Evaluation of Salmon and Steelhead Migration Through the Upper Sultan River Canyon Prior to Dam Construction

Prepared for

City of Everett
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Cover photographs (clockwise): Cascade 6, upper Cascade 7, leaping salmon in another watershed, survey crew negotiating Cascade 7.

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SUMMARY

Potential passage of anadromous salmon and steelhead through the upper Sultan River canyon prior to dam construction was evaluated. A high gradient reach was identified from initial field surveys and a 1913 longitudinal profile of the basin. The high gradient reach (avg. 5.1% gradient) extended approximately 0.7 miles downstream from Culmback Dam (RM 15.8-16.5).

Nine cascades were identified in the high gradient reach, but the fish passage analysis focused on four cascades having the greatest potential to inhibit fish migration. Profiles of the cascades were measured by a professional surveyor. Staff gages were installed in pools above, below, and within cascades and linked to water surface elevations during minimum flow of 20 cfs. Water surface elevations at staff gages were documented from a helicopter during flows of approximately 200 cfs, 312 cfs, and 516 cfs. These readings were used to describe changes in height, distance, and gradient of cascades and falls.

Assessment of fish passage was based on methodology developed by Powers and Orsborn, field measurements of potential migration barriers at several flows, and video and still photography of the cascades at multiple flows. Fish leaping profiles were developed assuming ideal leaping conditions in the launching pool and landing site, and maximum fish condition; i.e., fresh from the ocean. Additionally, length of adult fish was added to the maximum leaping profile calculated from the Powers and Orsborn method. Leap angles were adjusted in order to maximize distance traveled over each cascade or falls, based on characteristics of each cascade.

Cascade 1 rose approximately 11.3 ft vertically over a distance of 38 ft at 20 cfs (30% gradient), but gradient declined as flows increased from 20 cfs to 516 cfs (30% to 23% gradient). Cascade 1 likely represented a partial barrier to migration that may have blocked the migration of coho salmon, and delayed or blocked the migration of some Chinook and steelhead.

Cascade 6 and Cascade 7 (RM 16.3) were formed by large boulders wedged in a narrow canyon with rock walls rising vertically approximately 200 ft. Cascade 6, which rose approximately 14 ft over a distance of 50 ft, would have blocked migration of all salmon and steelhead at all flows, based on the Powers and Orsborn methodology (see summer steelhead discussion below). The only potential migration route was through a narrow drop and chute that rose 10 ft over a distance of 23 ft. Leaping and swimming conditions were poor. Under ideal leaping conditions, steelhead would have landed 3.7-4.2 ft beneath and 5.5-5.6 ft short of the pool, depending on flow (200-516 cfs). Chinook salmon would have landed 4.9-5.6 ft beneath and 9.9-11 ft short of the pool. Coho salmon would have landed 5.2-6.1 ft beneath and 11-12 ft short of the pool. Fish would not have been able to swim over the drop after leaping or sustain multiple leaps because velocity, turbulence, and air entrainment were too high.

Cascade 7 rose approximately 32.5 ft over a distance of approximately 124 ft at 200 cfs to 516 cfs (avg. gradient 26%). Two falls (9.4 ft, 11.4 ft high) occurred in the lower portion of the cascade followed by a turbulent high gradient area (~35% over 35 ft) immediately upstream (no resting areas). Under ideal conditions, Chinook and coho salmon would not have been able to leap over the falls, but some steelhead may have reached the crest. However, conditions of the launching pools and landing sites were poor, indicating leaping performance of steelhead would

have been significantly reduced. The combination of poor leaping conditions, high vertical falls, and high gradient area immediately above the falls would have blocked the migration of most, if not all, steelhead.

Cascade 9 rose approximately 11.8 to 12.7 ft over a distance of 33 ft to 37 ft (32-33% gradient). Leaping over the cascade would not be possible, but conceivably some steelhead may leap over the lower portion then swim over the remaining cascade. Moderate launching conditions and good pool conditions at the cascade top would have facilitated passage.

Profiles of the cascades were based on flows ranging from 20 cfs to 516 cfs. These flows span median (and lower) unregulated flows in the Sultan canyon during July through October and January through March. Steelhead, coho, and late migrating fall Chinook salmon may have experienced median flows that were higher than flows in this study. Characteristics of each cascade change in response to channel features as flow increases above 500 cfs. The vertical height of some falls may decline with higher flows, but overall velocity, turbulence, and air entrainment would increase. Successfully migrating salmon and steelhead would need to negotiate all four turbulent cascades in addition to five smaller cascades, a high velocity chute below Cascade 6, and numerous smaller cascades in the lower Sultan canyon. It is unlikely that salmon and steelhead would successfully negotiate the upper Sultan canyon at flows higher than 516 cfs.

Summer steelhead have a protracted period of migration and sexual maturation in freshwater and superior leaping and swimming abilities that enhance the likelihood of reaching upper watershed areas. In recognition of these unique characteristics and to present an optimistic view of fish passage, it is conceivable that a few individuals may have negotiated passage through the canyon in some years. Nonetheless, fish passage would be intermittent and insufficient to form a sustained run of summer steelhead.

Anecdotal information was gathered on passage of salmon and steelhead through the Sultan canyon based on observations prior to the completion of Culmback Dam in 1965. This information suggests salmon and steelhead were unable to migrate through the Sultan canyon to reach the Sultan Basin. These observations are consistent with the fish passage analysis, which indicates no sustained populations of anadromous salmon and steelhead were present upstream of the Sultan canyon prior to dam construction.

INTRODUCTION

At an early stage of the relicensing process for the Jackson Hydroelectric Project, a request was forwarded by the Washington Department of Fish and Wildlife (WDFW) and the Washington Department of Ecology (WDOE) for conduct of certain studies which might involve a determination of the historic upstream extent of the anadromous zone in the Sultan River. At the time of the request, the City of Everett and the Snohomish County Public Utility District (PUD), as co-licensees of the Project, informed WDFW, WDOE, and other stakeholders that information defining the upstream extent of the anadromous zone already exists in several forms and documents. The co-licensees offered to assemble this information and prepare a single comprehensive report containing and summarizing their existing information. This report uses maximum fish leaping and swimming abilities in conjunction with field observations at multiple flows to assess the potential for salmon and steelhead to migrate through the Sultan River canyon.

The Sultan River is a major tributary of the Skykomish River in the Snohomish River Basin (Fig. 1). The Sultan River has a long history of water use and removal to support human activities. The river currently provides water for the City of Everett and electricity for customers of the PUD. In the 1800s, water was used for hydraulic mining of gold throughout much of the basin. In 1889, an area known as Horseshoe Bend (River Mile (RM 7)) was bypassed with a 0.25 mile long tunnel in order to dewater the river channel and expose gold (see USGS 1914) (Fig. 2). From 1902-1914, a 22 ft high dam was built and operated near RM 3.6 to supply water to a trout farm (Fig. 3). The controversial “Trout Farm Dam” reportedly blocked the migration of all salmon and steelhead for more than 10 years (Lane and Lane 1981). In addition to the Trout Farm Dam, a longitudinal profile of the Sultan River by USGS (1914) identified a 4 ft high “dam” at RM 1.5, which likely hindered the migration of fishes (Fig. 3). In 1916, the City of Everett constructed a water diversion dam at RM 9.5 (completed in 1918) in order to supply the City with approximately 20 cfs of water. In 1930, a new water diversion dam was constructed immediately upstream at RM 9.7 to supply more water to Everett. The water diversion dam blocked the migration of most salmon and steelhead, but some steelhead reportedly migrated passed the diversion dam when the flood gate was opened to flush debris (Pfeifer et al. 1998). In 1965, Culmback Dam was completed at RM 16.5, an area bordering a river canyon below and a broad valley (Sultan Basin) above. Stage II of Culmback Dam (Jackson Hydroelectric Project) was completed in 1984 and is the subject of ongoing FERC relicensing investigations.

Present Spawning Migrations

Spawning surveys since the 1970s show that most pink and chum salmon typically do not migrate into the lower river canyon, which begins near RM 3 (PUD & City of Everett 2005). Summer/fall Chinook, summer and winter steelhead, and coho salmon are known to migrate up to the Everett Diversion Dam (RM 9.7).

During December 2004, a large landslide occurred in the Sultan River near RM 7.3. The slide was captured on video by a group of kayakers (www.kayakingsucks.com/sultan/sultan.html) and it temporarily blocked flow in the river. Salmon and steelhead migration initially appeared to be blocked by the slide based on the lack of salmon or steelhead redds observed as of July 2006 (8 salmon and 11 steelhead surveys). However, during steelhead spawning surveys in spring 2006, approximately 30 coho fry and one spawned-out summer steelhead (hatchery origin) were observed upstream of the slide demonstrating that some adult coho and steelhead gained access above the slide (K. Binkley, PUD, pers. comm.).

Objectives

The objective of this investigation was to evaluate the potential for salmon and steelhead to negotiate passage through the upper Sultan River canyon to gain access to the Sultan Basin. Field effort extended from below the "stringer bridge" (~RM 14.3) to Culmback Dam (RM 16.5), but most survey effort focused on the high gradient reach that is within 0.7 miles of Culmback Dam. Surveys were conducted to estimate vertical height, horizontal distance, and gradient of key cascades and falls during existing base flow (20 cfs) and flows ranging from approximately 200 cfs to 516 cfs. We conducted still and video photography to provide a record of observations in the canyon. Additionally, we reviewed historical documents and spoke to a long-time resident to gather evidence of fish passage through the canyon.

METHODS

Physical Measurements of Sultan Canyon Cascades

The upper Sultan River canyon is difficult and dangerous to access, therefore several hikes into the canyon were required to photograph and document potential fish passage barriers from the stringer bridge to Culmback Dam. According to the City of Everett and the Snohomish County PUD personnel, few if any people had previously hiked through the upper canyon. Climbing ropes and gear were required to negotiate large boulders within 0.7 miles of Culmback Dam. We also used drysuits to swim through 5-6°C water because deep pools (up to 300 ft long) occurred between steep canyon walls rising approximately 250 ft. Discharge from Culmback Dam during the initial study period during fall 2002 was 20 cfs.

During July 2003, the PUD planned to release water below Culmback Dam in order to perform maintenance on the powerhouse tunnel. These releases provided an opportunity to further investigate potential fish passage by quantifying vertical and horizontal distances and flow characteristics of cascades within 0.7 miles of Culmback Dam. In preparation for the flow event, we installed staff gages (bolted to rock) above and below key drops in each of the cascades. The lower end of each staff gage was placed at water surface of pools or at a measured elevation relative to the nearest pool. A professional surveyor (Shane Putnam, Perteet Engineering, Inc.) used a Leica rangefinder to quantify vertical and horizontal distances and azimuth of water surface elevations at pools above, below, and within each cascade.

The PUD released approximately 200 cfs on July 18, 312 cfs on July 6, and 516 cfs on July 11, as well as similar flows throughout the period. Ground surveys of the canyon were unsafe even at 200 cfs, therefore measurements of water surface elevation at each staff gage were recorded from helicopter using binoculars. The helicopter was able to enter the canyon and occasionally land one leg on the top of a cascade boulder to allow observation of staff gages. Readings were based on mean water surface elevation as the water pulsed up and down. During each flow event, the helicopter made two trips through the upper canyon. Digital video and digital photographs were used to document flow characteristics at key cascades. Some of the still photographs from this survey are included in this report.

Fish Passage Analysis

The ability of salmon and steelhead to migrate through the upper Sultan River canyon was assessed using methodology developed by Powers and Orsborn (1985) and observations by other researchers (Orsborn 1983, Aaserude and Orsborn 1985). An important component of this analysis is the burst swimming speed of adult salmon and steelhead. The upper limit of burst swimming speeds (6 sec duration), as reported by Bell (1973) and Powers and Orsborn (1985), was used in the generation of fish leaping profiles[1]:

	Fish Speed (fps)		
Species	Sustained	Prolonged	Burst
Steelhead	0-4.6	4.6-13.7	13.7-26.5
Chinook	0-3.4	3.4-10.8	10.8-22.4
Coho	0-3.4	3.4-10.6	10.6-21.5
Sockeye	0-3.2	3.2-10.2	10.2-20.6
Pink & Chum	0-2.6	2.6-7.7	7.7-16.0

The leaping profiles assumed burst speeds of 26.5 feet per second (fps) for steelhead, 22.4 fps for Chinook, and 21.5 fps for coho salmon. Passage of pink and chum salmon was not assessed because they are known to be blocked by relatively small falls or cascades and relatively few migrate upstream of RM 3 in the lower Sultan River. High-end burst speeds reportedly could be sustained for 6 seconds, whereas speeds at the lower end of the range could be sustained for up to 15 seconds (Orsborn 1983). Webb (1995) reported that fatigue occurred more quickly (within 5 seconds) when swimming at 7 lengths per second, decreasing to <1 second when swimming at 10 lengths per second. The upper burst speed values used in this study meet or exceed the upper range of burst speed values reported by a variety of investigations (Table 1)[2]. Recent research on "fast-start" speeds, which represent dart reactions during predator-prey interactions (<1 second) was reviewed but did not provide information that indicated greater burst swimming speeds (Domenici and Blake 1997).

Salmon length influences burst swimming speed. Longer fish have the potential to swim faster, but the swim speed in terms of fish lengths per second declines rapidly with greater size. For example, Webb (1995) reported that maximum swim speed of salmonids increases from 9.7 lengths per second (16 fps) to 7 lengths per second (20.7 fps) as body length increases from 50 cm to 90 cm.

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[1] Prolonged swimming speed was defined to include activities that led to fatigue within 15 seconds to 200 minutes. Burst speeds were defined as speeds leading to fatigue within 15-20 seconds or less.

[2] A maximum steelhead burst speed of 34.4 fps was reported by Lane (1941); however, this value has not been relied upon by researchers because water current was not considered. Furthermore, the value was reported in "Country Life," a British popular magazine that has no scientific peer review.

