmon, and steelhead were known to migrate through the reach, the flow conditions conducive to their passage were unknown.

The regulated reach of Ward Creek extends downstream of the dam for about 4,114 m to Ward Lake and another 698 m to its confluence with salt water at Ward Cove. The passage studies were limited to the reach between Connell Dam and Ward Lake (Figure 1); no potential barriers were identified in the lower segment. Average annual flow in Ward Creek below Connell Dam was estimated to be 4 m^3/s (WESCORP 2001). The streamflow gauged in 1999 ranged from 0.11 m^3/s on 3 September to 45 m^3/s on 24 May. Historically, no instream flow releases were

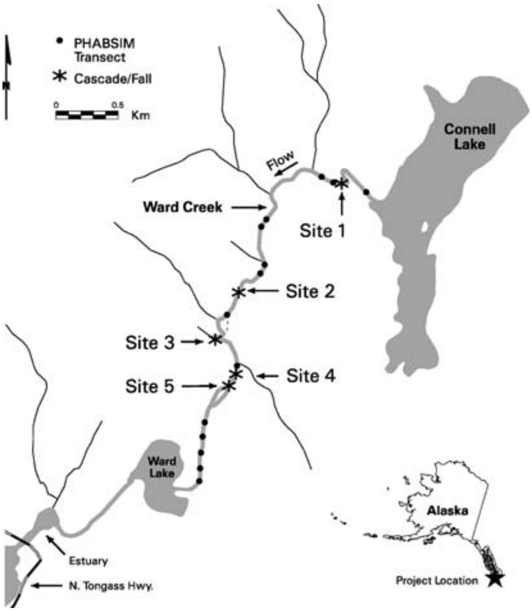

FIGURE 1.—Map of the study reach in Ward Creek, Alaska, showing the locations of barrier analysis sites (those with chutes, falls, or both) and PHABSIM transects where adult salmonid upstream migration ability under varying flow conditions was studied.

FIGURE 2.—Photographs of barrier site 4 on Ward Creek, Alaska, under flow conditions of about 0.91 m3/s (left photo) and 3.0 m3/s (right photo). Adult salmonid passage analysis focused on the chute located in the center of each photo.

required from Connell Dam. As a result, there were often periods (primarily July–September) when flows in the reach just below the dam were entirely dependent on seepage and accretion. During those times, flows in the study reach could range from 0.003 to 10.3 m^3/s and likely created formidable upstream passage conditions at times.

Methods

We classified habitat types (based on Hankin and Reeves 1988) in the reach of Ward Creek extending from just below Connell Dam to Ward Lake; habitat categories included riffle, run, glide, pool, and cascade—the latter containing areas of plunging, free-falling waters and falls. We visually identified five (numbered 1–5 from upstream to downstream) potential barrier sites (based on local channel geometry, channel gradient, and falls height), each having one to three discrete passage avenues warranting evaluation; a total of 10 potential barriers were identified (Table 1). Each site was surveyed (by use of a total station surveying instrument) under three controlled flow release conditions in 1998: about 0.91 m^3/s on 2 October, about 1.34 m^3/s on 3 October, and about 3.0 m^3/s on 6 October. Figure 2 depicts representative views of one of the sites (site 4) under flow conditions of 0.91 and 3.0 m^3/s. The surveys measured the hydraulics and channel geometry variations at passage portals that were most likely to be used by salmonids. Channel geometry was surveyed during the low flow; flow characteristics were measured for all three flow conditions (Tables 1, 2). At four of the five sites, we classified each of the potential barriers as a "chute" or "falls" based on the surveyed geometry; conceptual models of these barrier types in profile view and descriptive notations of each are displayed in Figure 3. A falls is associated with an abrupt drop in channel bottom. Water flowing over the top of a falls will separate from the brink of the falls and plunge in a free-fall trajectory. In contrast, the channel bottom of a chute does not drop as abruptly. The water passing through a chute does not separate from the channel bottom. The steep gradients of chutes are associated with high velocities (supercritical flow conditions). Although simplified, the barrier models shown in Figure 3 highlight important geometric characteristics that were considered in our analysis. The same definitions can also be found in Powers and Orsborn (1985). At one site (site 5), the potential barrier conditions consisted of shallow water depths, high velocities, or both.

Stage–discharge rating curves were developed for

TABLE 1.—Measured geometry of potential fish barriers in Ward Creek, Alaska. Site 1 is the most upstream site, site 5 the most downstream site; see Figure 1 for exact site locations. Abbreviations are as follows: Se = angle of the stream bed upstream of a falls; Sp = angle of a chute; LS = chute length; Z = vertical distance from the barrier bottom to the barrier crest.

Barrier site	Barrier identifier	Barrier classification	Se (% slope)	Sp (% slope)	LS (m)	Z (m)
1	1A	Falls	0.0			1.37
	1B	Falls	16.5			0.85
	1C	Chute	0.0	32.0	2.80	0.85
2	2A	Falls	0.0			1.52
	2B	Falls	0.0			1.13
	2C	Falls	0.0			1.01
3	3A	Falls	0.0			1.71
4	4A	Chute	0.0	28.1	7.98	2.16
5	5A	Depth/velocity				
	5B	Depth/velocity				

TABLE 2.—Measured flow characteristics for chute and falls barriers in Ward Creek, Alaska (H = vertical distance from the downstream pool water surface to the water surface at the crest; d_{pp} = flow depth of the downstream pool; d_c = water depth at the crest; FH = vertical distance from the downstream water surface elevation to the crest; Q = flow).

