Technical Memorandum

To: Alex Levell, Kelley Turner, and Tom Chance, Lummi Nation Natural Resources; Brian Scott and Ian Mostrenko, Herrera Environmental Consultants

From: Dan Scott, PhD; Jeff Johnson, PE; Bob Elliot, PE, Watershed Science & Engineering

Date: November 21, 2024

Re: South Fork Nooksack River Skookum-Edfro Reach Phase 1 Adaptive Management Geomorphic Assessment

1 BACKGROUND AND PURPOSE

Low flows on the South Fork Nooksack River (South Fork) do not provide sufficient depth for migrating salmonids to enter the outlet channel of the Skookum Creek Fish Hatchery (hatchery). The Lummi Nation Natural Resources Department (LNRD) has retained Herrera Environmental Consultants (Herrera) to evaluate the problem and design a solution to either 1) increase flow depths in the river at the existing outlet, or 2) to relocate the outlet to a more suitable location, to allow migrating salmonids to enter the hatchery outlet channel during low flows. Herrera retained Watershed Science and Engineering (WSE) to provide geomorphic support for this effort.

This technical memorandum presents WSE's geomorphic findings and considerations for potential design concepts and for the preferred alternative. We first discuss existing geomorphic conditions and trends, focusing on issues affecting flow depth near the existing hatchery outlet (inlet for salmonids). Then, we present the three design concepts that were considered and evaluated for their sustainability and need for adaptive management from a geomorphic perspective. Finally, we present a geomorphic assessment of the preferred alternative and lay out the potential need for adaptive management of that alternative.

2 SITE DESCRIPTION

Key Site Characteristics

- The hatchery outlet channel sits between two large, low-amplitude meander bends that contain the confluences of Skookum Creek (upstream) and Christie Creek (downstream).
- There is a large partially vegetated mid-channel bar (Skookum Island) just downstream of the hatchery outlet channel that reflects sediment deposition and channel widening that has limited flow depth at the outlet channel.
- The river in this reach tends to transport wood and sediment, except at the mid-channel bar, which retains those materials as the channel widens. There may be insufficient wood supply to sustain significant wood storage in the project reach.
- There is likely erosion-resistant bedrock near or just below the channel bed surface, although that bedrock is covered up by river sediment and likely only exposed and slowly eroded during large, infrequent floods.

The South Fork in the immediate vicinity of the hatchery flows through two low-amplitude meander bends separated by a large mid-channel bar (Skookum Island). This area is referred to as the Phase 1 reach. Skookum Creek enters the South Fork from the north at the upstream meander bend and Christie Creek joins it from the south at the downstream meander bend (Figure 1). The hatchery outlet channel enters the South Fork from the north just upstream of Skookum Island.

The segment of the South Fork extending approximately 1.2 miles downstream and 2 miles upstream of the hatchery is more confined than segments further upstream and downstream. This contributes to slow but variable rates of channel migration (Collins & Sheikh, 2004) through mostly erodible alluvium and glacial deposits (clays to gravels) with the exception of some bedrock cliffs (e.g., just downstream of the hatchery) that resist bank erosion.

Apart from the mid-channel bars around the hatchery (Skookum Island) and Edfro Creek (Edfro Island) about 1.25 miles upstream, this segment is dominantly a transport reach with respect to wood and sediment, when compared to multi-thread reaches further upstream and downstream. Sediment transported through this reach is slightly finer than the other, glaciated forks of the Nooksack (Anderson et al., 2019), but still contains abundant gravels, cobbles, and boulders. Forest harvest, bank armoring, and stream cleaning have reduced wood recruitment to and wood storage capacity in the channel. This has reduced in-stream wood loads compared to pre-European colonization (Brown & Maudlin, 2007). Excluding restoration projects, wood storage tends to be high only where there is readily recruitable wood adjacent to the channel (Brown & Maudlin, 2007). This calls into question whether there is sufficient wood supply from upstream to sustain high wood loads in the Phase 1 reach as wood decays and breaks, especially in reaches such as that around the hatchery, which has limited wood recruitment.

The South Fork has historically eroded down (incised) through glacial outwash deposits and is now likely incising into bedrock. The Phase 1 reach is estimated to be incising at a rate of 1 – 2 feet per decade. Based on results of hydraulic modeling completed by Herrea of the South Fork between Skookum Creek and the Saxon Road bridge 1.2 mi downstream, the South Fork is largely disconnected from its historic floodplains, which are now terraces, including the large terrace on the left (south) side of the Phase 1 reach adjacent to Skookum Island (Element Solutions, 2015). Bedrock exposure has been visually documented in the bank and valley walls (Lapen, 2000) and in water well logs around the fish hatchery (WA Department of Ecology). Well logs near the hatchery reveal bedrock at elevations ranging from 369 to 374 feet (22 feet below ground surface), elevations similar to that of the existing channel bed downstream of the hatchery. We did not see any outcrops of bedrock in the channel bed; the bed surface is comprised of sand- to boulder-sized alluvium, which likely covers the bedrock during all but large, highly erosive flood flows.