Maximum burst speed decreases as fish condition declines (Paulik and DeLacy 1958). Powers and Orsborn assumed a 25% reduction in burst swimming capacity for a fish described as "good condition, in the river for a short time, spawning colors partially developed, and still migrating upriver." For a fish in "poor" condition, they assumed fish burst swimming capacity to be reduced by 50%, i.e., the upper limit of prolonged swimming speed. It is likely that salmonids approaching the upper Sultan canyon were not in "excellent" condition after migrating 50 river miles without feeding and gaining 1,200 ft elevation. Water temperature may influence fish swimming speeds. Rapid acceleration may be somewhat greater at warmer temperatures within 5-15°C (Domenici and Blake 1997). Nevertheless, development of fish leaping profiles to assess fish passage in the Sultan canyon assumed fish were in excellent condition and that burst swimming speed was maximum.

The following text was extracted from Powers and Orsborn (1985), who quantified leaping profiles of salmon and steelhead based on burst swimming speeds and the trajectory of a projectile:

When fish leap at waterfalls, their motion can best be described as projectile motion (i.e., curved two-dimensional motion with constant acceleration). Neglecting air resistance, the equations for projectile motion are:

$$x = (V_o \cos\theta)t, \text{ and}$$
$$y = (V_o \sin\theta)t - (1/2)gt^2$$

where x = horizontal distance of the projectile, y = vertical distance of the projectile, V_o = initial velocity of the projectile, θ is the angle from the horizontal axis the projectile is fired, t = time, and g = acceleration of gravity (32.2 ft/sec^2). Rewriting the equations for x and y in terms of the components that relate to fish leaping at waterfall or steep cascade yields:

$$XL = [VF(\cos\theta L)]t \text{ and} \qquad (1)$$
$$HL = [VF(\sin\theta L)]t - (1/2)gt^2 \qquad (2)$$

where XL = horizontal distance or range of the leap at some time (t), HL = height of leap at some time (t), VF fish speed, θL = angle of leap from the plunge pool, and g = acceleration of gravity acting downwards (32.2 ft/sec^2). By combining equations (1) and (2) and eliminating t from them, we obtain:

$$HL = (\tan\theta L)XL - g(XL)^2/2(VF\cos\theta L)^2 \qquad (3)$$

This equation relates height of leap (HL) to leap distance (XL) and is the fish trajectory equation. Since VF, θL and g are constant for a given leap, equation (3) has the parabolic form of:

$$HL = b(XL) - C(XL)^2$$

Hence the trajectory of leaping fish is parabolic. At the highest point of the fish's leap, the vertical component of the velocity is zero, that is:

$VF_y = VF(\sin\theta L) - gt = 0$

Solving this equation for t gives:

$t = VF(\sin\theta L)/g$

Substituting this equation for t into equation (1) and (2) yields:

$$HL = (VF(\sin\theta L))^2/g - (1/2)\,(VF(\sin\theta L)^2/g$$
$$HL = (VF(\sin\theta L))^2/2g \qquad (4)$$
$$XL = (VF^2(\cos\theta L)(\sin\theta L/g) \qquad (5)$$

Equations (4) and (5) give the maximum height of the fish's leap and the horizontal distance traveled to the maximum height. These equations were used to generate fish leaping profiles in the Sultan canyon.

Maximum leaping trajectories for salmon and steelhead are shown in Fig. 5, assuming maximum burst speed and optimum fish condition. Steelhead have the greatest leaping ability (max. height: 10.9 ft at 90° trajectory), followed by Chinook (7.8 ft), coho (7.2 ft), sockeye (6.6 ft), pink and chum salmon (3.5 ft). Maximum leaping height declines as the horizontal distances needed to achieve success increases. For steelhead, the maximum horizontal leaping distance is approximately 21.8 ft when take-off angle is 40°, but the maximum height of this jump is only 5.5 ft (Fig. 6). Thus, leaping success of fish is related to both the height and horizontal distance of the migration impediment. For the Sultan canyon analysis, an iterative process was used to identify the leaping angle that maximized leaping distance relative to the gradient of each cascade or falls.

Aaserude and Orsborn (1985) stated that the aforementioned leaping curves may underestimate leaping height of fish because they do not consider continued burst swimming as the fish leaves the water. They estimated that this additional swimming effort may increase maximum leaping height by the addition of fish length. Thus, they note that maximum leap heights of steelhead and Chinook salmon may be up to 13.9 ft and 10.1 ft, respectively. These heights assume that the fish are able to achieve maximum thrust as they exit the water, i.e., little effect of turbulence and air entrainment on leaping. For the Sultan canyon analysis, length of fish was added to the leaping profile equations (Powers and Orsborn 1985) while adjusting for the angle of fish leaving the water. Assumed lengths were 32 inches for steelhead, 36 inches for Chinook, and 28 inches for coho salmon.

The addition of fish length to leaping profiles has implications for burst swim speeds estimated from observed leaping heights of fish. Aaserude and Orsborn (1985) note that burst swim speeds were overestimated when back-calculated from leaping height because these estimates did not consider fish length as the fish exited the water. The overestimation of burst swim speeds based on observations of leap heights was first noted by Paulik and DeLacy (1957).

A number of physical factors of a waterfall affect the ability of fish to pass in addition to the size of the falls. Table 2 summarizes the effects of these factors. Fish typically initiate their leap from the standing wave or hydraulic jump, which can have upwelling currents that provide an extra boost to the leaping fish. Launching pool characteristics that influence salmon leaping ability in the launching pool include pool depth, location of the standing wave, water turbulence, air entrainment, and orientation of water flow entering the pool. Success at the landing site is influenced by water velocity, orientation and plane of the landing fish, distance to the nearest pool or velocity refuge, and overhanging rock. Higher impediments lead to greater failure rates, which in turn can lead to reduced condition and swimming performance as the fish attempts to leap again.

RESULTS

Characteristics of Cascades and Falls in the Upper Sultan Canyon

Average gradient of the Sultan River increased sharply at approximately RM 15.8 where a bedrock cascade (Cascade 1) rose upstream from a large, deep pool. Average gradient between Cascade 1 and Culmback Dam, a distance of 0.7 miles, was approximately 5.1% (USGS 1914). Nine cascades were documented within this reach. The cascades were sequentially numbered from the lower to upper river. Our efforts focused on four cascades (Cascades 1, 6, 7, and 9) having the greatest gradient and potential for inhibiting fish migration. Measurements of the cascades were initially taken during minimum flows of 20 cfs; higher flows produced unsafe conditions for rock climbing, wading, and swimming that were necessary to access sampling locations throughout the upper canyon.

Cascade 1 rose approximately 11.3 ft vertically over a distance of 38 ft at 20 cfs (30% gradient), but the upper portion of Cascade 1 was near 50% gradient (Table 3, Fig. 7). Average gradient declined to 26% and 23% as flow increased from 200 cfs to 516 cfs, respectively.

A series of smaller cascades (Nos. 2-5) were located between Cascade 1 and Cascade 6. These cascades were separated by relatively deep pools (> ~10 ft) and/or boulder garden runs.

Cascade 6 and Cascade 7 (RM 16.3) were formed by large boulders wedged in a narrow canyon (~30 ft wide) with rock walls rising vertically approximately 200 ft. Cascade 6 rose 15 ft over a distance of 50 ft at 20 cfs (30% gradient) (Table 3). Average gradient ranged from 28-29% as flow increased to 516 cfs. Potential fish passage was possible only through a narrow drop and chute along the right rock wall (Fig. 8). A left bank channel fell nearly vertically for 15 ft and was not suitable for fish passage (Fig. 9).

A relatively deep pool separated Cascade 6 and Cascade 7 (Fig. 10). Cascade 7 rose 34.5 ft over a distance of approximately 124 ft at 20 cfs (average gradient 28%) (Table 3). Gradient declined slightly to 26% as flow increased to 516 cfs. The lower portion of this long cascade contained two channels (Fig. 10 and 11), which converged upstream on a relatively steep boulder area (Fig. 12; see cover photo). The lower right bank channel contained a narrow 10 ft vertical drop (20 cfs) that plunged into a shallow pool (Fig. 11). Vertical drop increased to 11.4-11.7 ft at flows of 200-516 cfs. The left channel cascaded over boulders before plunging approximately 8.3 ft (Fig. 12). Vertical drop increased to 9.4-9.8 ft at 200-516 cfs.

Cascade 9 was located immediately below a relatively deep pool that separated it from Culmback Dam. Cascade 9 rose from a deep pool approximately 12 ft over a distance of 32 ft at 20 cfs (gradient 38%) (Table 3). Gradient declined from 38% to 32% as flow increased from 200 cfs to 516 cfs.

Fish Passage Analysis

At Cascade 1, the significant lower drop observed at 20 cfs was partially inundated at 200 cfs to 516 cfs because elevation of the lower pool and the bedrock channel leading to it increased quickly as flow increased (Fig. 13). Fish could readily approach the base of Cascade 1 by swimming below turbulent surface waters within the narrow deep bedrock channel. Leaping over Cascade 1 would not be possible as it was too long (up to 38 ft), but fish may have used a combination of leaping and swimming. The lower gradient area between the two drops would likely facilitate passage. Nevertheless, Cascade 1 likely represented a partial impediment to migration that may have blocked the migration of some fish, especially coho salmon, and delayed the migration of most other fish.

Fish approaching Cascade 6 must first swim through a narrow ~20 ft long bedrock chute that transports all water up to at least 516 cfs (Fig. 14). At 20 cfs, the chute was a narrow pool. As flow increased, velocity in the chute rose because elevation of the upper pool increased rapidly (up to 3.9 ft) relative to the lower pool. Although we did not measure the cross-section of this chute, it was apparent in the video that water velocity was exceptional. For example, if we assumed that average depth and width increased from approximately 3.5 x 5 ft to 6 ft x 5.5 ft as flow increased from 200 cfs to 516 cfs, then velocity increased from 11.4 fps to 15.6 fps, respectively. While the accuracy of these visual calculations are unknown it is apparent from video taken at several flows that high velocity would impede, if not block, the migration of some salmonids at higher flows.

Cascade 6 represents the first cascade in which all migration of salmon and steelhead would have been blocked at all flow levels. The narrow drop and chute along the right rock wall was the only potential channel that might be attempted by migrating salmonids, as the left channel dropped nearly vertically for 14.1-15 ft (Table 3). Fish may have held in the deep pool below the cascade, then approached the drop and chute through the narrow, turbulent (air entrained) channel and turned right at the rock wall in order to gain access to the drop and chute. Holding in the small "pool" immediately below the chute would have been difficult because turbulent whitewater flushed the entire pool and pushed water up against the large rock immediately below the chute. Water conditions at the launching pool and landing site were poor (see Table 2). At all measured flows, leaping over the drop and chute would not have been possible because salmon and steelhead would have landed near the base of the drop or below even when assuming ideal leaping conditions (Figs. 15, 16, 17, 18). For example, under ideal conditions, steelhead would have landed 3.7-4.2 ft beneath and 5.5-5.6 ft short of the pool, depending on flow (200-516 cfs). Chinook salmon would have landed 4.9-5.6 ft beneath and 9.9-11 ft short of the pool. Coho salmon would have landed 5.2-6.1 ft beneath and 11-12 ft short of the pool. Swimming over the drop after leaping or multiple leaps would not have been possible because velocity, turbulence, and air entrainment were too high. For example, velocity of water in the 4 ft drop would approach 16 fps, based on velocity of a free falling object over 4 ft ($V = \mathrm{sqrt}(2gh)$).

At higher flows, some water poured through a notch in rocks at Cascade 6 and into the leap initiation pool. However, fish are attracted to dominant flow in a flow field; e.g., water momentum (discharge x velocity or area x velocity^2; Orsborn 1983), and the small volume of water spilling over this notch would not have attracted fish in the turbulent pool. Furthermore, vertical height of the drop (8-10 ft) and turbulence of the leap initiation pool would have prevented successful leaps.

Cascade 7 was approximately 124 ft long over a 26% gradient. Two separated falls and associated channels in the lower cascade converged onto a steep boulder cascade. The drop along the base of the right rock wall contained most of the water and likely would be more attractive to migrating salmonids compared with the left channel drop. Leaping conditions at the right channel drop were poor; the leap initiation pool was shallow (less than vertical height of falls), turbulent, and entrained with air, whereas the landing site was a high velocity cascade with no resting areas. Under ideal conditions, Chinook and coho salmon would not have been able to leap over the 11.4 ft falls, but some steelhead may have barely reached the crest (Figs. 19, 20, 21).

Leaping conditions at the left channel drop of Cascade 7 were less than ideal because: 1) a bolder was near the leap initiation pool and may have interfered with the leap, 2) a bedrock over-hang may have interfered with leaping salmon while in the air, and 3) the landing site was swift with little resting area. Under ideal conditions, Chinook and coho salmon would not have been able to leap over the 9.4-9.8 ft falls, but steelhead may have reached the crest (Figs. 19, 20, 21).

Both channels of lower Cascade 7 falls continued upstream through a steep cascade (~35% gradient) (Fig. 22). There are no resting areas in this area for approximately 35 ft before reaching another drop just below a pool. Steelhead, if any, that successfully leaped over the right or left channel falls would have to continue through the cascade for at least 35 ft before finding a large resting area. As shown in Fig. 22, steelhead would need to zigzag around boulders in swift water that could potentially knock fish off course and carry them downstream. Thus, Cascade 7 would have blocked the migration of Chinook and coho salmon at the falls, and it is likely that most steelhead would have been unsuccessful if attempting to pass the cascade due to the falls and to poor leaping and swimming conditions throughout the long cascade.

Cascade 9 rose approximately 11.8 to 12.7 ft over a distance of 33 ft to 37 ft (32-33% gradient). Salmon and steelhead would not have been able to leap over the cascade because the distance and height were too great (Figs. 23, 24). However, some individual steelhead may have been able to leap over the initial steep portion of the cascade then swim over the remaining cascade to the deep pool. The pool at the base of the cascade was relatively deep which is conducive to leaping, but the slope of the cascade pushed the standing wave away from the crest. The crest of the cascade was joined by a deep pool which would provide a resting area for successful fish.