Site	Barrier identifier	H (m)	d_{pp} (m)	d_c (m)	FH[a] (m)	Q (m^3/s)
1	1A	0.61	0.91	0.15	0.46	0.91
		0.52	1.07	0.21	0.30	1.34
		0.52	1.13	0.30	0.24	3.00
	1B	0.40	0.76	0.30	0.09	0.91
		0.30	0.94	0.43	−0.09	1.34
		0.40	1.07	0.52	−0.21	3.00
	1C	0.55	0.61	0.30	0.24	0.91
		0.43	0.76	0.34	0.09	1.34
		0.33	0.94	0.46	0.12	3.00
2	2A	0.49	1.22	0.18	0.30	0.91
		0.40	1.28	0.18	0.24	1.34
		0.18	1.49	0.15	0.03	3.00
	2B	0.46	1.37	0.70	−0.24	0.91
		0.64	1.34	0.85	−0.24	1.34
		0.55	1.52	0.94	−0.40	3.00
	2C	0.49	0.85	0.30	0.18	0.91
		0.52	1.01	0.52	0.00	1.34
		0.52	1.07	0.58	−0.06	3.00
3	3A	1.04	1.07	0.40	0.64	0.91
		1.00	1.16	0.46	0.55	1.34
		0.97	1.31	0.58	0.40	3.00
4	4A	2.74	0.46	0.30	1.71	0.91
		2.68	0.55	0.34	1.61	1.34
		2.41	0.67	0.18	1.49	3.00

[a] Negative FH values indicate higher water surface elevation in the downstream pool than at the barrier crest. This occurs when the velocity in the pool is much lower than the velocity at the crest.

the plunge pools and potential barrier crests by use of regression analysis and the measured data in Table 2. A logarithmic regression was performed between W and discharge Q, where W is either the pool depth (d_{pp}) or the water depth at the waterfall crest (d_c). Two rating curves ($Q \sim d_{pp}$ and $Q \sim d_c$) were developed at each potential barrier based on the three pairs of measured data in Table 2. The coefficients of determination (R^2) for the regression were generally about 0.9. The rating curves were then utilized to estimate the stages for the simulation flows. The flow velocity at the waterfall crest can be derived once the stage is determined.

We then compared the calculated hydraulics (i.e., velocity and depth) at various flow conditions against published information on the leaping and swimming capabilities of adult salmonids to compute the barrier potential of each site over a range of flows, from 0.23 to 11.33 m^3/s. We relied primarily on the information provided by Bell (1990) and Powers and Orsborn (1985) for defining leaping and swimming capabilities of salmonids (Table 3). Because the study reach of Ward Creek is within 5 km of salt water, no adjustments were made to any of the swimming capabilities to reflect deterioration in physical condition as fish move upstream from the ocean.

Although several conventions are used in describing the swimming capabilities of adult salmonids (Watts 1974; Bell 1990; Bjornn and Reiser 1991; Clay 1995), we used the definitions presented in Powers and Orsborn (1985): sustained, prolonged, and burst. At sustained

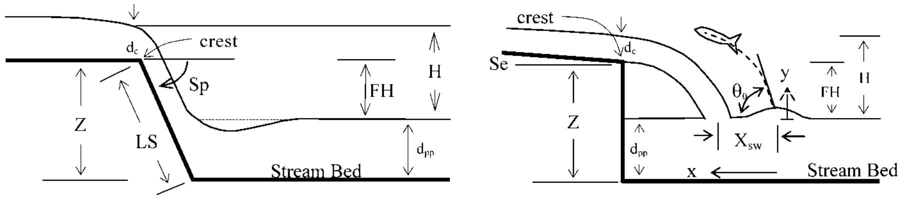

FIGURE 3.—Schematics of chute-type (left) and falls-type (right) potential barriers (adapted from Powers and Orsborn 1985). Variables are defined as follows: Z is the vertical distance from the bottom of the barrier to the crest of the barrier, H is the vertical distance from the downstream pool water surface to the water surface at the crest, d_c is the water depth at the crest, d_{pp} is the flow depth of the downstream pool, LS is the chute length, Sp is the angle of the chute, Se is the angle of the bed upstream of a falls, FH is the vertical distance from the downstream water surface elevation to the barrier crest, θ_0 is the initial leaping angle, and X_{sw} is the distance from the location of the impact of the falling water to the standing wave.

TABLE 3.—Typical leaping and swimming capabilities and migration periodicity of adult salmonids in Ward Creek, Alaska (Powers and Orsborn 1985; Bell 1990; Reiser and Peacock 1985; and National Oceanic and Atmospheric Administration 2006).

Variable	Steelhead	Coho salmon	Chinook salmon	Sockeye salmon	Pink salmon	Chum salmon
Sustained velocity (m/s)	0–1.40	0–1.04	0–1.04	0–0.97	0–0.79	0–0.79
Prolonged velocity (m/s)	1.4–4.17	1.04–3.23	1.04–3.29	0.97–3.11	0.79–2.34	0.79–2.34
Burst velocity (m/s)	4.17–8.07	3.23–6.55	3.29–6.82	3.11–6.27	2.37–4.57	2.34–4.57
Minimum swimming depth (m)	0.17	0.17	0.17	0.17	0.17	0.17
Fish body length (m)	0.70	0.70	0.91	0.55	0.58	0.73
Fish body depth (m)		0.14				0.20
Maximum jumping height (m)	3.35	2.19	2.38	2.10	1.21	1.21
Adult migration	Mar–Apr	Aug–Oct	Jun–Aug	Aug–Sep	Jul–Aug	Jul–Sep
Periodicity in Ward Creek (d)	(92)	(92)	(92)	(48)	(46)	(76)

velocities, fish can function normally for long periods of time without fatigue (Hoar and Randall 1978). Prolonged fish speeds can be maintained over long periods of time (15 s to 200 min). Burst speeds are used for short periods (15 s or less) to negotiate falls and high-velocity areas. Because the issue was potential flow-related passage impediments, we primarily used the range of burst swimming speeds in the barrier analysis.