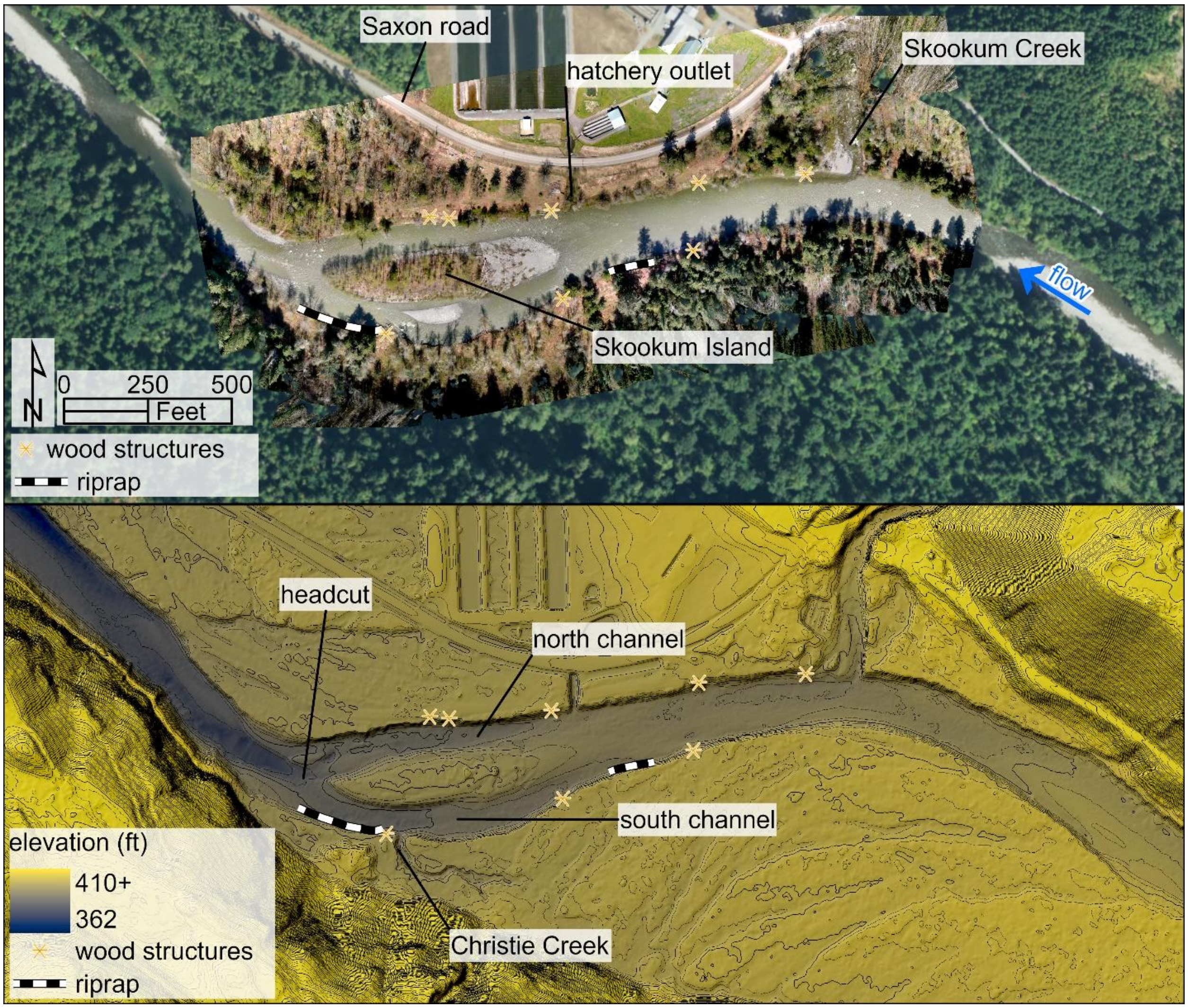

Figure 1: Site map showing a composite of imagery from 2023 (center) and 2017 (background) (top), and LiDAR topobathymetry from 2017 (bottom). Contour interval is 2 ft.

3 HISTORICAL GEOMORPHIC EVOLUTION

Key Findings

- Since the 1950s, the channel along the southern side of the mid-channel bar has been expanding and conveying more flow. This is directing flow away from the hatchery outlet channel, which is making it more difficult for fish to enter during low flows.
- Bank armoring (riprap) and, to a more limited extent, wood structures, within the Phase 1 reach have locally prevented bank erosion, although the riprap revetment that once slowed left bank erosion along the southern channel at the mid-channel bar is now partly gone.

There are two primary factors responsible for the low flow fish passage barrier at the hatchery outlet. First, summer low flows are getting lower due to climate change (Tohver et al., 2014). Second, the channel along the southern side of Skookum Island just downstream of the hatchery outlet is both widening and migrating away from the hatchery outlet, diverting flows away from the outlet channel.

The second factor, flow diversion away from the hatchery outlet, began when Skookum Island began growing and banks began eroding in the mid-1950s. The right bank (when viewed looking downstream) of the north channel eroded slightly as Skookum Island grew in the 1990 to 2010 period; however, most of the erosion has occurred along the left bank (when viewed looking downstream) of the south channel. In response, the south channel has enlarged considerably. This has diverted water away from hatchery outlet (Figure 2). Sediment deposition at the bar head close to the outlet channel has also caused a decrease in flow depth there.

Several infrastructure and restoration projects have also influenced the reach:

- Between 1966 and 1986, a road and cabin were built on the left floodplain of the southern channel along Skookum Island. The road and cabin were protected from erosion by a riprap revetment that likely extended along most of the left bank. The center portion of this revetment has either been removed or has failed (see Figure 1 above).
- In 2010, Saxon Road was moved further inland from its previous position along the right (north) bank. A series of engineered logjams (ELJ) were also constructed along the right bank to create pool habitat. Shallow probing conducted by LNRD of the right bank confirmed a lack of riprap along this bank near the surface.
- In 2017, multiple ELJs were built along the left bank of the south channel and some of the riprap revetment was removed to improve habitat conditions. At the same time, the right bank ELJs were augmented to extend further into the channel.

Figure 2: Historical geomorphic evolution of the project reach from 1938 to 2023. 2017 imagery has 1-ft topobathymetric contours.

4 EXISTING GEOMORPHIC TRENDS

The flow diversion and shallowing around the hatchery outlet are caused by two key geomorphic processes: frequent and ongoing bank erosion and mid-channel bar deposition (short-term), and headcutting causing incision over decades to hundreds of years (long-term).

4.1 FLOW DIVERSION AWAY FROM THE HATCHERY OUTLET DUE TO BANK EROSION AND MID-CHANNEL BAR DEPOSITION

Key Findings

- Bank erosion is widening the south channel along the mid-channel bar, which is diverting flow away from the hatchery outlet. The north channel is not currently widening and is thus losing flow to the south channel over time.
- Under existing conditions, the left bank of the south channel is likely to continue eroding, diverting more flow away from the hatchery outlet in the future. As this occurs, the north channel could eventually infill with sediment and stop conveying low flows.