DISCUSSION

The Sultan canyon fish passage analysis used methodology presented by Powers and Orsborn (1985) and Aaserude and Orsborn (1985). Some recent field observations of salmon and steelhead support the methodology suggested by these researchers. For example, Bradford et al. (1996) investigated leaping success of salmon and steelhead at the Kalama Falls Hatchery barrier dam[3]. The barrier rises vertically approximately 11.15 ft at low flows, but this distance decreases at higher flows. They reported that 0% of 13,823 coho salmon leaps, 0.08% of 76,563 Chinook salmon leaps, and 0.9% of 68,517 steelhead leaps were successful (Table 4). Greatest leaping success occurred during summer when flows were relatively low and fish could initiate leaps closer to the vertical falls. Although higher flows led to reduced vertical height, high flows pushed the standing wave farther downstream, leading to reduced leaping success. Few steelhead attempted to leap during winter (November to March) and none were successful. The authors suggested that leaping behavior was reduced during this period in response to higher flows, turbulence, air entrainment, and lower temperatures. Kalama Falls is a vertical barrier with a pool and a landing site that are much more conducive to leaping success compared with those in the upper Sultan canyon. The Kalama Falls study indicates a very small percentage of steelhead and Chinook were able to leap over a falls that is near the maximum estimated leap-height of steelhead.

In order to provide an "optimistic" estimate of passage through the Sultan canyon, leaping profiles were generated using ideal leaping conditions, optimum fish condition, and the addition of fish length to the leaping curves (Aaserude and Orsborn 1985). Nevertheless, migration of Chinook and coho salmon and steelhead would have been blocked during all measured flows at Cascade 6, and Chinook and coho would have been blocked by the lower falls at Cascade 7. Leaping and swimming conditions at each of the cascades were poor (see photographs), and leaping ability of salmon and steelhead would have been reduced compared with assumptions used in the leaping analyses.

Fish passage analyses were based on flows that were approximately 20 cfs, 200 cfs, 312 cfs and 516 cfs. These flows span median (and lower) unregulated flows in the Sultan canyon during July through October and January and March (Fig. 25). Median flows during April to June and November to December were higher than the flows examined in this study. Thus, steelhead, coho, and late migrating fall Chinook salmon may have experienced median flows that were higher than flows in this study. Characteristics of each cascade will change as flow increases above 500 cfs in response to channel characteristics and hydraulic control points. It is likely that vertical height of some falls would decline with higher flows, but overall velocity through the high gradient reach would increase. Successfully migrating salmon and steelhead would need to negotiate all four major cascades discussed here in addition to five smaller cascades, the high velocity chute below Cascade 6, and numerous smaller cascades in the Sultan canyon, which extends approximately 12.8 miles below the high gradient upper reach. At higher flows, Cascade 7, which rose approximately 32 ft over a distance of 124 ft, would have high velocities, turbulence, and air entrainment that would most likely block the migration of all salmon and steelhead. At high flows, Cascades 6 and 7 would likely form a single turbulent cascade. Powers and Orsborn (1985) ranked turbulent cascades as the most difficult type of barrier for fish passage, independent of barrier height and velocity. Bradford et al. (1996) observed few salmon and steelhead attempting leaps over Kalama Falls when flows increased during fall through spring, presumably because conditions were less than optimal and success was unlikely.

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[3] The barrier dam was constructed over a large cascade and a fishway was installed to enable fish to gain access to the upper watershed. Many fish still attempt the leap over the falls, but most gain access to the upper watershed through the fishway.

It is unlikely that salmon and steelhead would successfully negotiate the upper Sultan canyon at flows higher than 516 cfs.

Fish passage analysis assumes that the channel characteristics observed in the study were present prior to dam construction. USGS (1914) identified this reach as a high gradient reach, but detailed characteristics of each cascade are not available. Photographs show that the cascades and falls were created by large boulders wedged between narrow canyon walls and bedrock formations. Although exceptionally high flows can occur in the Sultan canyon, it is unlikely that these flows would significantly move the large boulders that provide the foundation for the large cascades. Thus, passage conditions observed in the study were likely similar to those experienced by salmonids prior to dam construction.

Summer steelhead have the greatest ability among salmon and steelhead races to negotiate migration barriers. Summer steelhead typically enter freshwater in May though October and hold in pools while waiting for adequate flow conditions before moving upstream through areas of difficult passage. Unlike other salmon, gonad development of summer steelhead is low when they enter freshwater and leaping performance is likely enhanced by this trait. Summer steelhead do not spawn until the following spring. While the fish passage analysis presented here, based on the Powers and Orsborn methodology, indicates steelhead would not be able to pass through the Sultan canyon, it is conceivable that a small number of summer steelhead might occasionally pass the cascades under ideal flow conditions in some years. This statement recognizes the unique abilities of these fish. However, it is unlikely that sustained populations of summer steelhead would have been supported upstream of the Sultan canyon.

Historical Fish Passage Information

Anecdotal information was gathered on passage of salmon and steelhead through the Sultan canyon based on observations prior to the completion of Culmback Dam in 1964. Lane and Lane (1981) reviewed history and Indian use of the Sultan River for the Bureau of Indian Affairs. The following quotation was extracted from a paragraph that discussed Indian activities in the Sultan Basin (i.e., area of Spada Lake) near 1890 or so:

> *"The Sultan Basin was a favorite resort for elk hunting in the early days. Indian people resident in the Sultan area as well as people living at the Tulalip and at villages elsewhere in the drainage system used to go to the Basin in summer to hunt. These parties would fish in the upper Sultan system while hunting in the Basin………People living downstream in villages near the present town of Monroe and upstream villages near the present town of Index traveled to the Sultan Basin in summer and early fall. The fish taken in the upper reaches of the river were primarily resident trout species." (p. 22)*

Pfeifer et al. (1998) reviewed anecdotal information regarding the passage of salmon and steelhead to the Sultan Basin. A former employee of Everett Water Department (Dave Mundell, 1952-1988) recalled a WDG warden claiming to have caught 5-6 inch "steelhead smolts" at the confluence of the north and south fork Sultan River in 1955. Presumably the fish were somewhat silvery in color, leading the warden to speculate that the fish were smolts. However, recent studies in other regions indicate resident rainbow trout can produce anadromous smolts (Busby et al. 1996, Pascual et al. 2000, J. Nielsen, USGS geneticist, pers. comm.). The Everett employee also reported to Pfeifer et al. that "a friend of my uncle" caught huge trout in the Sultan Basin during the late 1930s or early 1940s. However, the *1946 Ben Paris Fishing and Hunting Guide to the Northwest* stated: "SULTAN RIVER…The upper reaches, together with Williamson Creek (i.e., above Spada Lake), a fair sized tributary, where road ends at a ranger station bridge, offer exceptionally good fishing for rainbow trout and cutthroat trout of average size." Pfeifer et al. noted that none of the lakes and streams of the upper Sultan had been stocked at that time by WDG, although other federal and county agencies were known to stock trout or char in regional waters prior to 1933.

Russ Orell, a retired Washington Department of Fisheries (WDF) biologist and a long-time resident and angler of the Sultan area, was interviewed by Pfeifer et al. and Ruggerone. He clearly recalled numerous trips to the Sultan Basin with Grant Bryson, also a long term resident prior to Stage 1 development. The river and forks above the canyon were apparently heavily-laden with trout "as you could catch 20 at any point along the river. Most were 7 to 9 inches, but some ranged from 12 to 14 inches." These men would hike from the forks confluence "about a mile" downstream into the upper canyon "to the barrier," which consisted of a vertical drop of roughly 10 ft over a bedrock shelf. Orell was cautious to point out that this shelf was not a steep boulder cascade. Orell noted that in his opinion, the chance that rainbow in the upper basin were of steelhead origin was "pretty unlikely." While noting that a 10 ft vertical falls would block all salmon migration, Pfeifer et al. noted that summer steelhead might pass the falls under ideal conditions. Pfeifer et al. concluded that the genealogy of rainbow and cutthroat trout in the Sultan Basin is likely a combination of a relict stock present since the last glaciation, with possible additions of one or more hatchery stocks.

In summary, anecdotal information provided by Lane and Lane (1981) and Pfeifer et al. (1998) suggest it was unlikely that salmon and steelhead were able migrate through the Sultan canyon to reach the Sultan Basin. These observations are consistent with the fish passage analysis.

CONCLUSIONS

Fish passage analyses, based on the Powers and Orsborn methodology and field measurements of cascades and falls at flows of 20 cfs to 516 cfs, indicate salmon and steelhead would not have been able to migrate through the upper Sultan canyon at any flow levels to reach the Sultan Basin. Complete blockage would have occurred at one or more cascades in the canyon. Anecdotal historical information supports this conclusion. In recognition of the unique migration pattern and superior leaping ability of summer steelhead, it is possible that a few summer steelhead may have gained passage during some years, but intermittent passage of a few individuals would not be sufficient to support a sustained population of summer steelhead upstream of the upper Sultan canyon.

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Table 1. Estimates of salmon burst swimming speeds and duration. Also see Wolter and Arlinghaus (2003), Domenici and Blake (1997).

Species	Fish Length (ft)	Velocity (ft/s)	Velocity (length/s)	Time (s)	Comment	Source
Steelhead	2.0-2.7	13.7-26.5		5-10		Bell 1986
	1.9-2.2	6.1-7.4	2.8-3.7	10-15	Annular trough	Paulik and DeLacy 1957
	2.0-2.7	17.6-26.8	7.5-13.4	1.1	Timed over distance in fishway; max velocity declined after 30 ft	Weaver 1963
	~2.8	26.2		NA		Wardle & He 1988
	Adult	18.0-34.4		NA	Hook & Line; reported in "Country Life" a popular UK magazine, current not considered	Lane 1941; see Beamish 1978
Chinook	Adult	10.8-22.4		5-10		Bell 1986
	1.7-3.2	17.8-21.9	6.9-10.7	1.4	Timed over distance in fishway; max velocity declined after 30 ft	Weaver 1963
Coho	Adult	10.6-21.5		5-10		Bell 1986
	1.4-2.2	5.3-7.1	2.7-4.4	10-15	Annular trough	Paulik and DeLacy 1957
	1.7-2.5	7.2-12.2	4.3-6.4	0.1	Annular trough	Paulik and DeLacy 1957
	1.2-2.0	9.4-17.5	6.2-9.2	1.7	Timed over distance in fishway	Weaver 1963
Sockeye		10.2-20.6		5-10		Bell 1986
	1.8-2.3	5.1-6.7	2.2-3.1	10-15	Annular trough	Paulik and DeLacy 1957
		8.8-10.3		NA		Beamish 1978
Chum	Adult	7.7-15		5-10	Based on leap height of 3-4' at falls	Bell 1986
Pink	Adult	7.7-15		5-10	Based on leap height	Bell 1986
Salmon (general)	40-60	13.1-20	10		video tape experiment	Beamish 1978

Table 2. Characteristics of falls and steep cascades that influence passage by salmon and steelhead. Sources: Stuart (1962), Orsborn (1983), Powers and Orsborn (1985).

Characteristic	Comment
Launching pool	Depth of pool should be greater than length of fish for maximum propulsion; a good takeoff pool is essential if fish are to leap to any reasonable height; adequate pool conditions needed so that fish's orientation and propulsive power are unimpaired.
	Depth of falling water penetration should be less than depth of plunge pool; if not turbulence disorients fish & standing wave reduced and shifted downstream from where falling water strikes bed of pool.
	Fish approach to leap is usually made downstream of standing wave with the body at an angle between 20° an 30° to pool surface and head pointed downward; often tail broke surface of water (Stuart 1962).
	Pool depth should be 1.25 times that of falls height to maximize standing wave effect (Stuart 1962). This was verified hydraulically at WSU (J. Orsborn, pers. comm.).
Light & shade	High contrast between crest of falls and background (sky or trees) is needed for fish orientation. Leaping stops at dusk and heavy overcast (Stuart 1962).
Standing wave	Fish typically hold in and leap from standing wave to gain momentum and additional elevation; without a standing wave the fish will attempt to swim over the obstruction (Stuart 1962). A standing wave produced from vertical falls will be closer to the falls and will produce conditions more conducive of successful passage compared with a wave produced by a chute (Stuart 1962).
Turbulence	Burst speed and jumping height reduced by excessive turbulence and air entrainment; unstable pools disorient and reduce fish's leap trajectory.
Falls height	Maximum leaping height (steelhead) is 10.9 ft, thus "falls exceeding 11 ft water surface elevation are total barrier"; however, Aaserude suggests fish length should be added to height. Maximum height only possible at vertical falls.
Splash rocks	Water may strike rock as it cascades over falls or as it plunges into pool. Splash rocks affect horizontal and vertical angle of attraction flow by modifying the standing wave, which fish use to judge their angle of leaping at the falls. This signal is key to successful leaping of salmon and it is the most critical factor affecting leaping success if height is within reach (Orsborn 1983, J. Orsborn, pers. comm.).
Falls horizontal distance	Height of passable falls is reduce to extent horizontal distance increases, e.g. maximum height of steelhead reached at horizontal distance of 4 ft when leaping at 80° angle. Thus, high gradient chutes can be difficult to leap over.
	If the standing wave is located distant from the crest of the fall beyond the visual range of the fish, as is found below a chute or long sloping weir, the leaps may not be oriented and passage may be unsuccessful (Stuart 1962).
Horizontal angle of falls	In plan view of cascade, the horizontal angle of falls relative to the upstream landing area is important to leaping success. If inadequate, fish may miss the upper pool or strike their heads on an overhang or land on shore where they may not be able return to the stream.
Landing site	A landing site having high velocity and turbulence will reduce leaping success. Optimal when crest of falls enters deep, calm pool.
Orientation	The fish's angle of approach to the crest must be aligned with the flow or the fish will be swept back.
Water velocity	For more energetically capable salmonids, such as steelhead and Chinook, leaping is more energetically efficient than swimming when drop reaches approximately 1.25 ft or 9 fps. Less capable species, such as chum salmon, will attempt to swim through the drop.
	Velocity at or near the landing site should be within the range of the sustained swimming speed for the species (e.g., steelhead: less than 4.6 ft/s; Chinook & coho: 3.4 ft/s; sockeye: 3.2 ft/s); greater velocities will reduce success depending on distance to refuge.
	Because of the violence and air entrainment in turbulent flow and the effect it has of reducing fish capabilities, Powers and Orsborn (1985) assumed that "any waterfall that is steep enough to accelerate the flow into violent turbulent white water is a total barrier to all fish species attempting to swim up the barrier. Fish can only pass if they leap and clear the area of turbulence before landing."
Fish condition	Fish condition can have a significant impact on leaping ability. Fish traveling relatively long distances and holding in freshwater for prolonged periods will have reduced leaping ability compared with "fresh" fish that recently left the sea (Powers and Orsborn 1985).