For potential falls barriers, successful passage would require the fish to leap from a standing wave to the waterfall crest. Also, the flow velocity at the waterfall crest must be less than the burst speed and water depth must be greater than the fish body depth. The standing wave is the higher water surface elevation just downstream of the point where falling water strikes the plunge pool, as shown in Figure 3. As the fish leaps through the air, its path can be described by the following trajectory equations (e.g., Sears et al. 1976):

$$x = V_e \cos \theta_0 t \tag{1}$$

$$y = V_e \sin \theta_0 t - \frac{1}{2} g t^2, \tag{2}$$

where y is the vertical distance above the pool water surface elevation, x is the horizontal distance measured upstream from the standing wave, g is the gravitational acceleration, θ_0 is the initial leaping angle measured from the horizontal, and V_e is the speed of the fish as it exits the water. In this analysis, the exit velocity V_e was assumed to be equal to the maximum burst velocity in Table 3, because the study site was within a few kilometers of the ocean and the fish were assumed to be in excellent condition.

From Figure 3, the horizontal (X) and vertical (Y) distances a fish has to leap to reach the waterfall crest can be expressed by

$$\begin{aligned} X &= V_{\mathrm{dc}} t_f + X_{\mathrm{sw}} \\ Y &= Z - d_{\mathrm{pp}} + 0.09m, \end{aligned} \tag{3}$$

where V_{dc} is the flow velocity at the waterfall crest, t_f is the travel time of the water from the crest to the moment it strikes the pool and is equal to $\sqrt{2H/g}$, H is the elevation difference between the water surface elevation at the waterfall crest and the pool surface, X_{sw} is the distance between the standing wave and the water striking location and is assumed to be 0.3 m (Powers and Orsborn 1985), Z is the elevation difference between the waterfall crest and the pool bottom, d_{pp} is the water depth of the plunge pool, and 0.09 m is a constant that takes into account the fish body depth because the trajectory equation (equation 1) was derived for the centroid of an object (a fish). Critical flow condition (Froude number = 1.0) is assumed to occur at the crest of the falls, and thus V_{dc} is equal to $\sqrt{g d_c}$ (Chow 1959).

The use of equations (1)–(3) to determine a successful leap requires iterations, and therefore Powers and Orsborn (1985) developed a series of charts to help decide whether a successful leap would occur. In this analysis, instead of using charts, we derived an analytical equation that can be used to determine a successful leap. We start from equation (2) and use $t = x/(V_e \cos\theta_0)$ to eliminate the time variable. After applying the condition $y = Y$ at $x = X$ for a successful leap, using trigonometric identities (e.g., $\sin\theta_1 \cos\theta_2 + \sin\theta_2 \cos\theta_1 = \sin[\theta_1 + \theta_2]$) to combine the two terms on the right-hand side of equation (2), and taking $\sin^{-1}$ to single out θ_0, we obtain equation (4), as follows:

$$\theta_0 = \frac{1}{2}\left[\tan^{-1}\left(\frac{Y}{X}\right) + \sin^{-1}(\beta)\right], \tag{4}$$

where

$$\beta = \left(Y + \frac{gX^2}{V_e^2}\right) \Big/ \sqrt{X^2 + Y^2}\,. \tag{5}$$

Equations (4) and (5) can be used to determine whether a fish is able to reach the waterfall crest after traveling horizontal distance X and vertical height Y with exit velocity V_e and initial leaping angle θ_0. The criteria for a successful leap to the waterfall crest require β to be less than 1 and θ_0 to be less than 90°; barrier conditions exist if β is greater than 1. There is no need to consider the value of θ_0 if β is greater than 1. When determining whether a leap is successful, we can directly substitute X, Y, and V_e into equation (5) to calculate β and then into equation (4) to calculate θ_0 without iterative calculations or the use of charts. Importantly, no difference in the results occurs from the use of either equations (4) and (5) or the charts presented by Powers and Orsborn (1985).

An alternative form of equation (5) that explicitly shows the minimum exit velocity required for a fish to successfully leap to the waterfall crest (i.e., $\beta < 1$) can be expressed by the equation

$$V_e > \sqrt{\frac{gX^2}{\sqrt{X^2 + Y^2} - Y}}. \qquad (6)$$

By means of equation (6), a family of velocity contours can be developed to illustrate the limits to the distance and height for different exit velocities of the fish, as shown in Figure 4. The velocity limits for each species in Table 3 are shown in bold curves. Based on equation (6), a successful jump can be determined graphically based on the geometry of the potential falls barrier and the species of interest. To use Figure 4, first determine the exit (burst) velocity of the fish of interest and draw a curve on the figure for the exit velocity parallel to the contours. Then enter the travel distance (X) and vertical height (Y). If the point (X, Y) is below the velocity curve of the fish, this would be a successful leap. Otherwise, the leap would be unsuccessful. For example, if the distance and height are both 1.5 m, the potential barrier is passable by all species except chum and pink salmon.

We also considered minimum plunge pool depth. Although Stuart (1964) suggested that optimum leaping conditions occur when the ratio of falls height to pool depth is around 1.25, he did not address the concept of minimum pool depth—that is, the depth of water below which a fish's leaping capacity is reduced. Powers and Orsborn (1985) indicated that (1) the penetration depth of falling water should be less than the plunge pool depth and (2) the plunge pool depth should be greater than or equal to the length of the migrating fish. In this study, we assumed that the first condition was always met, while for the second condition we assigned a minimum pool depth equal to 1.1 times the fish length. For this, we used average fish lengths (Table 3) based on visual observations of spawning fish in Ward Creek, as well as average length data (e.g., Powers and Orsborn 1985; Bell 1990; Groot and Margolis 1991).