As Skookum Island grows and the south channel widens and migrates via bank erosion, the south channel is growing faster than the north channel. This is leading to flow diversion down the south channel and away from the hatchery outlet and sediment deposition at the head of the bar near the outlet. While the north channel grew slightly from 1990 to 2010 via erosion of its right bank (Figure 3), that erosion has since stopped. The lack of erosion along the right bank could be due to some combination of factors, including:

- The ELJs built in 2010 to create pool habitat likely reduce bank erosion in the immediate vicinity of each structure.
- Flow diversion down the south channel along Skookum Island may be depriving the north channel of sufficient discharge during floods to erode the bank.
- Skookum Creek, which flows into the mainstem near the upstream meander bend apex, may disrupt the normal hydraulic pattern along the right bank, reducing the river's ability to erode its right bank for some distance downstream. An example of this is illustrated in the 2023 photo shown in Figure 2: The clear water of Skookum Creek doesn't fully mix with the turbid water of the South Fork until approximately 300 ft downstream of the confluence, at a discharge of 1,700 cfs in the South Fork (larger than the average annual flow rate, but less than the 2-year flow event). Examination of the two-dimensional (2D) hydraulic model results of the existing condition (i.e., the pre-Phase 1 Adaptive Management project conditions) showed a significant reduction in flow velocity near the bank extending down to the second 2010 ELJ (approximately RM 14.2) from the Skookum Creek confluence, indicating a likely suppression of bank erosion provided that Skookum Creek floods coincidently with the South Fork.

The left bank of the south channel has experienced ongoing erosion since the 1950s, continuing into the present (Figure 4). This bank erosion was likely slowed and, in places, reversed by road and revetment construction in the 1990s (remaining riprap is shown on Figure 3). However, after the middle section of riprap was eroded through (late 2000s) and partially removed (2017), bank erosion has been able to continue upstream of the Christie Creek confluence. From September 2022 to April 2023 alone, the bank eroded up to 10 ft to the south, mainly just upstream of the Christie Creek confluence.

Expansion of the south channel via left bank erosion has diverted flow away from the north channel and the hatchery outlet channel. This bank erosion shows no sign of slowing (Figure 4), nor of restarting along the north channel. Therefore, we predict that under existing conditions, the left bank of the south channel will continue to erode, and the south channel will continue to widen. This will further deprive the north channel and hatchery outlet of flow and exacerbate the existing fish passage problem. As the channel migrates south, the north channel may eventually infill with sediment, vegetate, and stop conveying low flows entirely.

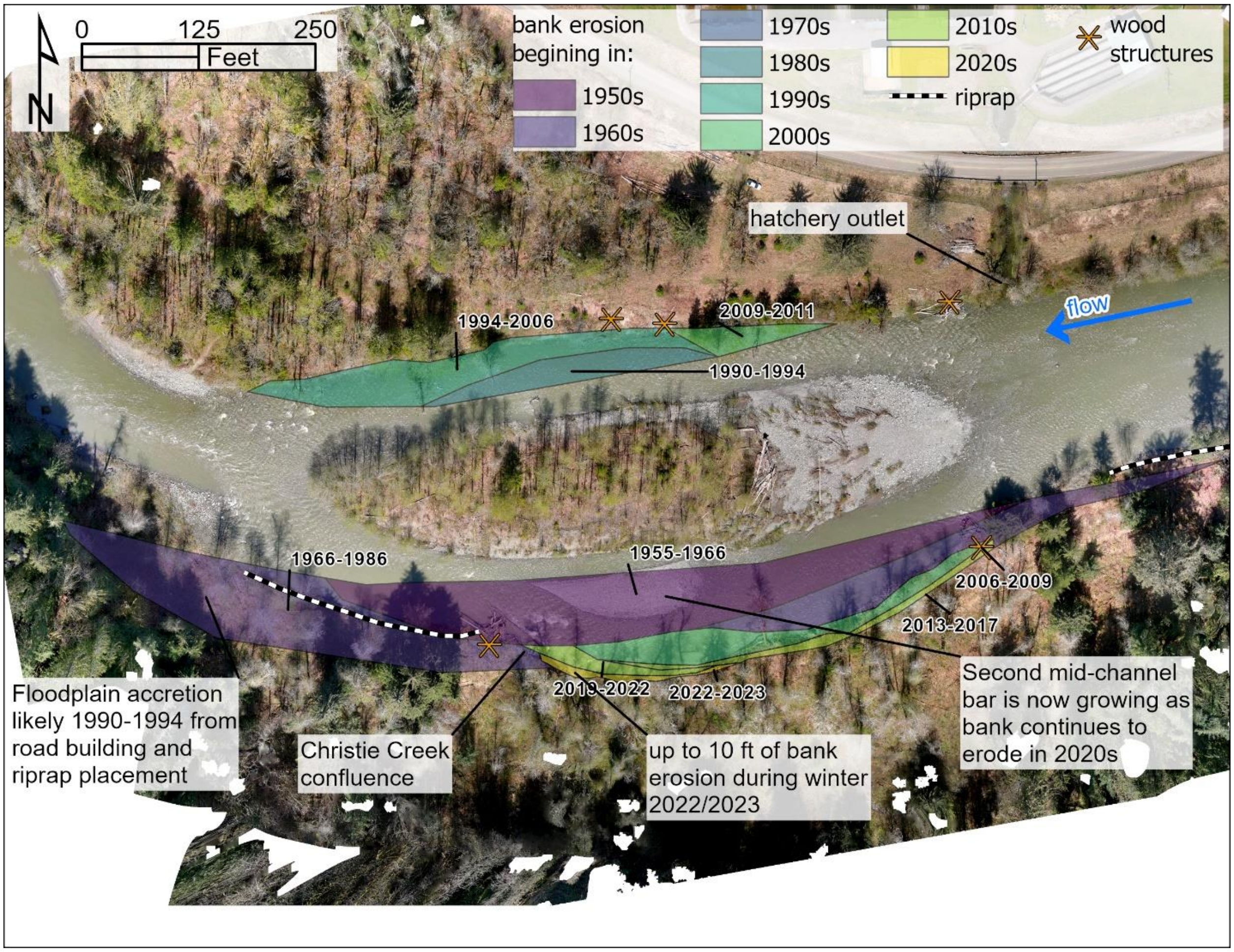

Figure 3: Bank erosion around Skookum Island just downstream of the hatchery outlet. Polygons represent the area of floodplain that was eroded during each time period (i.e., the riverward edge of the polygon represents the bank position at the labeled start date and the landward edge of each polygon represents the bank position at the labeled end date)