Table 3. Characteristics of Sultan cascades during four discharge levels.

		20 cfs			200 cfs			312 cfs			516 cfs		
Cascade	Section	Vertical (ft)	Horizontal (ft)	Gradient	Vertical (ft)	Horizontal (ft)	Gradient	Vertical (ft)	Horizontal (ft)	Gradient	Vertical (ft)	Horizontal (ft)	Gradient
1	Drop 1	3.5	7	50%	3.8			3.7			3.5		
	"pool"		15										
	Drop 2	7.8	16	49%	6.2			5.8			5.1		
	Total	11.3	38	30%	10.0	38	26%	9.5	38	25%	8.6	38	23%
6	Drop & chute	11	23	48%	10	23	43%	10	23+	43%	see photos	23+	
	Total @ toe	15	50	30%	14.4	50	29%	14.1	50	28%	14.4	50	29%
7	upper	11	15	73%	9.5	see photos		9.4	see photos		9.4	see photos	
	mid-pool		47										
	abv RT drop	11	31	35%	10			9.7			10.1		
	Lower RT drop	10	4	250%	11.4	7	163%	11.7	8.0	146%	11.4	11	104%
	"pool"		26										
	drop	2.5	1										
	Lower LT drop	8.3	9	92%	9.4	10	94%	9.8	11	89%	9.8	13	75%
	Total	34.5	124	28%	32.4	124	26%	32.6	124	26%	32.7	124	26%
9		12	32	38%	12.7	33	38%	12.2	37	33%	11.8	37	32%

Table 4. Leaping success of salmon and steelhead at Kalama Falls Hatchery barrier dam. Height of falls (surface of plunge pool to top of falls) was approximately 11.15 ft during low flow, but height declined with higher flows. Greatest success occurred during June, July and August. Leaping activity declined sharply during fall, winter and spring. No leaping activity by cutthroat trout or other species was observed. Source: Bradford et al. 1996.

Year	Sampling Months	Steelhead Leaps	% success	Chinook Leaps	% success	Coho Leaps	% success
1988	May-December	36,447	0.95%	53,196	0.10%	9,392	0.00%
1989	January-December	19,720	0.81%	16,723	0.05%	3,001	0.00%
1990	January-December	9,368	1.02%	6,510	0.02%	1,430	0.00%
1991	January-June	2,992	0.53%	134	0.00%	0	

Few fish attempted to jump over falls during November through March and none were successful.

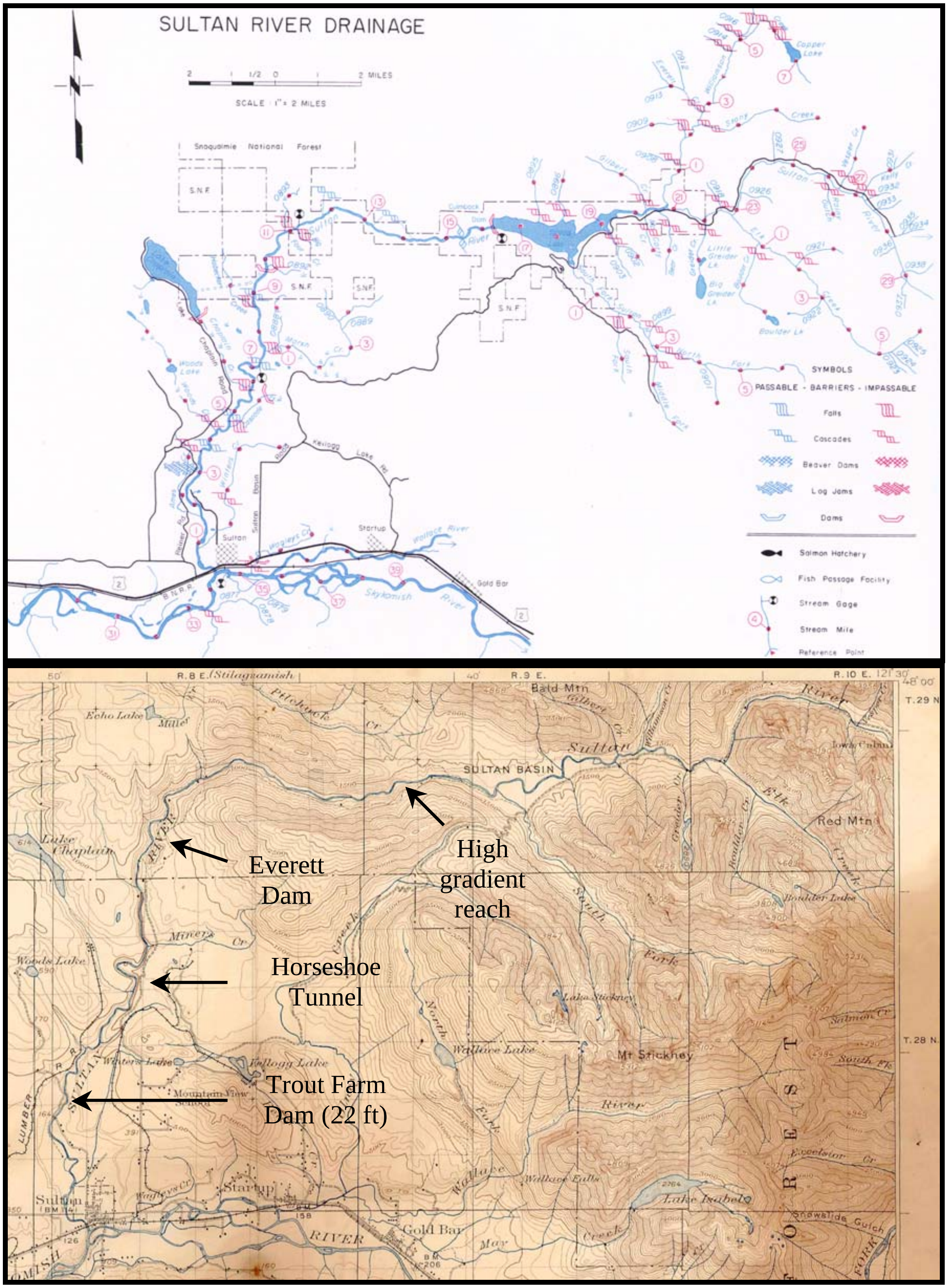


Fig. 1. Fisheries map (upper; WDF 1975) and 1919 topographic map (lower) of the Sultan River drainage. Major cascades identified in the current study were not previously identified by WDF.

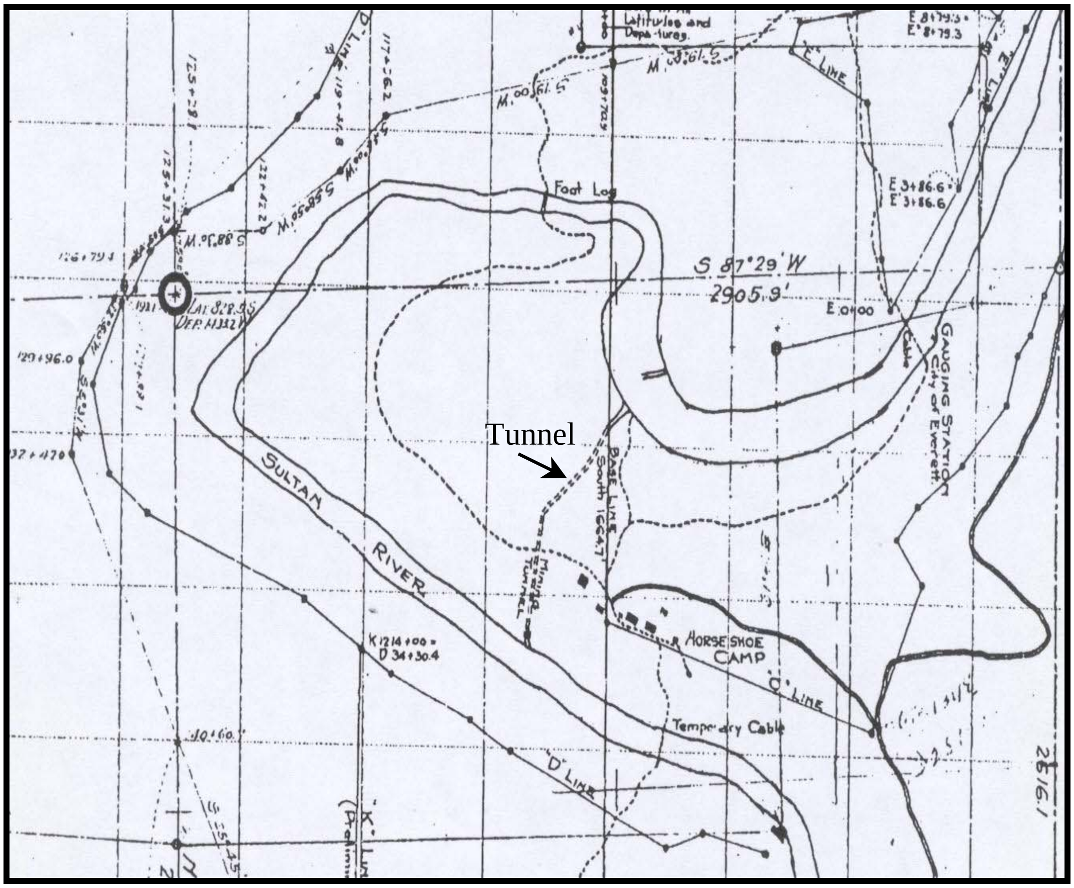


Fig. 2. Map showing the location of the bypass tunnel at Horseshoe Bend (near RM 7). In 1889, the river was channeled through the quarter-mile tunnel to expose gold deposits in the dry river bed. Source: City of Everett.

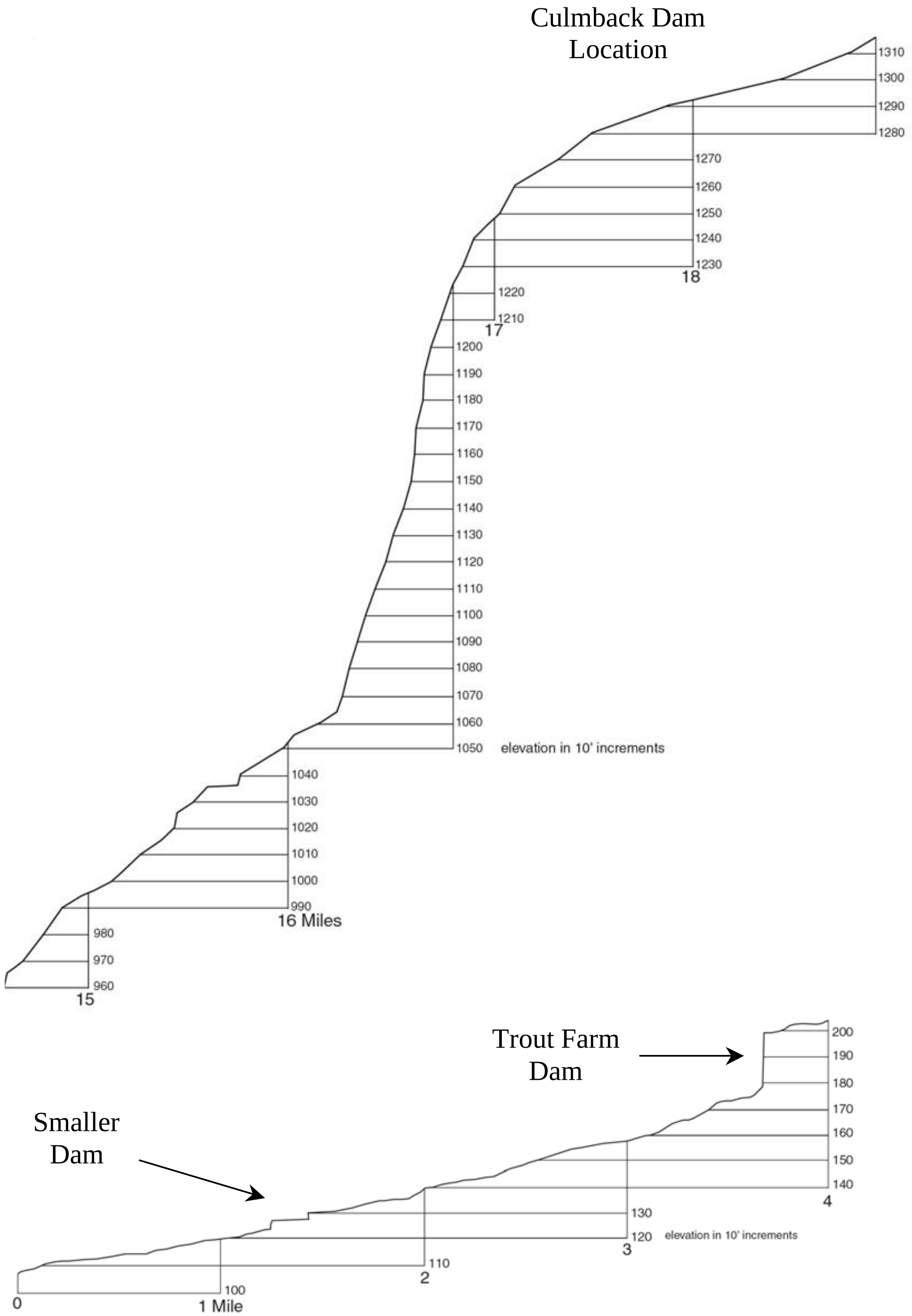


Fig. 3. Sultan River profile of the lower 4 miles and the high gradient reach immediately below the current location of Culmback Dam. Profiles scanned from USGS (1914), who surveyed entire river during 1913, i.e., prior to construction of Everett Diversion Dam and Culmback Dam. Location of Trout Farm Dam (1902-1914) and 4 ft high dam at RM 1.5 are shown. USGS classified the 4 ft drop as a “dam”.