As noted by Stuart (1964), when a fish lands at a falls crest it is geared for immediate propulsion. However, the successful transition from leaping to upstream swimming that occurs at the top of the falls requires swimming capabilities to be greater than the critical velocities at the crest (V_{dc}). We assumed that when the fish reaches the barrier crest, it has consumed some energy; we therefore conservatively compared crest velocity to the lower range of burst velocities (i.e., upper range of prolonged velocities; see Table 3) rather than the maximum burst speeds as a means to determine passage success. In other words, we assumed that if a fish's lower burst velocity is greater than V_{dc} at a given crest, the fish will continue its upstream migration; if its lower burst velocity is less than V_{dc}, then the fish will fall back downstream. We also assumed that the critical flow condition occurs at the crest of the falls. Based on typical fish dimensions (Table 3), we assigned a minimum water depth of 0.17 m (to cover the fish's body) as necessary at the crest to allow successful fish passage; crest water depths less than 0.17 m were considered to be impassable.

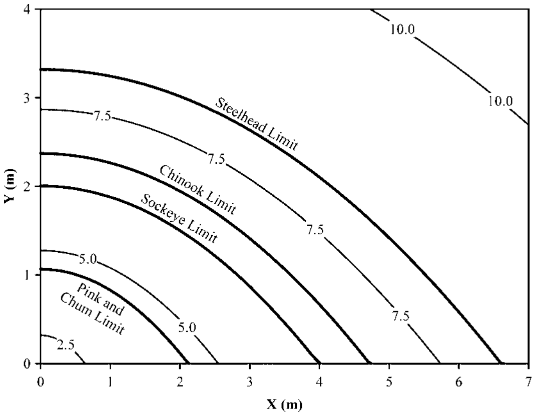

FIGURE 4.—Horizontal travel distance (X) and vertical height (Y) limits for different salmonid species based on burst swimming speed velocities. The numbers indicated on the contours are the exit velocities of the fish (based on data from Bell 1990, Powers and Orsborn 1985, and Reiser and Peacock 1985).

For potential chute barriers, the average chute velocity was compared with the burst speed to determine whether the chute was a barrier. We estimated flow velocity in the chute and used energy conservation to convert potential energy to kinetic energy. The total energy at any point in the chute is equal to the kinetic energy at the chute crest plus the potential energy gain due to elevation drop and minus the energy loss due to turbulence and friction. As a result of the change to the energy form, the flow velocity along the chute is constantly changing. For simplicity, when determining whether a fish was able to migrate upstream, the average velocity over the chute length from chute crest to pool surface was compared with the fish burst speed. Due to the difficulty of estimating energy dissipation quantity by turbulence and friction, we assumed that the dissipation was small relative to the potential energy gain. Therefore, no energy loss was included in estimating average chute velocity. This assumption, however, results in an estimated average chute velocity higher than what the actual average velocity in the chute would be. Our assessment was therefore conservative in that it accounted for realistic capabilities of the target species versus targeting the largest, healthiest, and most energetic individuals. Thus, it would likely result in some flow conditions being considered as barriers when in reality, some fish may be able to pass. With the assumption, the velocity at any point in the chute can be expressed by $\sqrt{V_{\text{ch}}^2 + 2gl\sin(\text{Sp})}$, where Sp is the chute angle, as illustrated in Figure 3, V_{ch} is the flow velocity at the chute crest before entering the chute, and l is the distance from the chute crest. After taking the integration from chute crest ($l = 0$) to pool surface ($l = \text{LS} - d_{\text{pp}}/\sin[\text{Sp}]$), the average chute velocity, V_p, can be written as

$$V_p = \frac{\left\{V_{\text{ch}}^2 + 2g[\text{LS}\sin(\text{Sp}) - d_{\text{pp}})]\right\}^{3/2} - V_{\text{ch}}^3}{3g[\text{LS}\sin(\text{Sp}) - d_{\text{pp}}]}, \quad (7)$$

where LS is the total chute length from crest to pool bottom. If the critical flow condition (Froude number = 1.0) occurs at the chute crest, then V_{ch} is equal to V_{dc}. Due to the assumption of no energy loss, equation (7) should be applied to chutes with short lengths. The chute barrier analysis considered whether a fish's burst velocity would be sufficient to pass through the chute within 15 s against V_p. In this case, due to the proximity of the chute to salt water, we used the fish's maximum burst velocity in the analysis.

Results

Although a set of 30 flows ranging from 0.23 to 11.33 m^3/s was applied for each species and each of the five site locations, only sites for which flows and the corresponding variables were found to influence passage conditions are presented in Table 4 and discussed below. Site 5 (lower site) was not included in any of the tables, since predicted water depths and velocities indicated that suitable passage conditions would exist for all species over the entire flow range.

The channel hydraulics for site 4 over the range of modeled flows suggested that the site would be a total passage barrier to pink and chum salmon; the lowest chute velocity (5.46 m/s) was greater than the burst velocities of chum and pink salmon (4.57 m/s), as shown in the last column of Table 4. The burst velocities of coho and sockeye salmon, steelhead, and Chinook salmon all exceeded the average chute velocities, and hence these species should be able to pass through this location.

For site 3, the analysis indicated that steelhead and coho salmon should be able to pass the falls under all modeled flows; Chinook and sockeye salmon would require flows over 0.59 and 0.23 m^3/s (Table 4), respectively, to pass; and pink and chum salmon could not pass under modeled flows (V_{dc} exceeded the lower-range burst velocities for these species at flows greater than 2.9 m^3/s and the long horizontal distance from pool to crest).

A series of three potential barriers (designated 2A–C) were located at site 2; the occurrence of barrier conditions at any one of the obstacles rendered the entire site impassable. Results for 2A suggested that barrier conditions (related to low water depths at the falls crest) would exist for all five species for a range of flows from 0.23 to 0.59 m^3/s but that all species could pass at flows greater than 0.59 m^3/s up to the highest modeled flow (11.33 m^3/s), as shown in Table 4. At 2B, only steelhead would be able to pass over the modeled flow range (0.23–11.33 m^3/s), while passage for pink and chum salmon would only occur at the two lowest flows (0.23 and 0.34 m^3/s). Results for 2C indicated that steelhead, coho salmon, and sockeye salmon could pass the falls at flows greater than 0.34 m^3/s. A flow of at least 1.70 m^3/s would be needed to provide a 1.0-m plunge pool depth for leaping by Chinook salmon at 2C; pink and chum salmon could pass 2C at flows higher than 0.45 m^3/s but less than 2.90 m^3/s.