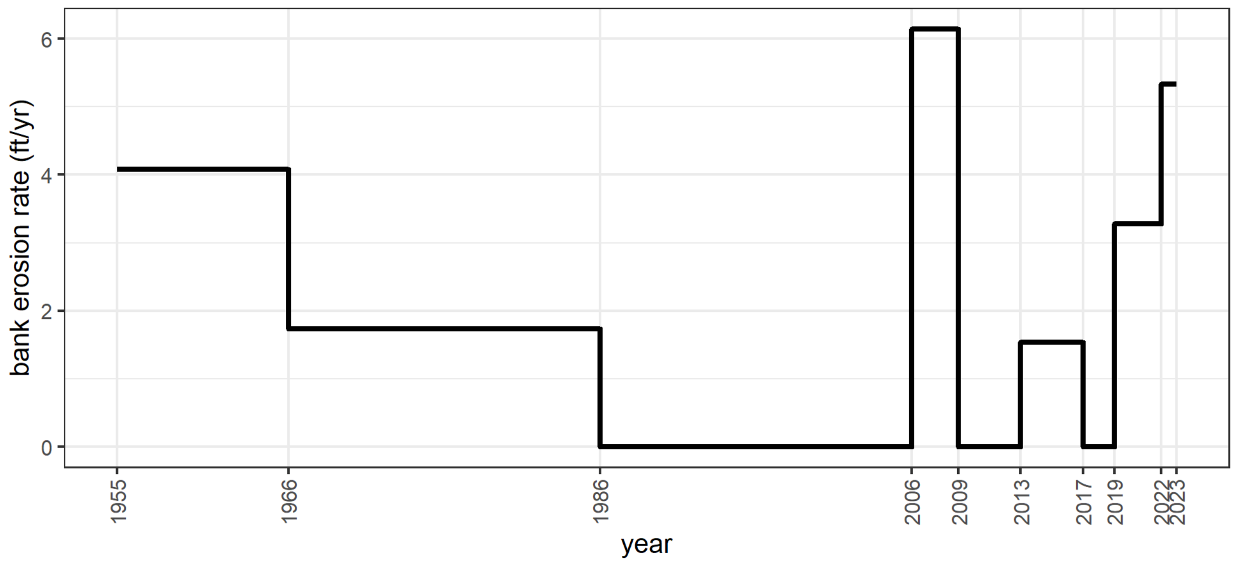

Figure 4: Bank erosion rate averaged along the length of the portion of bank that was eroding in each period of observation for the left bank.

4.2 LONG-TERM INCISION DUE TO HEADCUTTING

Key Findings

- A pre-1884 meander cutoff likely generated a stepped headcut eroding into bedrock beneath the alluvial bed of the South Fork.
- The downstream end of the mid-channel bar is the upper step of the headcut. If the headcut moves upstream, it will divert more flow into the channel that is conveying more flow at that time, which is currently the south channel. This would divert more flow away from the hatchery outlet.

LiDAR topography and historical imagery and maps indicate that before the 1884 General Land Office mapping of this area, the South Fork cut off a large meander bend about 3,000 feet downstream of the hatchery (Figure 5). Meander bend cutoffs shorten channel length but maintain the same drop in elevation, producing a locally steepened reach known as a headcut (note that while headcuts are often discrete drops in the channel bed, they can disperse along a reach, creating a steepened length of stream with multiple headcuts). Headcuts typically cause channel incision (elevation loss) upstream because they elevate sediment transport capacity.

In the South Fork's longitudinal elevation profile (Figure 6), we observe two unusually steep drops that could correspond to headcut incision from the pre-1884 meander bend cutoff. The first is approximately 3,000 feet downstream of the hatchery near the site of the meander cut off. It may not have eroded very far since it formed over a century ago. The second is at the downstream end of Skookum Island. Based on headcut steepness and well log boring near the fish hatchery that shows bedrock at elevations just below the channel bed, we hypothesize that both headcuts have been slowed by erosion-resistant bedrock.

When a headcut erodes into bedrock or other resistant material, it typically remains steep, as opposed to slowly diffusing, or reducing its slope, as it does when it erodes through alluvium (Stein & Julien, 1993). Headcuts in bedrock commonly create multiple steps as the river erodes through different rock layers, or strata. Bedrock underlying this reach is dominantly foliated metamorphic rocks (Lapen, 2000), which tend to not have predictable stratification (layering), so we do not know exactly what kind of material the headcuts are eroding through or how the depth to bedrock varies upstream of the upper headcut. This, combined with the channel bed alluvium that obscures the bedrock, makes predicting future headcut migration and channel incision difficult.

While the headcut presents the possibility of future incision, whether and how fast that incision could occur is uncertain. Skookum Island reduces flow energy and may have kept the headcut from migrating upstream or slowed its migration in the past. However, as the south channel becomes more dominant, it may eventually convey sufficient flow energy to allow the headcut to migrate upstream or accelerate its migration. The rate at which the headcut will migrate upstream, if it does, is highly uncertain, and associated incision could occur over timeframes of tens to hundreds of years. However, if this incision occurs away from the hatchery outlet channel as it may if the south channel continues to become more dominant, it could further exacerbate the current fish passage problem.