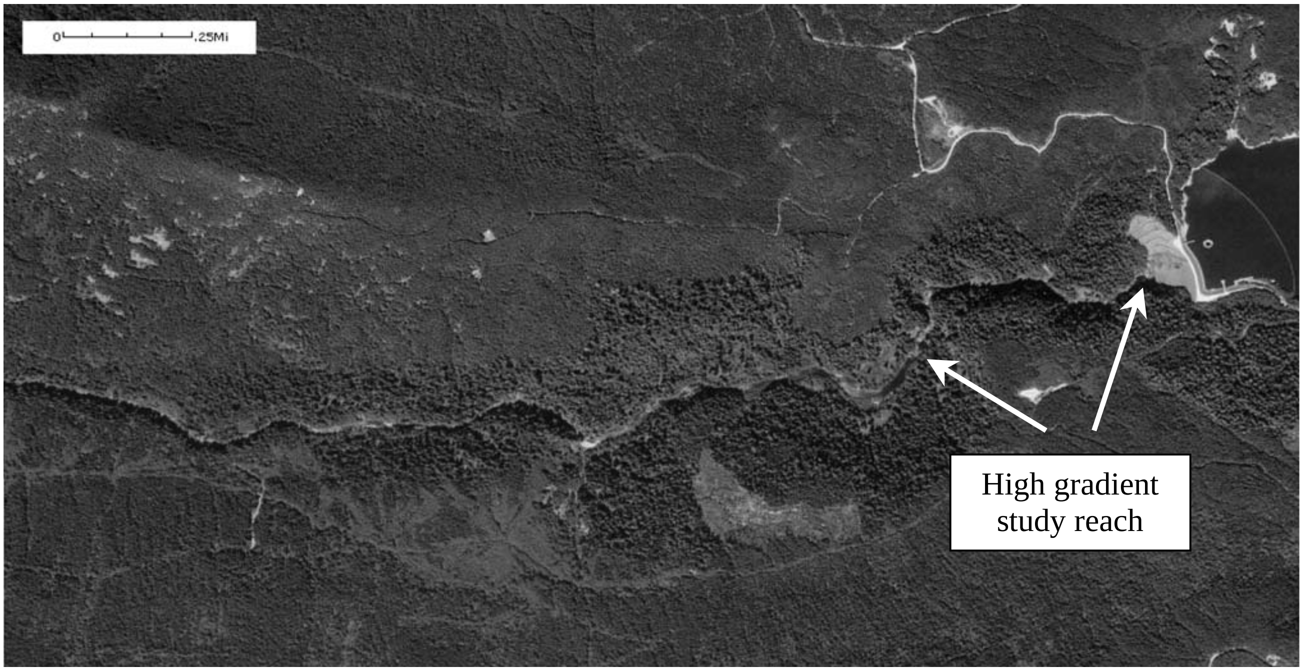


Fig. 4. Aerial view of upper survey reach immediately below Culmback Dam.

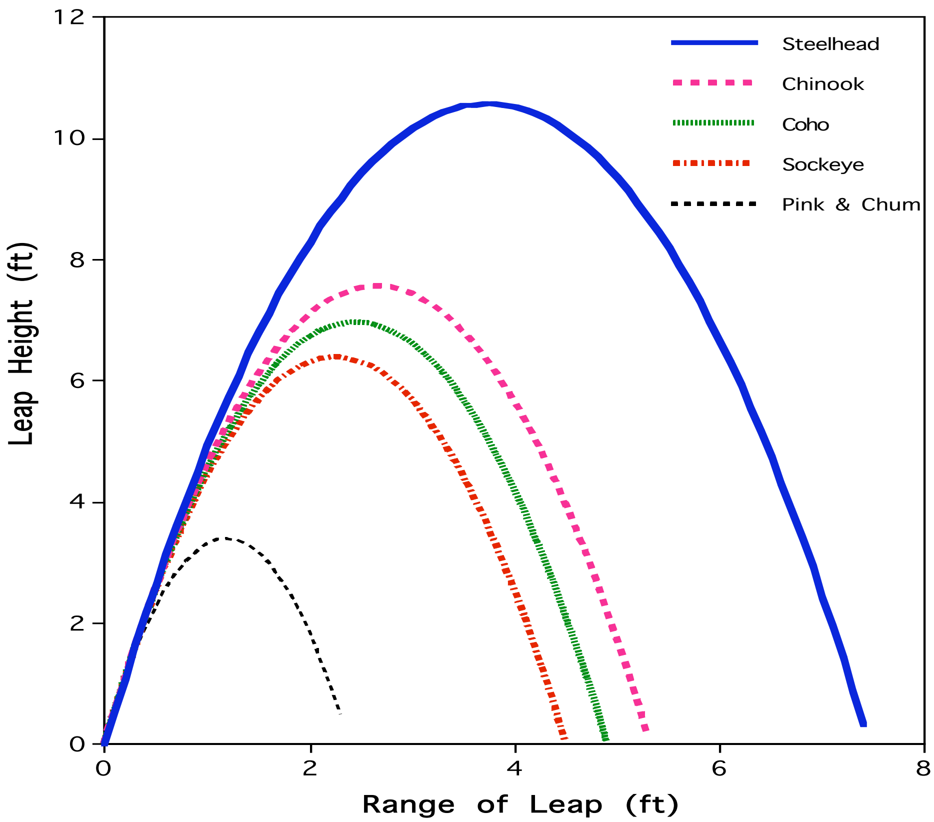


Fig. 5. Maximum salmon and steelhead leaping abilities assuming 80° leaping angle, maximum burst speed, and maximum body condition. Data Source: Powers and Orsborn 1985.

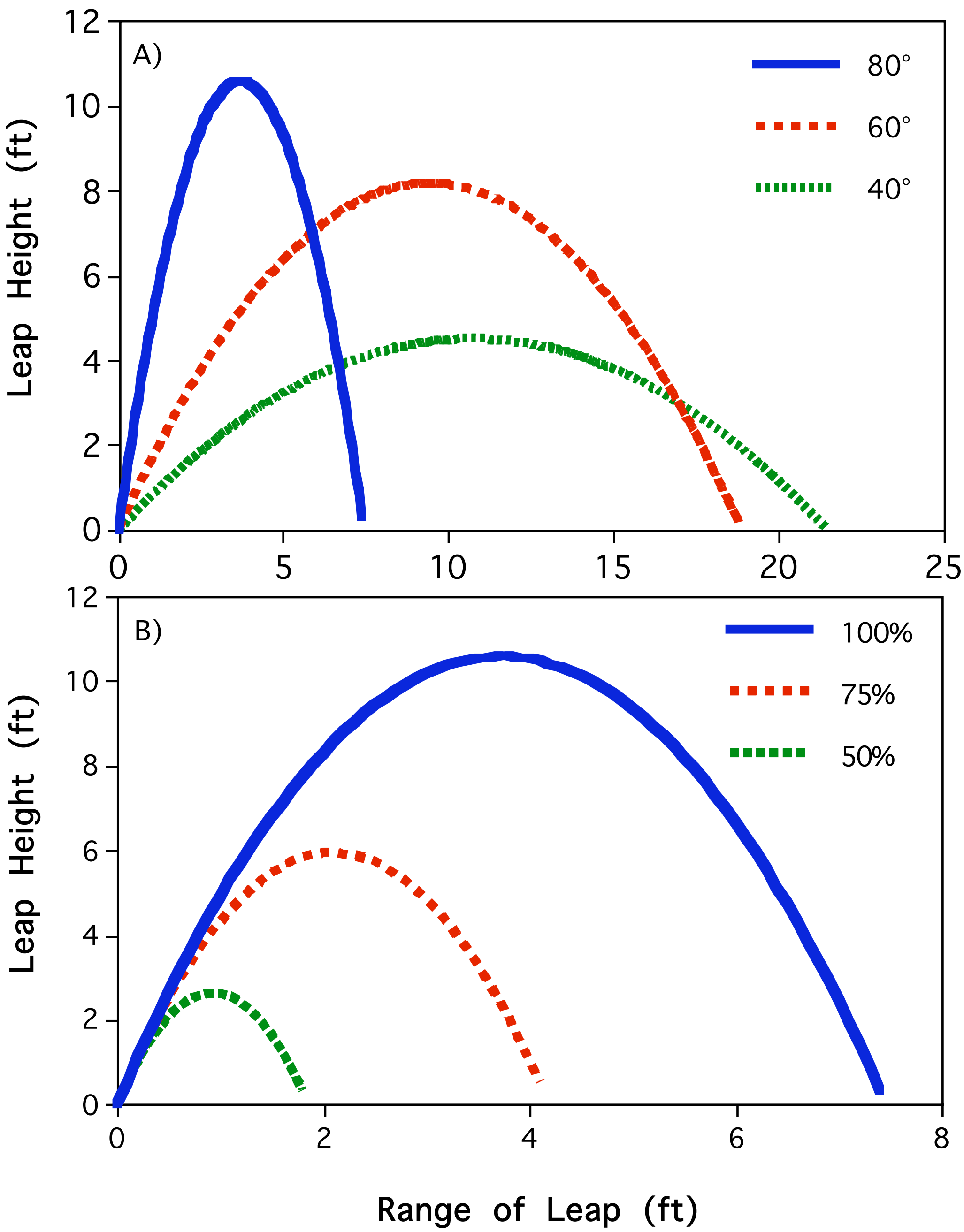


Fig. 6. (A) Steelhead leaping ability assuming maximum burst speed (26.5 ft/s) and 100% swimming efficiency, and (B) steelhead leaping ability assuming 80° leap angle and varying degrees of fish condition, which is influenced by distance from and elevation above Puget Sound.. Data source: Powers and Orsborn 1985.

Fig. 7. Cascade No. 1 at 20 cfs. Launching pool is relatively deep. All water flows beneath bedrock.

Fig. 8. Looking upstream at Cascade No. 6. Flow is 20 cfs.

Fig. 9. Cascade 6: looking down from pool above to pool below at left bank channel. Salmon migration was not possible at this falls.

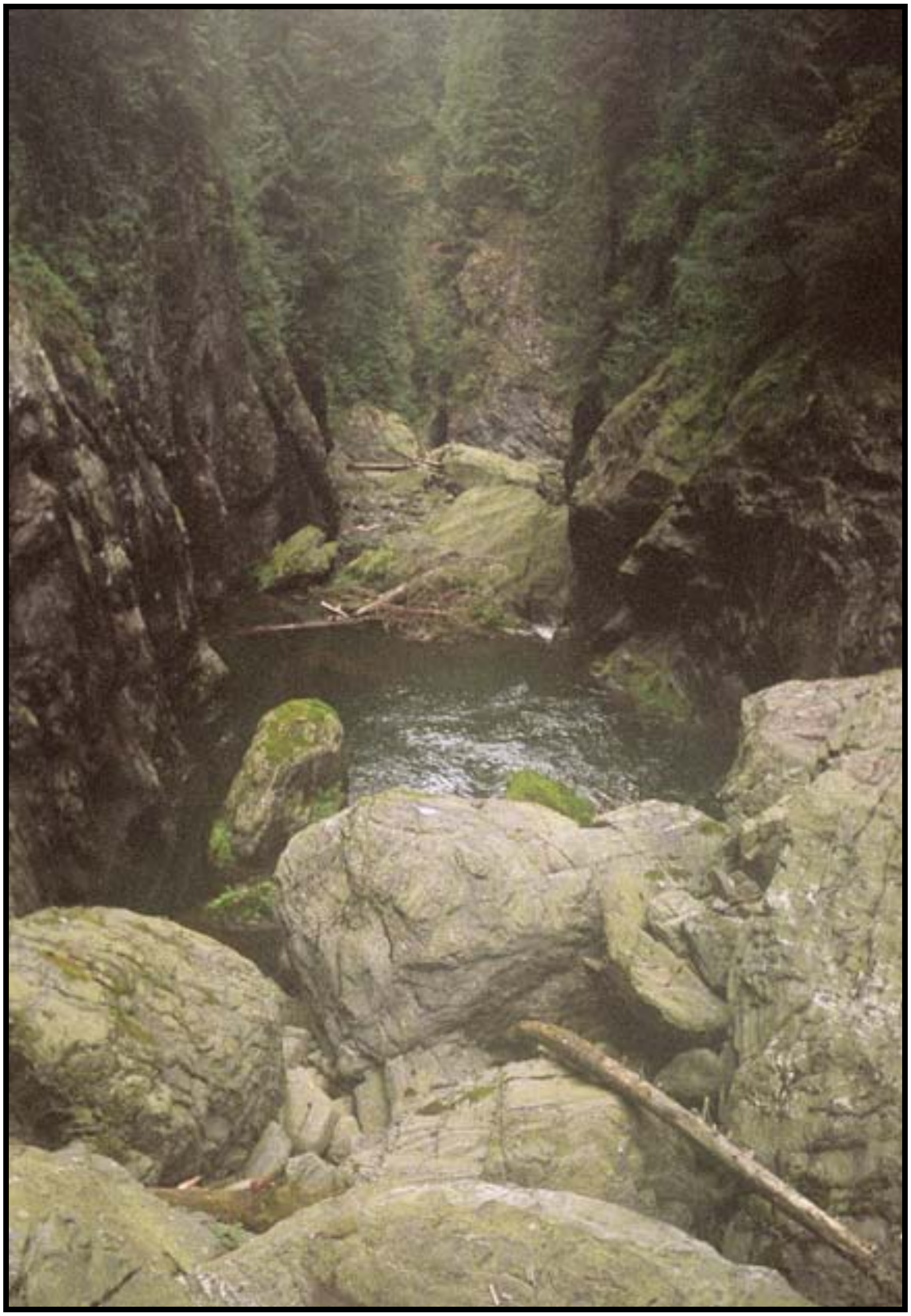


Fig. 10. Lower portion of Cascade 7 looking downstream through left channel and toward Cascade 6 (below pool). All flow (20 cfs) is through right channel (Fig. 11).

Fig. 11. Installation of staff gage in pool above 10 ft drop at right bank channel of Cascade 7. Pool elevation controlled primarily by bedrock rather than logs shown in picture. A staff gage was also located in shallow plunge pool below.

Fig. 12. Upper portion of Cascade 7 where lower channels converge (20 cfs). Surveyor shows direction of flow.