Three potential barriers existed at site 1, consisting of two falls-type features (1A and 1B) and one chute-type feature (1C). Falls 1A and 1B, located upstream of 1C, represent two alternative upstream routes for fish. Barrier conditions would exist when hydraulic conditions preclude fish passage through site 1C (i.e., prevent access to 1A or 1B) or when conditions allow passage at 1C but preclude passage at both 1A and 1B. Analysis indicated that successful passage at 1A would occur at all modeled flows for all species except Chinook salmon (which could not pass at flows less than 0.91 m^3/s) and pink and chum salmon (which could not pass at flows less than 0.66 m^3/s) (Table 4). Barrier conditions at 1B would occur (all species) at the lowest modeled flow, 0.23 m^3/s. Suitable conditions at 1B begin to occur in concert with species sizes: at flows of 2.27 m^3/s for Chinook salmon, 0.66 m^3/s for steelhead, 0.59 m^3/s for coho salmon, and 0.34 m^3/s for pink and sockeye salmon. Flows for coho salmon, steelhead, sockeye salmon, and Chinook salmon would

TABLE 4.—Range of passage flows (Q) for different fish species in Ward Creek, Alaska. Numbers in bold italics indicate impassable conditions due to the hydraulic condition indicated in the column header (d_{pp} = plunge pool depth; d_c = crest water depth; V_{dc} = crest critical velocity; X = horizontal distance; Y = vertical height; V_P = chute velocity).