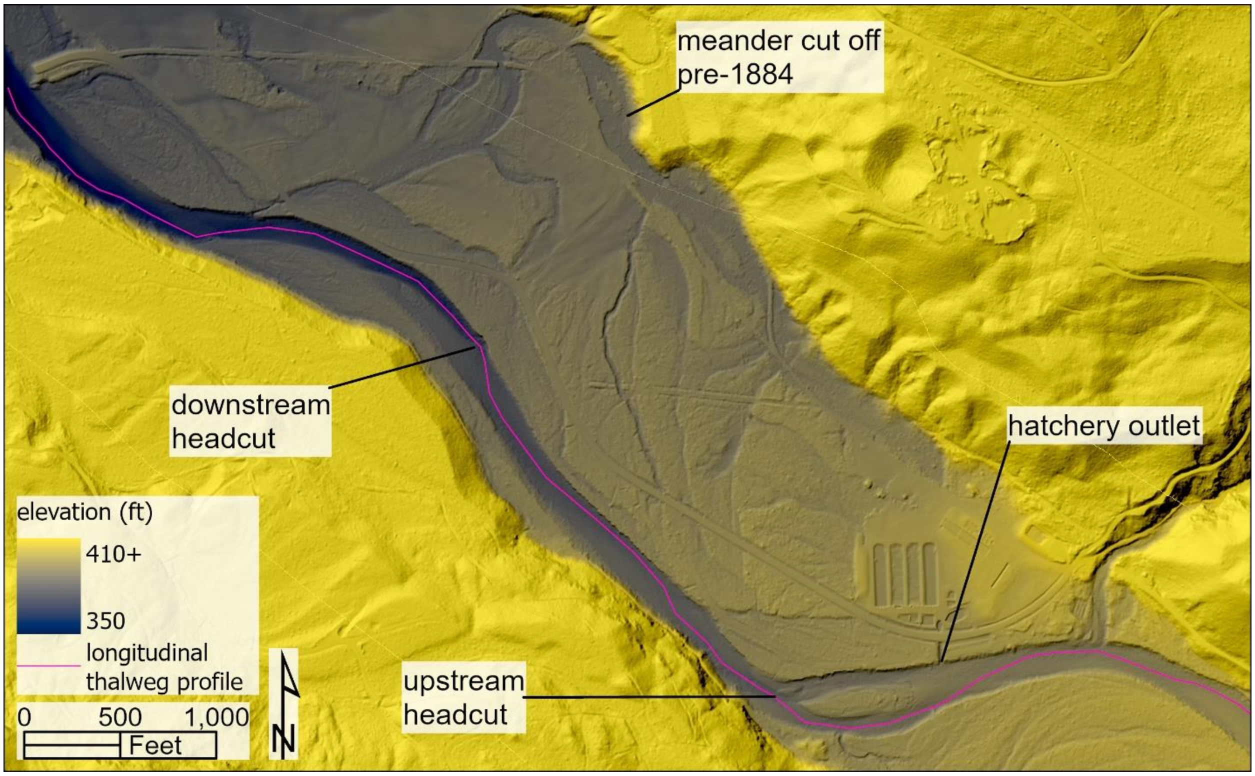

Figure 5: 2017 LiDAR topography showing the cutoff meander and resulting headcut locations.

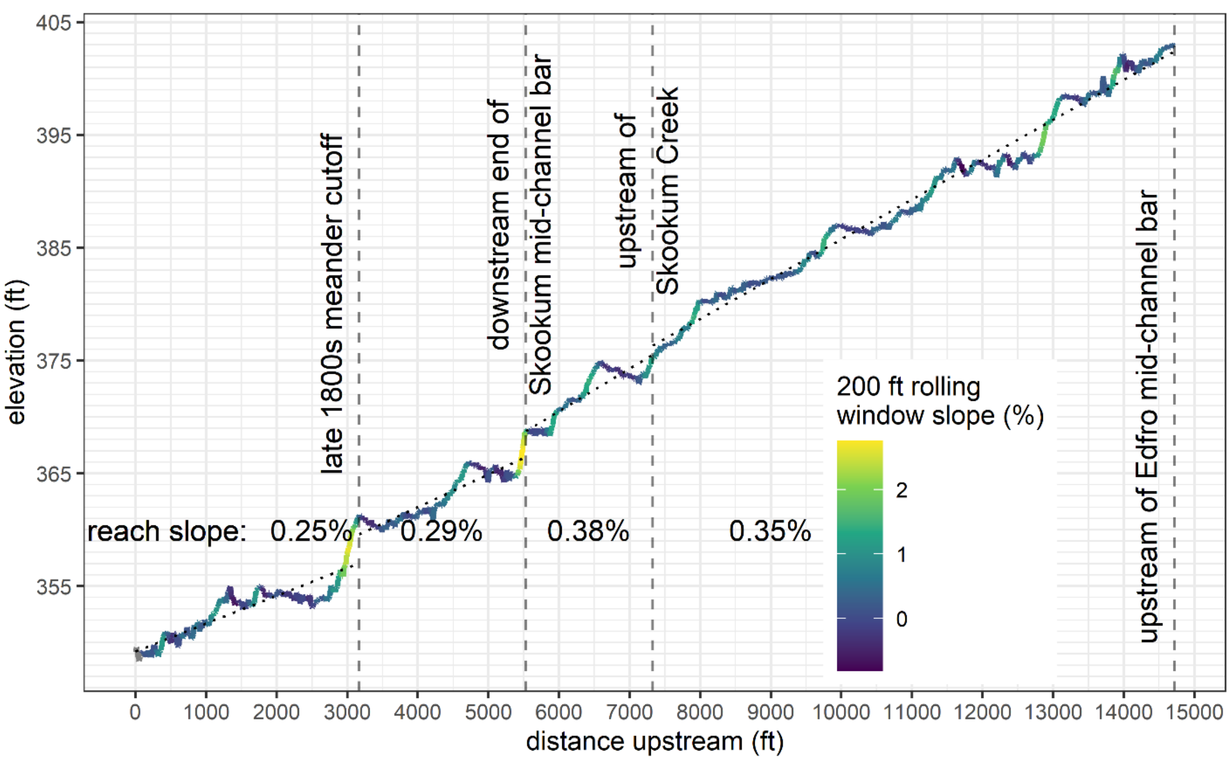

Figure 6: Longitudinal thalweg profile (alignment shown in Figure 5) from Saxon Bridge (downstream) to the upstream end of the Edfro mid-channel bar. Reach-average slopes are shown as dotted lines for each reach.

5 GEOMORPHIC DESIGN CONSIDERATIONS

To ensure that salmonids can access the hatchery outlet, it is crucial for the hatchery outlet channel to sustainably connect with the South Fork where water depth is adequate even during low flow conditions, both today and in the future, as climate change further reduces summer baseflow (Tohver et al., 2014) and the site continues to geomorphically change. There must also be no other fish passage barriers downstream that prevent them from reaching the outlet.

There are two potentially complementary ways to reach this solution:

A) Rearrange the South Fork to promote incision and/or constrict flows at the hatchery outlet and prevent channel migration away from the outlet.

B) Relocate the hatchery outlet channel to a position where there will be sufficient depth during low flows.