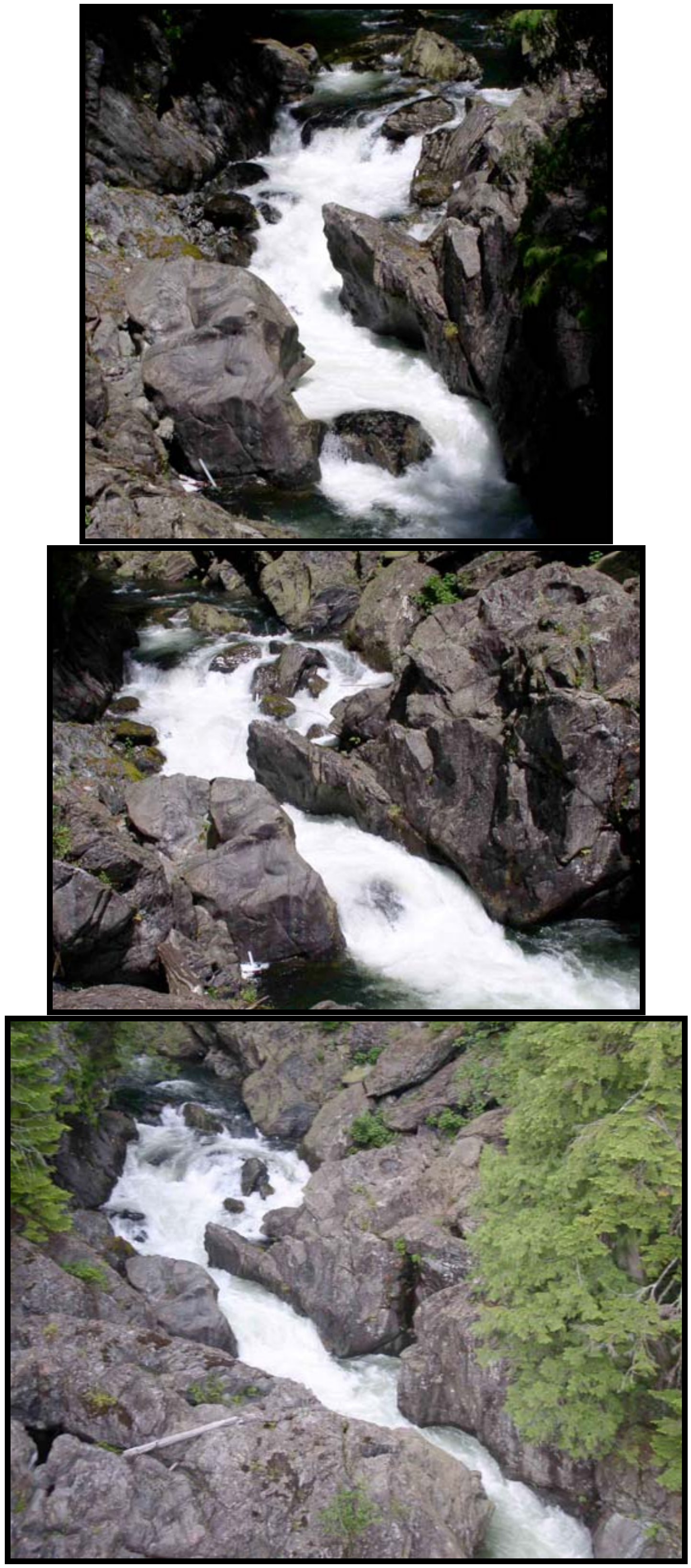


Fig. 13. Cascade 1 at 200 cfs (upper), 312 cfs (middle), and 516 cfs (bottom). Average gradient decreased from 26% to 23% as flow increased from 200 cfs to 516 cfs.

Fig. 14. Cascade 6 reach at 516 cfs. Note high velocity bedrock chute below Cascade 6.

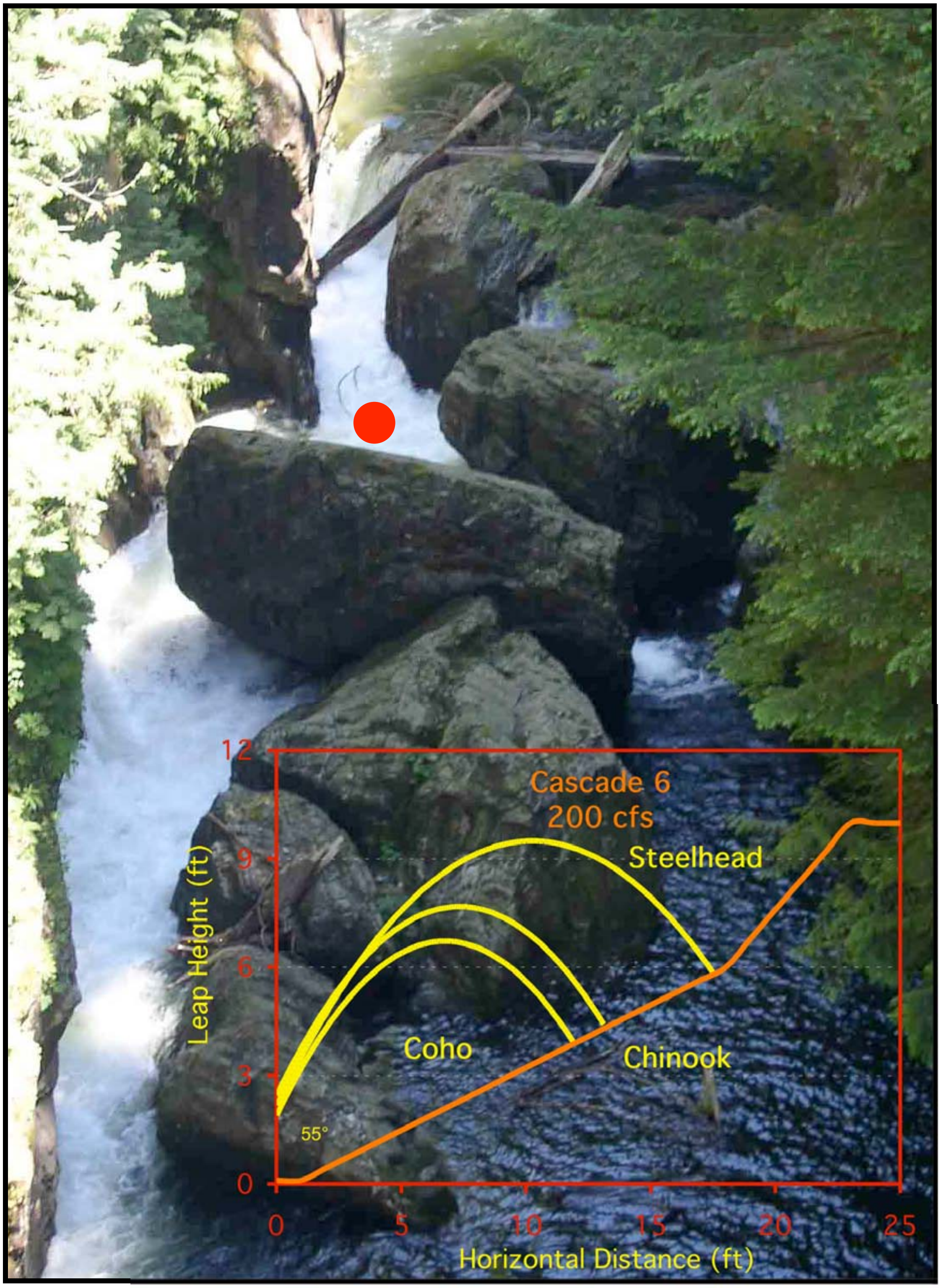


Fig. 15. Cascade 6 at 200 cfs. Red dot indicates potential initiation of leap at base of drop and chute. Maximum leaping curves are shown.

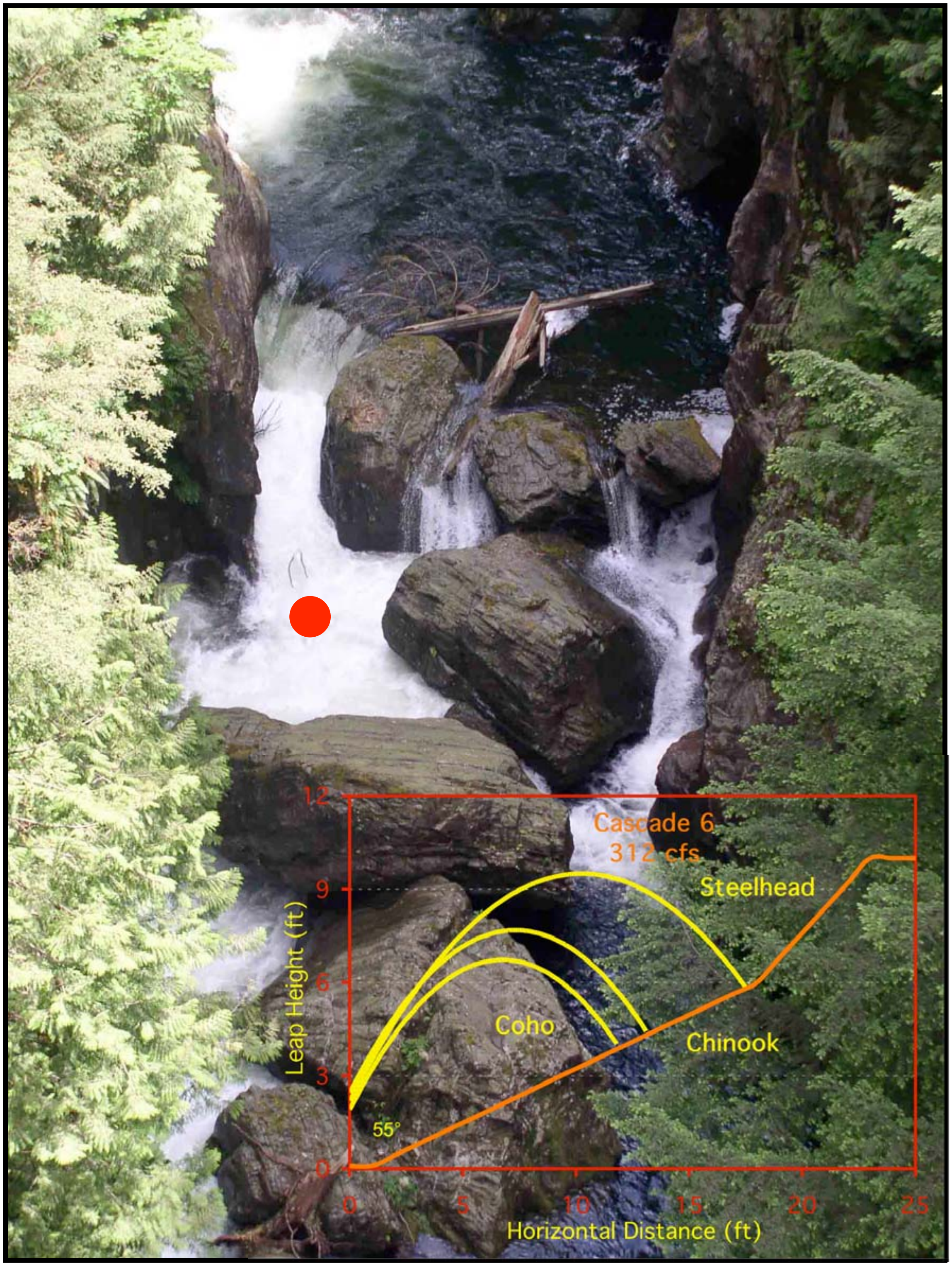


Fig. 16. Cascade 6 at 312 cfs. Red dot indicates likely initiation of leap at base of drop and chute. Maximum leaping profiles are shown.

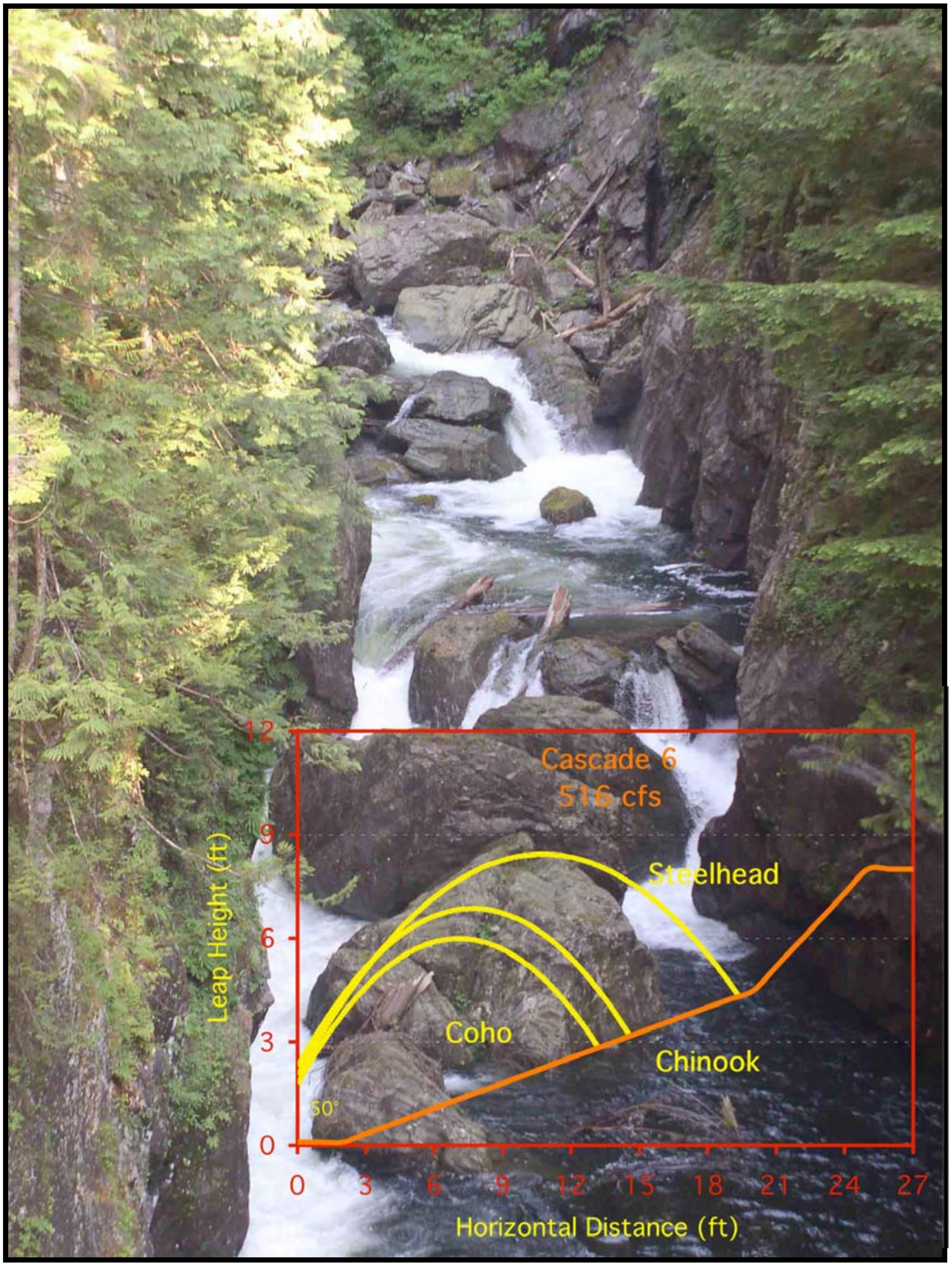


Fig. 17. Cascade 6 and lower left channel Cascade 7 at 516 cfs. Maximum leaping profiles for the drop and chute are shown.