		Site and variable													
		1A		1B			2A	2B	2C			3A			4A
Species	Q (m^3/s)	d_{pp} (m)	d_c (m)	d_{pp} (m)	d_c (m)	V_{dc} (m/s)	d_c (m)	V_{dc} (m/s)	d_{pp} (m)	d_c (m)	V_{dc} (m/s)	d_{pp} (m)	V_{dc} (m/s)	X or Y a barrier?[a]	V_P (m/s)
Steelhead	0.23	0.78	***0.04***	***0.56***	***0.16***	1.3	***0.14***	2.1	***0.66***	***0.07***	0.8	0.79	1.3	N	5.80
	0.34	0.84	***0.08***	***0.64***	0.22	1.5	***0.15***	2.3	***0.73***	***0.15***	1.2	0.87	1.6	N	5.77
	0.45	0.88	***0.11***	***0.70***	0.26	1.6	***0.16***	2.4	0.78	0.21	1.4	0.93	1.7	N	5.75
	0.59	0.92	***0.14***	***0.76***	0.30	1.7	***0.16***	2.5	0.82	0.27	1.6	0.98	1.8	N	5.72
	0.66	0.94	***0.15***	0.78	0.32	1.8	0.17	2.6	0.84	0.29	1.7	1.01	1.8	N	5.71
	0.91	0.98	0.18	0.85	0.36	1.9	0.18	2.7	0.89	0.36	1.9	1.07	2.0	N	5.58
	11.33	1.34	0.44	1.36	0.72	2.7	0.25	3.4	1.31	0.88	2.9	1.58	2.8	N	5.46
Coho salmon	0.23	0.78	***0.04***	***0.56***	***0.16***	1.3	***0.14***	2.1	***0.66***	***0.07***	0.8	0.79	1.3	N	5.80
	0.34	0.84	***0.08***	***0.64***	0.22	1.5	***0.15***	2.3	***0.73***	***0.15***	1.2	0.87	1.6	N	5.77
	0.45	0.88	***0.11***	***0.70***	0.26	1.6	***0.16***	2.4	0.78	0.21	1.4	0.93	1.7	N	5.75
	0.57	0.92	***0.14***	***0.75***	0.29	1.7	***0.17***	2.5	0.82	0.26	1.6	0.98	1.8	N	5.73
	0.59	0.92	***0.14***	0.76	0.30	1.7	***0.16***	2.5	0.82	0.27	1.6	0.98	1.8	N	5.72
	0.66	0.94	***0.15***	0.78	0.32	1.8	0.17	2.6	0.84	0.29	1.7	1.01	1.8	N	5.71
	0.91	0.98	0.18	0.85	0.36	1.9	0.18	2.7	0.89	0.36	1.9	1.07	2.0	N	5.69
	5.10	1.22	0.36	1.20	0.61	2.4	0.23	3.2	1.18	0.71	2.6	1.42	2.5	N	5.53
	5.64	1.24	0.37	1.22	0.62	2.5	0.23	***3.3***	1.19	0.74	2.7	1.44	2.6	N	5.53
	11.33	1.34	0.44	1.36	0.72	2.7	0.25	***3.4***	1.31	0.88	2.9	1.58	2.8	N	5.46
Chinook salmon	0.23	***0.78***	***0.04***	***0.56***	***0.16***	1.3	***0.14***	2.1	***0.66***	***0.07***	0.8	***0.79***	1.3	N	5.80
	0.59	***0.92***	***0.16***	***0.76***	0.30	1.7	***0.16***	2.5	***0.82***	0.27	1.6	***0.98***	1.8	N	5.72
	0.66	***0.94***	***0.15***	***0.78***	0.32	1.8	0.17	2.6	***0.84***	0.29	1.7	1.01	1.8	N	5.71
	0.91	***0.98***	0.18	***0.85***	0.36	1.9	0.18	2.7	***0.89***	0.36	1.9	1.07	2.0	N	5.69
	1.27	1.03	0.22	***0.91***	0.41	2.0	0.19	2.8	***0.95***	0.43	2.0	1.14	2.1	N	5.66
	1.70	1.07	0.25	***0.97***	0.45	2.1	0.20	2.9	***1.00***	0.49	2.2	1.20	2.2	N	5.63
	2.27	1.11	0.28	1.03	0.49	2.2	0.20	3.0	1.04	0.55	2.3	1.26	2.3	N	5.61
	6.23	1.25	0.38	1.24	0.64	2.5	0.23	3.28	1.21	0.76	2.7	1.46	2.6	N	5.52
	6.80	1.27	0.39	1.25	0.65	2.5	0.23	***3.31***	1.22	0.77	2.8	1.48	2.6	N	5.51
	11.33	1.34	0.44	1.36	0.72	2.7	0.25	***3.35***	1.31	0.88	2.9	1.58	2.8	N	5.46
Sockeye salmon	0.23	0.78	***0.04***	***0.56***	***0.16***	1.3	***0.14***	2.1	0.66	***0.07***	0.8	0.79	1.3	***Y***	5.80
	0.34	0.84	***0.08***	0.64	0.22	1.5	***0.15***	2.3	0.73	***0.15***	1.2	0.87	1.8	N	5.77
	0.45	0.88	***0.11***	0.70	0.26	1.6	***0.16***	2.4	0.78	0.21	1.4	0.93	1.7	N	5.75
	0.59	0.92	***0.14***	0.76	0.30	1.7	***0.16***	2.5	0.82	0.27	1.6	0.98	1.8	N	5.72
	0.66	0.94	***0.15***	0.78	0.32	1.8	0.17	2.6	0.84	0.29	1.7	1.01	1.8	N	5.71
	0.91	0.98	0.18	0.85	0.36	1.9	0.18	2.7	0.89	0.36	1.9	1.07	2.0	N	5.69
	2.27	1.11	0.28	1.03	0.49	2.2	0.20	3.0	1.04	0.55	2.3	1.26	2.3	N	5.61
	2.90	1.14	0.30	1.08	0.53	2.3	0.21	3.04	1.08	0.60	2.4	1.31	2.4	N	5.58
	3.01	1.15	0.31	1.09	0.53	2.3	0.21	3.07	1.09	0.61	2.4	1.31	2.4	N	5.58
	3.69	1.18	0.33	1.13	0.56	2.3	0.22	***3.13***	1.12	0.65	2.5	1.35	2.4	N	5.56
	11.33	1.34	0.44	1.36	0.72	2.7	0.25	***3.45***	1.31	0.88	2.9	1.58	2.8	N	5.46
Pink and chum salmon	0.23	0.78	***0.04***	***0.56***	***0.16***	1.3	***0.14***	2.1	***0.66***	***0.07***	0.8	***0.79***	1.3	***Y***	***5.80***
	0.34	0.84	***0.08***	0.64	0.22	1.5	***0.15***	2.3	***0.73***	***0.15***	1.2	0.87	1.6	***Y***	***5.77***
	0.45	0.88	***0.11***	0.70	0.26	1.6	***0.16***	***2.4***	***0.78***	0.21	1.4	0.93	1.7	***Y***	***5.75***
	0.55	0.91	***0.13***	0.74	0.29	1.7	***0.16***	***2.5***	0.81	0.25	1.6	0.97	1.8	***Y***	***5.73***
	0.59	0.92	***0.14***	0.76	0.30	1.7	***0.16***	***2.5***	0.82	0.27	1.6	0.98	1.8	***Y***	***5.72***
	0.66	0.94	***0.15***	0.78	0.32	1.8	0.17	***2.6***	0.84	0.29	1.7	1.01	1.8	***Y***	***5.71***
	0.91	0.98	0.18	0.85	0.36	1.9	0.18	***2.7***	0.89	0.36	1.9	1.07	2.0	***Y***	***5.69***
	2.27	1.11	0.28	1.03	0.49	2.2	0.20	***3.0***	1.04	0.55	2.3	1.26	2.3	***Y***	***5.61***
	2.90	1.14	0.30	1.08	0.53	2.3	0.21	***3.1***	1.08	0.60	***2.4***	1.31	***2.4***	***Y***	***5.58***
	3.69	1.18	0.33	1.13	0.56	2.3	0.22	***3.1***	1.12	0.65	***2.5***	1.35	***2.4***	***Y***	***5.56***
	3.96	1.19	0.34	1.14	0.57	***2.4***	0.22	***3.2***	1.13	0.66	***2.5***	1.37	***2.5***	***Y***	***5.56***
	8.50	1.30	0.41	1.30	0.68	***2.6***	0.24	***3.4***	1.26	0.82	***2.8***	1.52	***2.7***	***Y***	***5.49***
	9.06	1.31	0.42	1.31	0.69	***2.6***	0.24	***3.4***	1.27	0.83	***2.9***	1.54	***2.7***	***Y***	***5.48***
	11.33	1.34	0.44	1.36	0.72	***2.7***	0.25	***3.4***	1.31	0.88	***2.9***	1.58	***2.8***	***Y***	***5.46***

[a] Indicates whether *X, Y,* or a combination of both is a barrier to fish passage; Y = yes, N = no.

continue to afford passage conditions up to the upper modeled flow (11.33 m^3/s), while flows greater than 3.96 m^3/s at 1B become impassable for pink and chum salmons. At 1C, all species can pass under all flow conditions, and therefore no analyses are presented.