Option A works against the existing geomorphic trajectory of the reach, as described above. That makes it inherently more difficult to sustainably accomplish than option B or some combination of the two options.

6 DESIGN CONCEPTS

To address the fish passage barrier problem, Herrera and WSE developed three conceptual design alternatives. Alternative 1 relies entirely on option A, rearranging the South Fork to ensure sufficient low flow depth at the hatchery outlet. Alternative 2 uses both options A and B, moving the hatchery outlet upstream to allow for less rearrangement of the South Fork. Finally, Alternative 3 relies entirely on option B, moving the hatchery outlet channel while only minimally changing the South Fork.

The three alternatives are illustrated in Figure 7 and compared in Table 1 in terms of their anticipated geomorphic evolution and need for adaptive management.

Alternative 1 is least likely to be geomorphically sustainable because it involves the greatest manipulation of the river and deviates most from the river’s current geomorphic trajectory. As the existing ELJs decay, the river could resume its current trajectory of expanding the south channel and diverting flow away from the hatchery outlet, which would require adaptive management in the form of ELJ structure replacement.

Alternative 2 involves moving the outlet channel upstream to where the South Fork is already narrower and deeper. While this alternative still relies on ELJs to increase flow depth near the outlet channel, it is more likely to remain sustainable as the structures decay, and it does not deviate from the existing geomorphic trajectory as much as Alternative 1.

Alternative 3 involves moving the outlet channel downstream to an existing pool formed by the headcut at the end of Skookum Island. This pool may last for decades or longer, given that the river is confined against a bedrock cliff along its left bank, even if the headcut eventually migrates further upstream, which may take decades or longer. Sediment deposition may pose a potential sustainability issue. A small gravel bar located where the outlet channel would enter the South Fork may block flow from the outlet channel; however, the flows from the hatchery may keep sediment from depositing or scour it away after it deposits, or ELJ structures placed in the South Fork could maintain a scour pool that would hold the outlet open.

Common to all alternatives is a dependence on artificial wood structures (ELJs). Wood is a transient component of riverscapes, not a permanent feature — it decays and breaks down over time. Conifers in rivers typically lose half their mass to decay alone in 20 to 30 years (Hyatt & Naiman, 2001; Merten et al., 2013; Sass, 2009; Scherer, 2004). For ELJs to have long-lasting geomorphic effects, they must induce sediment and wood deposition, and promote vegetation growth to replace the impact of the decaying structures (Collins et al., 2012).

Please note that predictions of future geomorphic change are inherently uncertain due to the complexity of interacting physical processes, uncertainties regarding site conditions (e.g., bed and bank material), and the possibility of channel altering extreme floods. Especially during large or extreme floods, unanticipated channel migration or other geomorphic hazards can occur.

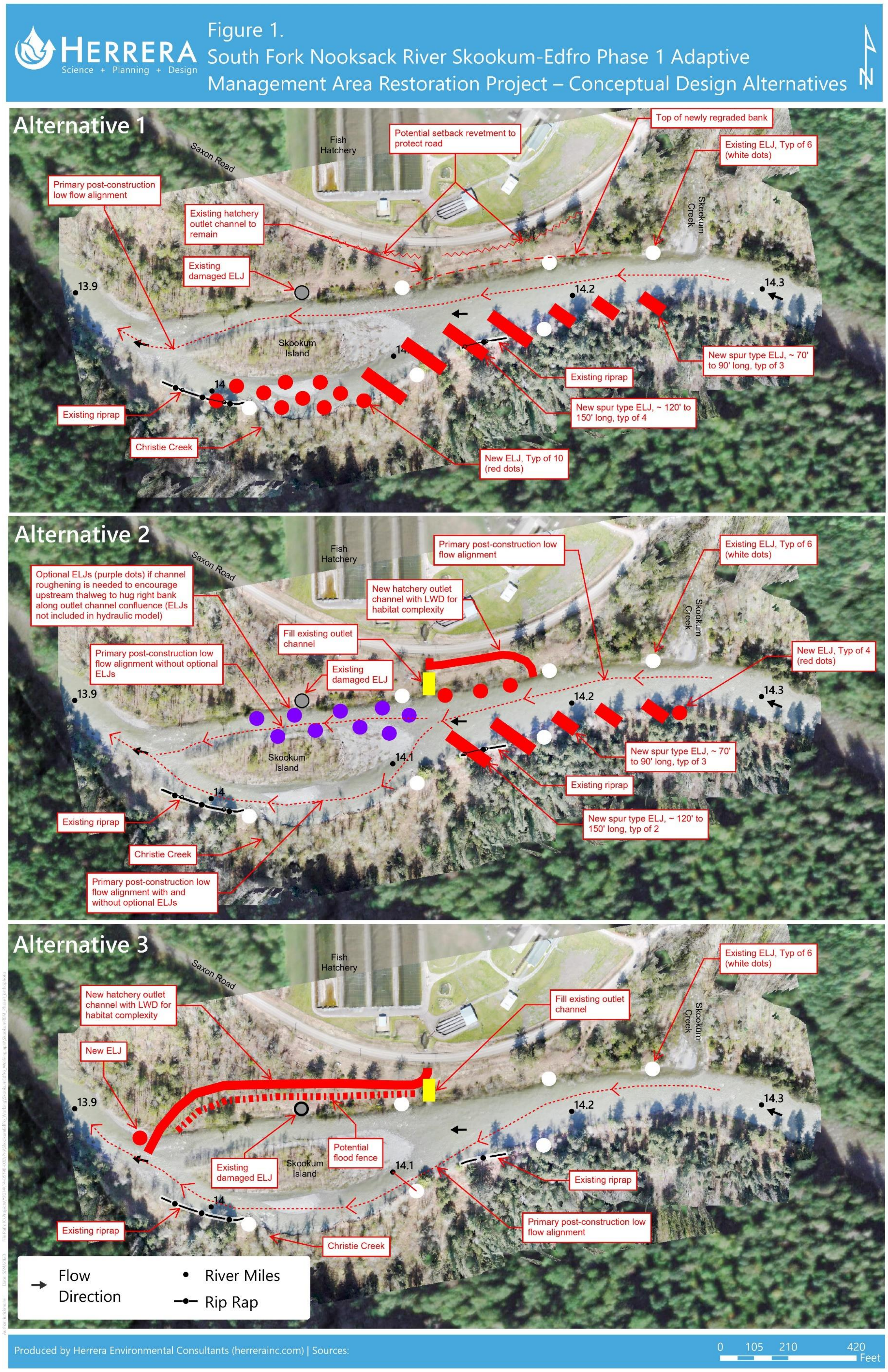

Figure 7: Design alternatives. Note that features shown are approximately located.