Fig. 18. Looking downstream at Cascade 6; flow is 516 cfs. Elevation change between large pools was 14.4 ft.

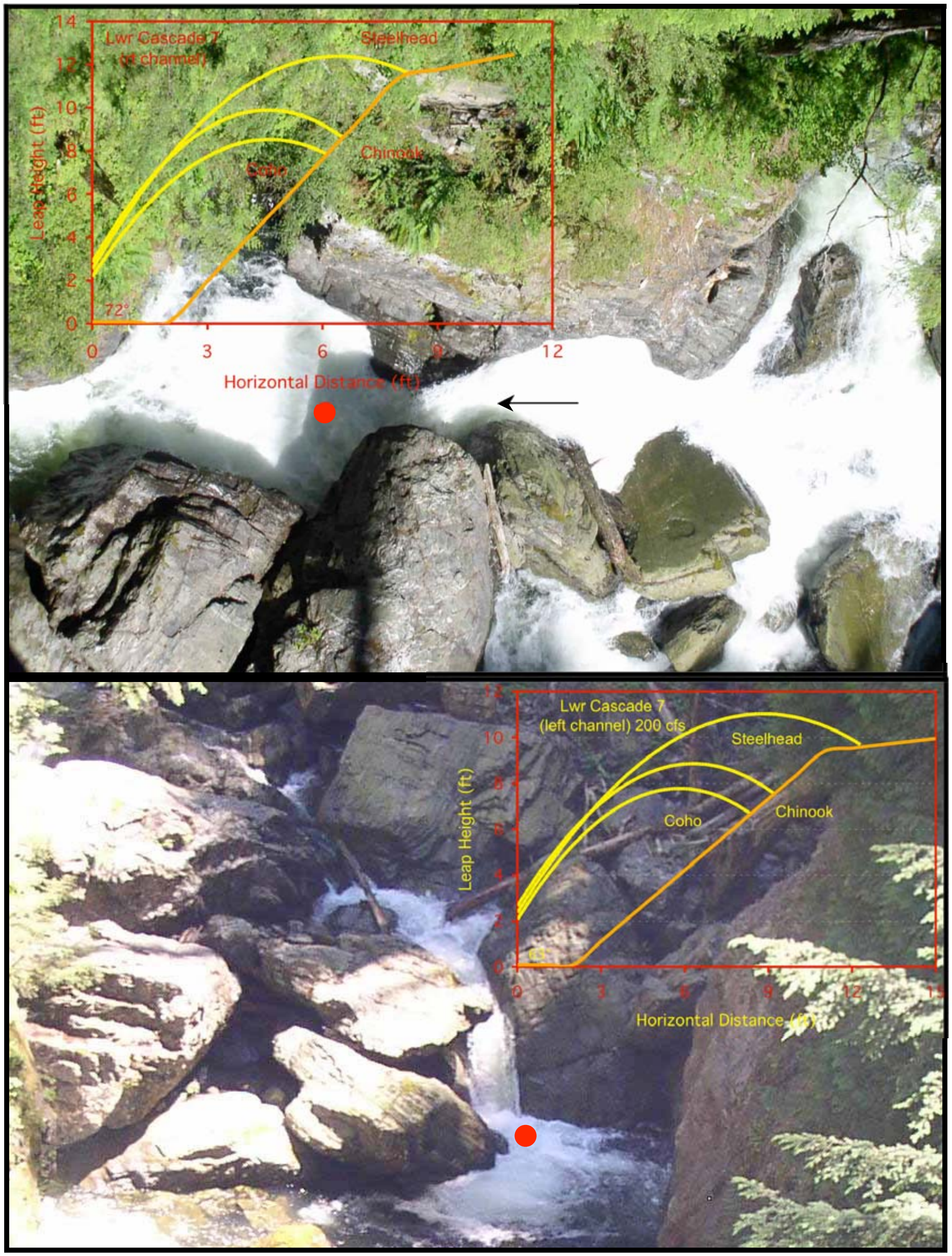
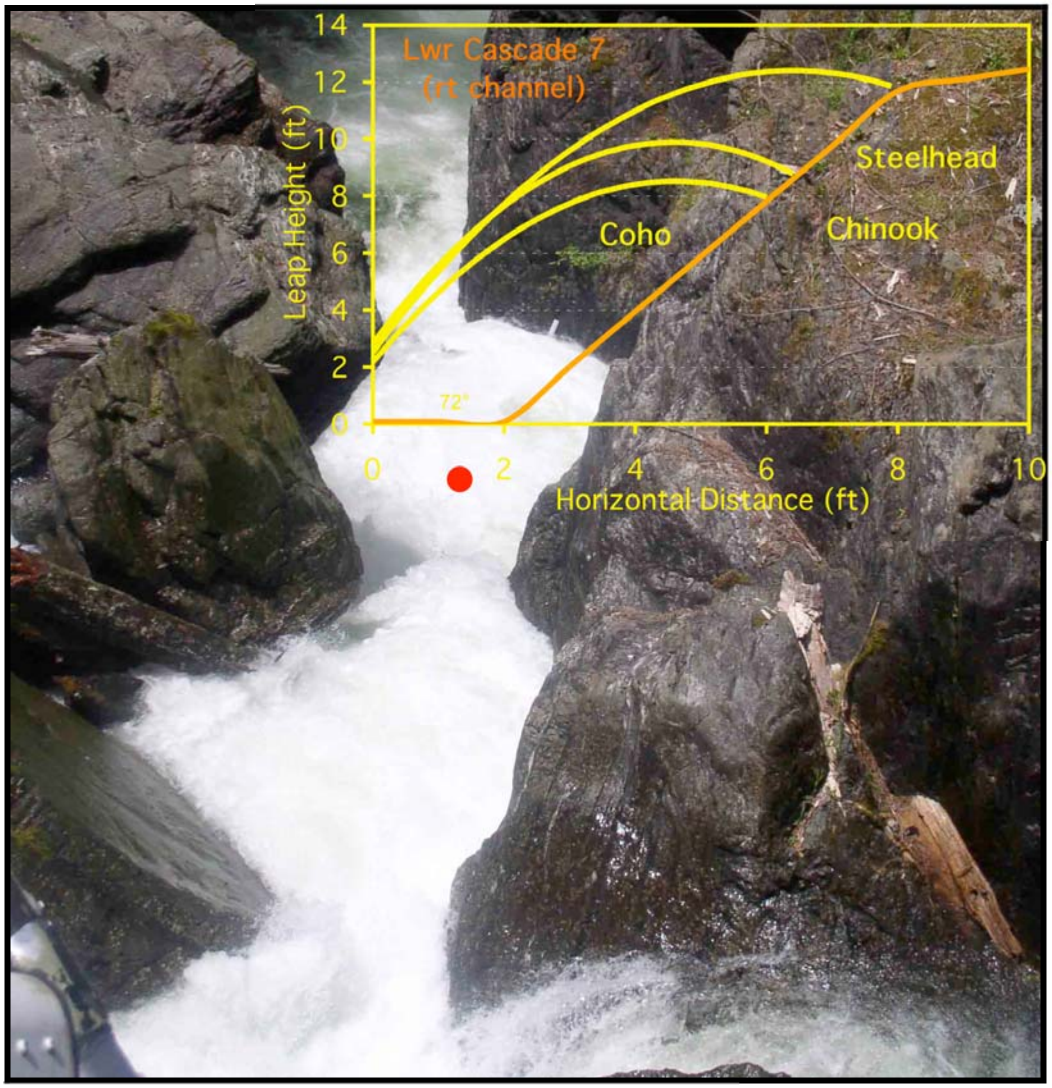


Fig. 19. Right (top) and left (bottom) channels of lower Cascade 6 at 200 cfs. Maximum leaping profiles are shown. Arrow indicates falls.



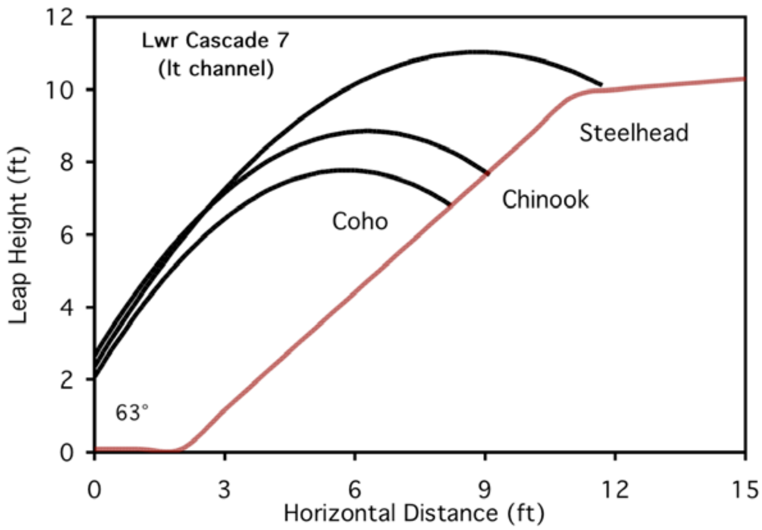
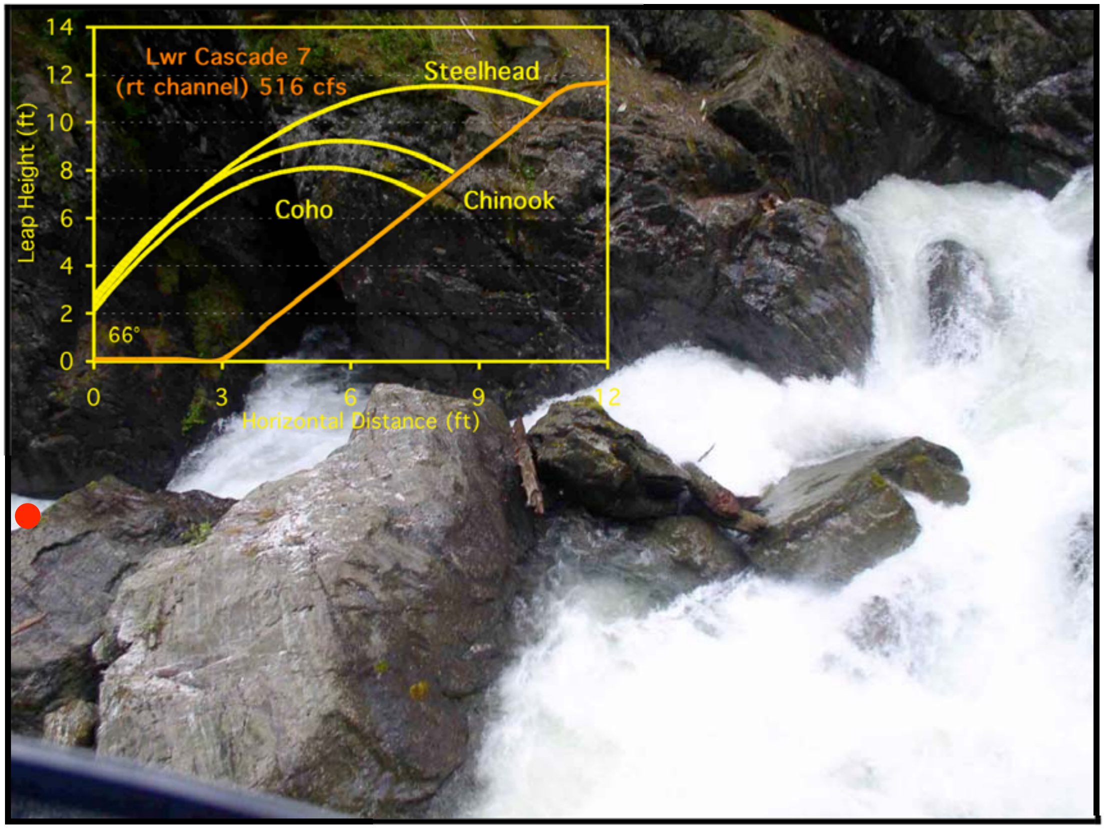


Fig. 20. Right channel of lower Cascade 6 at 312 cfs. Maximum leaping profiles for right and left channels are shown. No still photo of left channel at 312 cfs (see video).