Integration of results for each site allowed for the identification of a species-specific range of flows that afford passage conditions throughout the entire 4,114-m reach of Ward Creek. This range of flows, termed "flow windows," is depicted in Figure 5, the details of

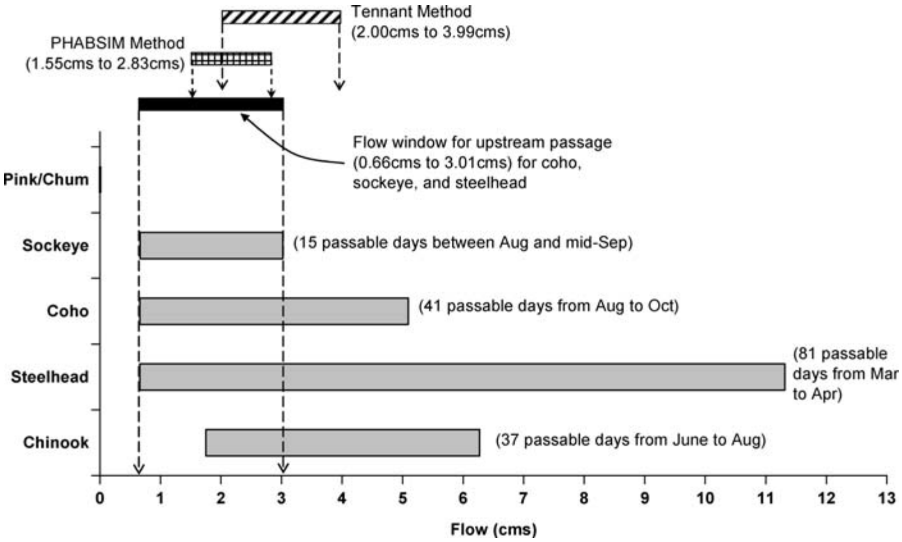

FIGURE 5.—Flow windows (cms = m^3/s) providing suitable upstream passage through a series of five cascades–falls for adult salmonids in Ward Creek, Alaska. The dashed vertical lines depict the flow window that is suitable for all species. The numbers of passable days are the numbers of days for which species-specific flow windows are likely to occur during a given year based on flow duration analysis. The PHABSIM and Tennant (1976) flow ranges are depicted at the top of the figure.

which are presented in Table 4. From the table, we were able to isolate the location and flow conditions that would preclude both pink and chum salmon from migrating throughout the reach. This occurs at the site-4 chute, where velocities under all modeled flows exceed pink and chum salmon burst velocities. Spawning of these two species under all flows would be relegated to a 1,385-m segment of Ward Creek above Ward Lake. Even if passage were afforded above this site, barrier conditions for pink and chum salmon occur at other sites, including the next upstream set of falls at site 3. In contrast, the analysis identified distinct flow windows that should allow successful passage of coho salmon (0.66–5.10 m^3/s), sockeye salmon (0.66–3.01 m^3/s), Chinook salmon (1.70–6.23 m^3/s), and steelhead (0.66–11.33 m^3/s) throughout the entire study reach. Flows lower or higher than those depicted for a given species would probably result in passage impediments at one or more of the sites.

For each flow window, we enumerated the number of "potential passage days" (days within each species' migration period; Table 3) and then computed the average annual number of passable days via comparison of the species-specific flow windows with a flow duration analysis for the same time periods based on a 10-year flow record (WESCORP 2003). The average number of passable days (and percentages of potential passage days) ranged from 15 d (33%) for sockeye salmon to 81 d (88%) for steelhead (Figure 5).

As expected, individual metrics that created the barriers varied by site and flow but typically included problems of plunge pool depths that were too shallow (reducing leaping ability) and shallow crest depths when flows were low, while under high-flow conditions problems included excessive chute velocities that exceeded burst swimming speeds and crest velocities that exceeded the lower range of burst swimming speeds. Body length was especially important for determining the lowest passage flow. Chinook salmon have the greatest body lengths, and, as a result, their lowest passage flow (2.27 m^3/s) was greater than those of the other three species.

Discussion and Management Implications

This study analyzed the geometry and associated hydraulics of a number of potential natural barriers in Ward Creek over flows ranging from 0.23 to 11.33 m^3/s. The analysis allowed us to define a set of species-specific flow windows that would afford suitable upstream passage conditions throughout the reach. For the three species that were historically found in the upper watershed (coho salmon, sockeye salmon, and steelhead), a flow window of 0.66–3.01 m^3/s should provide suitable upstream passage conditions from Ward Lake to the base of the dam. In this case, the upper flow limit was based on the species with the lowest upper flow limit that afforded passage (i.e., sockeye salmon).

The results of a recent fall spawning escapement survey (Lundberg 2001) confirmed that coho salmon, but not pink or chum salmon, were able to negotiate all five of the potential barriers. Pink, chum, and sockeye salmon were all observed in a lower segment of stream below site 5. The absence of pink and chum salmon from the upper reaches was consistent with our passage analysis, which indicated that these species would be limited to the lower reaches. However, the absence of sockeye salmon from the upper reach was surprising, since our analysis indicated that they should be able to pass all five potential barriers under the flow windows. We identified four possible explanations for this: (1) there were relatively few (102) sockeye salmon (compared to over 900 coho salmon) observed during the surveys, and it is possible that all these fish volitionally selected spawning sites within the lower reaches; (2) the number of sockeye salmon that migrated to the upper reaches was small and went undetected; (3) flow conditions during the spawning migrations exceeded the upper limits for sockeye salmon (i.e., 3.01 m^3/s) but were still within limits for coho salmon (i.e., <5.10 m^3/s), a situation that could occur given the comparatively low number of sockeye salmon passable days (15 d) expected to occur in Ward Creek; and (4) the current sockeye salmon population has adapted a life history strategy that is more ecologically linked with Ward Lake than with Connell Lake. In that case, the homing stimuli of sockeye salmon adults would be tempered once the fish have passed Ward Lake, and spawning would be concentrated in the lower reaches of Ward Creek. Related to this, it has been over 50 years since the construction of Connell Dam and the elimination of sockeye salmon from the upper watershed. Although our analysis suggests that sockeye salmon should be able to migrate through the reach within the range of the flow windows, the impetus to do so may be lacking; this possibility must be accounted for in other projects involving dams in which the reconnection of fragmented habitats via provision of fish passage is being considered. Additional escapement surveys that monitor passage at each of the five sites and that are conducted under varying flow conditions (including the flow windows) would be useful for testing our overall predictions.