Table 1: Summary of concepts and anticipated geomorphic response. Potential adaptive management needs are bolded. Outlet channel slopes are approximate.

Alternative	Key Elements	Outlet Channel Slope	Anticipated Short-term Geomorphic Response (0 – 5 years)	Anticipated Long-term Geomorphic Response (5 – 50 years)
1	• Roughen south channel sufficiently to cause sediment deposition and infilling. • Roughen left bank sufficiently to prevent bank erosion (bank spurs). • Excavate right floodplain upstream of outlet channel to encourage slight outer bend and thalweg development near hatchery outlet channel. • Consider bank protection for Saxon Rd (log/rock roughening).	1.6% (existing)	• Right side channel will likely incise (deepen) and may widen, capturing more flow. • Left side channel will likely infill.	• Right side channel may incise via headcut migration upstream, further deepening the channel. • Bank erosion may occur along the right bank near the hatchery outlet channel, requiring setback road protection. • As wood structures decay, left side channel may eventually reopen, producing widening around the hatchery outlet, **likely requiring wood structure replacement.**
2	• Reorient hatchery outlet channel 350 feet upstream away from the sediment deposition occurring around Skookum Island. • Roughen left bank opposite outlet channel to constrict flow against the new outlet channel and right bank. • (Optional) Roughen the north channel to constrict most of high flows to the south channel but allow flushing flows and create a low flow pathway down the north channel.	0.8%	• Thalweg will likely form along the right bank bend near the new outlet channel location as the left bank downstream continues to erode. • Right bank may erode towards Saxon Rd, especially around existing outlet channel location (erosion is less likely closer to Skookum Creek). • North channel may develop a low flow pathway (scour pools around wood structures).	• Right bank may erode and threaten Saxon Rd, **justifying adaptive management to protect the road.** • As wood structures decay, channel may widen slightly around the new hatchery outlet location, but far upstream location makes fish passage barrier formation less likely than Alt 1. **Wood structures may need to be replaced if vegetation, wood deposition from upstream, and new channel alignment are not sustainable.**

3	• Reorient hatchery outlet channel downstream 1000 ft to the large pool at the downstream end of Skookum Island. • Install wood structures along new outlet channel to provide spawning habitat. • Install wood structure at end of outlet channel to encourage scour and prevent existing gravel bar from infilling channel. • (Potentially) Install flood fence riverward of the outlet channel on the floodplain to prevent outlet channel infilling with floodplain overbank sediment.	1.2%	• Mid-channel bar area will continue to evolve as it is currently (left bank erosion). • Depending on wood structure performance, end of new hatchery outlet channel may **require excavation due to gravel bar and sediment deposition.**	• Overbank flows may eventually cause outlet channel infilling if flood fence becomes ineffective or breaches, **requiring excavation.** • Right bank could erode and threaten outlet channel, but this is unlikely given the lack of right bank curvature and generally slow migration rates observed historically. • As wood structures decay, habitat in outlet channel may degrade, **requiring wood replacement along the outlet channel and where the outlet meets the South Fork**.

7 ANTICIPATED GEOMORPHIC RESPONSE TO THE PREFERRED ALTERNATIVE

Alternative 2 was selected by LNRD and modified by Herrera as requested by LNRD to represent the preferred alternative for advancing to final design and construction (Figure 8). We evaluated Herrera's 2D hydraulic modeling results of the preferred alternative and revisited this geomorphic assessment to predict how the Phase 1 reach may respond.

The preferred alternative was revised by Herrera to include certain base design elements that will be constructed in the as-built condition and elements that will be unpermitted and not constructed unless necessary for adaptive management. These include (Figure 8):

- Base elements:
  - New hatchery outlet channel with an outlet moved 300 ft upstream of the existing outlet
  - Wood habitat structures in the new outlet channel to provide hydraulic heterogeneity and to maintain a consistent thalweg (not shown on Figure 8)
  - Three ELJs along the right bank adjacent to the new outlet channel to provide scour pool habitat for upstream migrating salmon before ascending into the new outlet channel (orange wood structures on Figure 8). These structures also provide limited bank protection to help safeguard the new outlet channel from right bank erosion.
  - An emergency fishway vault located within the lower half of the existing outlet channel that can be activated if necessary to maintain flow from the hatchery into the South Fork if repairs or maintenance is needed within the new outlet channel. This vault is not shown in Figure 8 for clarity.
- Unpermitted adaptive management elements:
  - ELJs on the left bank intended to constrict flow towards the hatchery outlet on the right bank (not shown on Figure 8)
  - Removal of the revetment rock lining portions of the left bank downstream of the hatchery outlet (not shown on Figure 8)