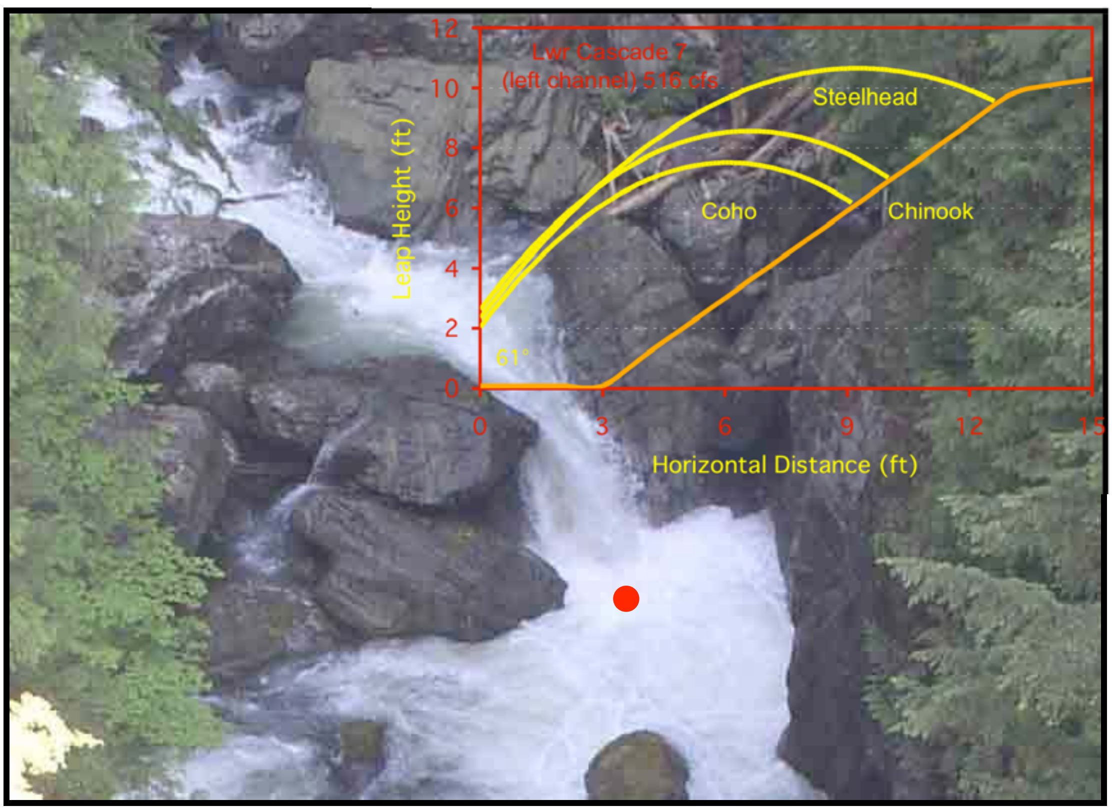


Fig. 21. Right and left channels of lower Cascade 6 at 516 cfs. Maximum leaping profiles are shown.

Fig. 22. Upper portion of Cascade 7 at 312 cfs (upper) and 516 cfs (lower). Channels extending upstream from left and right falls in the lower portion of Cascade 7 are shown.

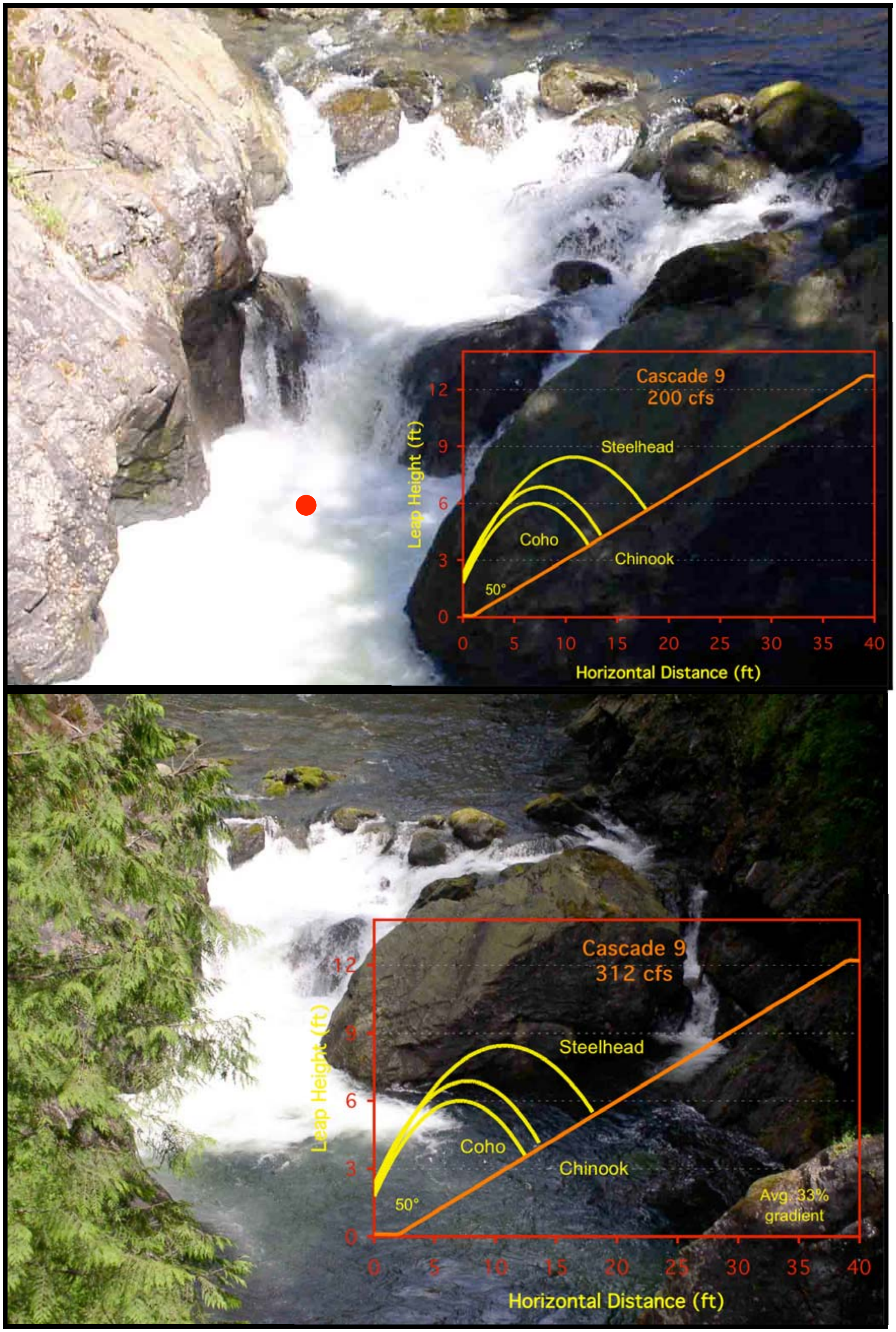


Fig. 23. Cascade 9 at 200 cfs and 312 cfs. Maximum leaping profiles are shown.

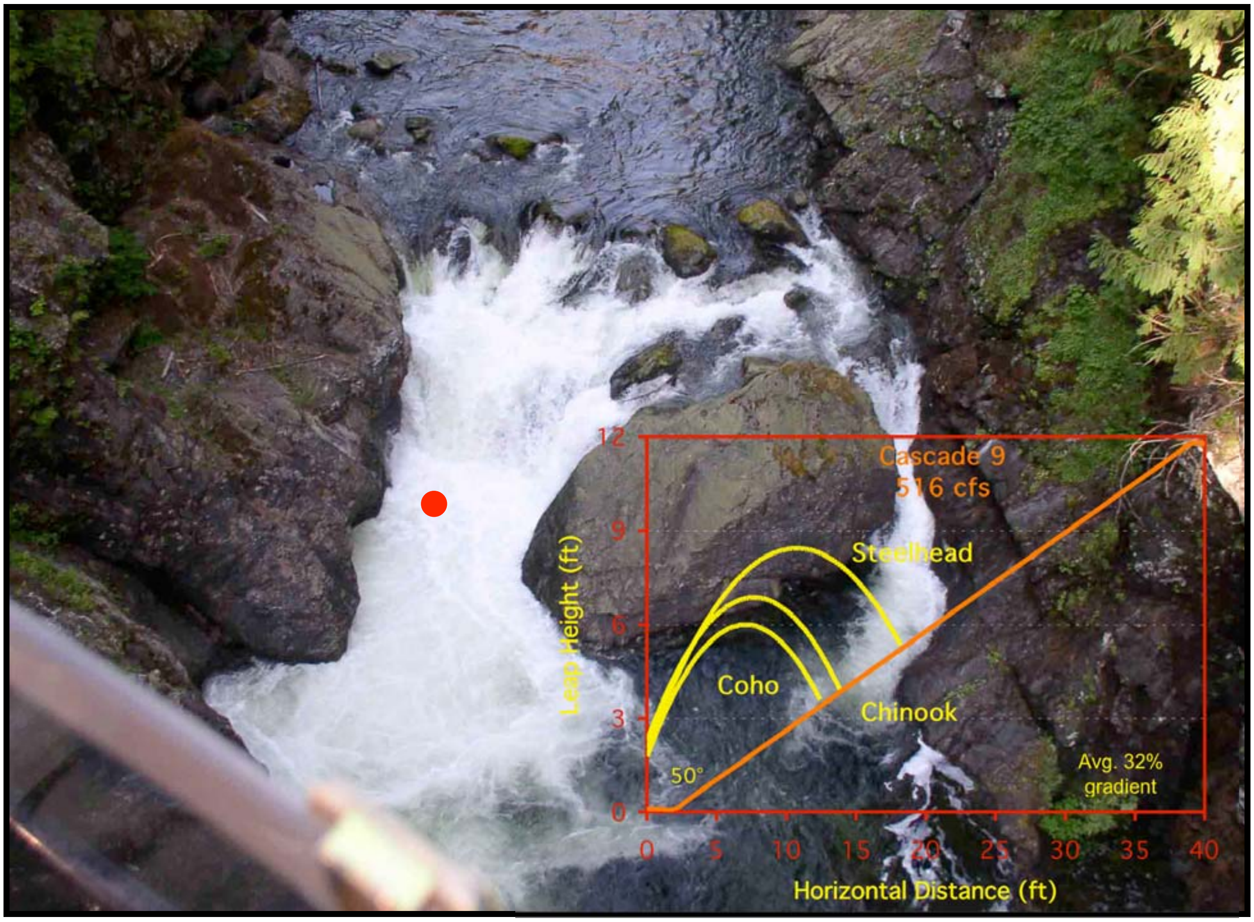


Fig. 24. Cascade 9 at 516 cfs. Leaping curves shown.

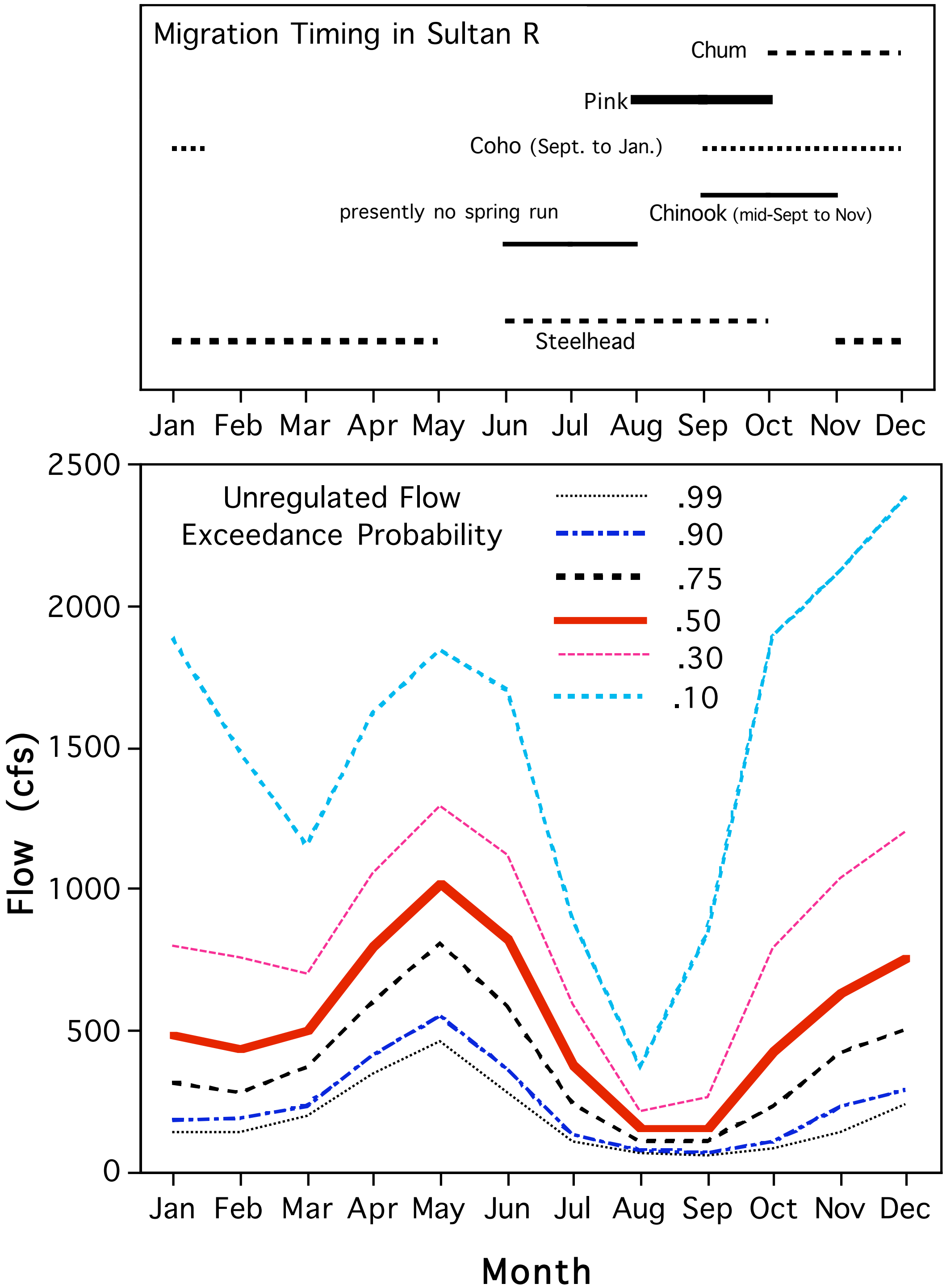


Fig. 25. Migration timing of salmon and steelhead in the Sultan River in relation to pre-dam daily flow exceedance probabilities during each month (Startup Gage 12137500 @ RM 11.3, years 1934-1960). Timing sources: PUD & City of Everett (2005).