An ancillary question is whether instream flow needs directed toward meeting the spatial requirements of the target species would be consistent with the needs for passage. Two sets of analyses were used for that comparison, including a set of monthly instream flow recommendations formulated by the Alaska Department of Fish and Game (ADFG 1990) for their instream-flow water right application based on the Tennant (1976) method and a PHABSIM analysis that was completed in parallel with this study (R2 Resource Consultants 2003). Those analyses resulted in flow recommendations for adult migration periods of fall-spawning fish: 2.00–3.99 m^3/s based on the Tennant method and 1.55–2.83 m^3/s based on the PHABSIM analysis. The range of flows suggested by the PHABSIM analysis is nested within the flow window for passage, and hence the two are compatible. However, the upper flow (3.99 m^3/s) suggested by the Tennant method could be problematic for sockeye salmon passage, as it exceeds the upper flow limit (3.01 m^3/s) affording passage conditions for that species. Likewise, the 10% exceedance flows for the species-specific periods of migration that may be used to define upper-limit design flows for culverts (Powers and Saunders 2002) ranged from 6.46 m^3/s for Chinook salmon to 11.56 m^3/s for coho salmon. These flows ranged from more than 1.75 to over 3.0 times the upper limit of the combined flow window. Clearly, reliance on a single approach for defining instream flow needs could result in flow management decisions that are inconsistent with resource management objectives. Care should be taken when evaluating instream flow needs to ensure that all flow-sensitive and potentially resource-limiting factors are considered.

We would like to make a few comments regarding the methods we employed and the assumptions used in our analysis. The methodology we used for assessing barrier conditions for each of the falls and chutes is similar to the one outlined by Powers and Orsborn (1985). Using the methodology, we were able to estimate passage-sensitive hydraulic and physical parameters at differing natural channel features over a wide range of flows, an approach similar to that used by Reiser and Peacock (1985) for evaluating passage problems at small-scale dams. However, unlike Reiser and Peacock (1985), who classified barrier conditions into different categories (definite, probable, possible, and unlikely) based on parameter values or combinations thereof, we assigned barrier conditions when at least one of the primary parameters fell outside of the swimming or jumping capabilities of the target fish species. Thus, our approach is likely to be conservatively protective in identifying barrier conditions, especially at the upper and lower bounds of the flow windows. Our use of the lower range (rather than maximum) burst speeds in computing passage success at falls was likewise conservative. That is, the upper and lower flows identified as creating barrier conditions may actually be passable by some fish, given inherent differences in sizes, swimming capability, condition, and stamina. However, the focus of this study was on identifying a flow regime that would allow for adult passage of target species throughout the reach, and therefore the identification of upper and lower passage bounds that may still allow some passage is not at odds with the overall study objective. If, however, the management objective is to prevent upstream passage through flow manipulation—for example, to control distribution of nonnative fish species that have distinctly different swimming and jumping capabilities than a native species—then greater emphasis would be needed on defining absolute barrier conditions. Some type of a decision tree system could be easily integrated into the approach we used.

One of the biological assumptions used in our analysis was that fish encountering the potential barriers were in excellent condition, since the obstacles were only a short distance from salt water. We correspondingly applied the maximum burst velocities in estimating fish passage success through potential chute-type barriers, which is dependent on swimming performance. However, the question of whether this same assumption would apply for anadromous salmonids encountering potential barriers that are quite distant from salt water merits discussion. Studies have been conducted that have evaluated the effects of a variety of biotic and abiotic factors on swimming performance, including temperature (Webb 1978) and dissolved oxygen (Davis et al. 1963; Brett 1964). According to Webb (1995), the significance of environmental factors would probably differ between sustained or prolonged swimming speeds and burst performance and such factors would exert greater influence on the former; burst performance is supported by anaerobic metabolism that tends to be rapidly fatiguing but proceeds with high rates of energy release. Webb (1978), for example, determined that the burst speed of rainbow trout was largely independent of temperature. However, declines in swimming speeds were reported for pink salmon as they progressed through their migration and spawning cycle (Williams and Brett 1987). Since both prolonged and burst speeds are employed by salmonids when attempting to pass a potential barrier, we believe that prior migration history (length of migration, previous obstacles encountered, water quality conditions, etc.), at least of semelparous salmonids, probably factors into a fish's ability to pass a given obstacle. This is an area warranting further investigation, especially since it may have implications for fishway design criteria.

Although much has been learned regarding the design and construction of fishways that successfully pass upstream-migrating salmonids, there are still data gaps in understanding and identifying flow-dependent barrier conditions in both regulated and unregulated streams. Many states in the Pacific Northwest are undergoing widespread programs to identify and correct passage problems associated with road crossings (e.g., WDFW 2003) in an effort to restore anadromous and resident fish habitat. There are likewise many hydroelectric projects that are undergoing relicensing activities; flow regulation and instream flow releases below dams and diversion structures will also be up for consideration. For those streams in which flow-dependent fish passage issues may be a factor, we believe an evaluation of such should be included into any instream flow needs assessment for the reach. We believe that the general method we used for Ward Creek could be applied to a variety of streams where falls and cascade chutes may, under varying flows, create barrier conditions to upstream-migrating fish. Coarse-scale reviews of site topography coupled with site field visits can and should be used as an initial assessment of barrier potential. In some instances where barrier conditions obviously exist (e.g., steep, vertical waterfalls), these reviews may be all that is needed to determine barrier conditions. However, for sites possessing intricate channel morphologies that create complex, multichanneled cascades and chutes, we believe that site-specific surveys should be considered under a range of flow conditions experienced by fish in the system.

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