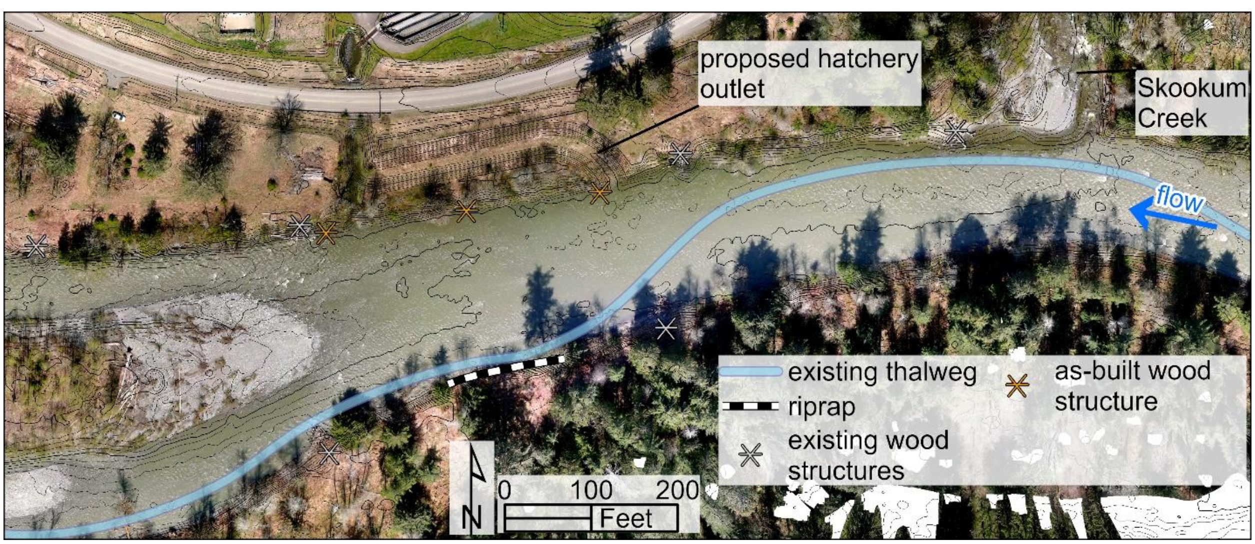

Figure 8: Elements of the selected alternative. Contours are at a 1 ft interval and represent the proposed terrain merged with the 2017 topobathymetric LiDAR surface. Basemap is 2023 drone imagery.

Compared to the original Alternative 2 described in section 6 above, the modified Alternative 2 (i.e. the preferred alternative described immediately above) does not as aggressively constrict flow against the hatchery outlet. While this makes it slightly less likely to ensure sufficient flow depth (and thalweg formation) against the right bank and hatchery outlet, the preferred alternative is still likely to ensure sufficient depth at the hatchery outlet in the short-term. The relocated hatchery outlet will be in a large, planar section of channel. This planar area is bound by a more defined outer right bank thalweg on the right upstream and a thalweg that has formed along the left bank of the south channel downstream of the flow split at Skookum Island. While moving the outlet upstream and away from Skookum Island will move it into an area of sufficient flow depth in existing conditions, it remains possible that future geomorphic change in the Phase 1 reach may cause a more defined thalweg to form away from the hatchery outlet, possibly depriving the outlet of sufficient flow depth during late summer low flows.

Typically, in a sinuous river with pool-riffle morphology, the thalweg forms against the outer bank and shifts to the opposite bank around the transition point where one bend curves into another and the upstream outer bank becomes an inner bank (i.e., the point of inflection). The existing thalweg near the existing hatchery outlet follows this pattern (Figure 8). The preferred alternative moves the hatchery outlet closer to this point of inflection. However, left bank erosion, as shown in Figure 3, has been moving the point of inflection and thus the thalweg upstream over time. We cannot predict how far upstream the left bank may eventually erode, but it is conceivable that it could erode far enough upstream to move the thalweg closer to the left bank at the new hatchery outlet, again depriving the outlet of sufficient flow or at least the connectivity between deeper areas and the hatchery outlet required for fish to pass upstream to the outlet.

We judge it to be unlikely that left bank migration upstream will pull the thalweg away from the new hatchery outlet and cause deposition there. The following evidence suggests that instead, what is more likely, is that the channel geometry around the new hatchery outlet is likely to remain similar to existing conditions:

- The channel upstream of the relocated hatchery outlet has remained very similar to its current planform since at least 1938.
- The riprap and ELJs along the left bank opposite of the hatchery outlet should resist upstream migration of the left outer bank, although they are unlikely to be reliable long-term channel migration barriers due to their life expectancies.
- Skookum Creek appears to help maintain a thalweg against the right bank upstream of the new hatchery outlet and prevents the thalweg from running along the left bank there.
- As the left bank continues to erode downstream of the hatchery outlet (along the south channel), it may more fully divert flow and sediment transport capacity away from the north channel. This, in combination with potential headcutting (see section 4.2) may help develop a more defined thalweg through the planar area close to the new hatchery outlet, which could actually deepen the area near the new hatchery outlet.
- We find no evidence in the 2D hydraulic model results for the preferred alternative to suggest that migration of the thalweg far upstream along the left bank is particularly likely in the as-built condition.

While we judge it to be more likely that the thalweg and general channel geometry will remain similar to existing conditions around the new hatchery outlet, we recommend monitoring for the following signs of geomorphic change that could threaten the hydraulic performance of the new hatchery outlet:

- Left bank and thalweg migration upstream (i.e., into the area across from the new outlet)
- Sediment deposition around the new hatchery outlet mouth
- Substantial mainstem channel widening around the outlet (even in the absence of left outer bank migration upstream)
- Substantial sediment deposition within the outlet channel during floods (e.g., sand to fine gravel deposition throughout the outlet channel length).

Should any of these geomorphic changes occur, we recommend considering adaptive management along the left bank (e.g., such as those shown in the original Alternative 2 described in section 6) that could constrict flow against the right bank and the hatchery outlet or maintenance to clear the outlet channel. Clearing the outlet channel of sand manually after floods may be required frequently, depending on how effectively the outlet channel could be hydraulically flushed. Adaptive management may also be required if climate change should reduce late summer baseflows sufficiently to deprive even the new outlet of sufficient low flow depth to be functional.

8 CONCLUSIONS

The South Fork has been migrating via bank erosion and mid-channel bar growth away from the existing hatchery outlet, creating a low flow depth fish passage barrier. Solving this issue could be accomplished by some combination of realigning the hatchery outlet channel to meet the South Fork at a deeper portion of the channel or rearranging the South Fork to deepen the channel around the outlet. Here, we presented and discussed three design alternatives that span this spectrum, ranging from solely moving the South Fork channel (Alternative 1) to solely moving the hatchery outlet (Alternative 3), with an intermediate alternative (Alternative 2) that involves a combination of hatchery outlet channel and mainstem modifications. In general, the alternatives that involve some movement of the hatchery outlet channel are more likely to be sustainable geomorphically than those that do not. After analyzing the preferred alternative (the modified Alternative 2 described in section 7), we find that it will place the hatchery outlet in a position that is less likely than the current position to be deprived of sufficient flow depth in the short-term. While its long-term performance is likely, it is less certain. As such, monitoring and possibly adaptive management will be necessary to ensure long-term hatchery outlet performance as the Phase 1 reach continues to change geomorphically.

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