Draft Technical Memorandum

To: Alex Levell, 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: June 9, 2023

Re: South Fork Nooksack Skookum-Edfro Reach Geomorphic Assessment

1 BACKGROUND AND PURPOSE

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

The technical memorandum presents WSE's geomorphic findings and considerations for potential design concepts. We first discuss existing geomorphic conditions and trends, focusing on issues affecting flow depth near the hatchery outlet (inlet for salmonids). Then, we present the four design concepts currently under consideration and evaluate their sustainability and need for adaptive management from a geomorphic perspective.

2 SITE DESCRIPTION

Key Site Characteristics

- The Skookum Fish 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 mid-channel bar 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 Nooksack River in the immediate vicinity of the Skookum Fish Hatchery flows through two low-amplitude meander bends separated by a large mid-channel bar. 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 the mid-channel bar.

The segment of the South Fork Nooksack extending approximately 1.2 miles downstream and 2 miles upstream of the Skookum Fish 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.

With the exception of the mid-channel bars around the hatchery and Edfro Creek 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 in-stream wood loads compared to pre-European colonization by reducing wood recruitment and wood storage capacity (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 as wood decays and breaks, especially in reaches such as that around the Fish 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 Skookum Reach is estimated to be incising at a rate of 1 – 2 ft per decade, and based on hydraulic modeling, is largely disconnected from its historic floodplains, which are now terraces, including the large terrace on the left (south) side of the reach adjacent to the mid-channel bar (Element Solutions, 2015). Bedrock exposure has been visually documented in the bank and valley walls (Lapen, 2000) and in well logs around the fish hatchery (WA Department of Ecology). Well logs near the hatchery reveal bedrock at elevation 369 to 374 ft, 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.

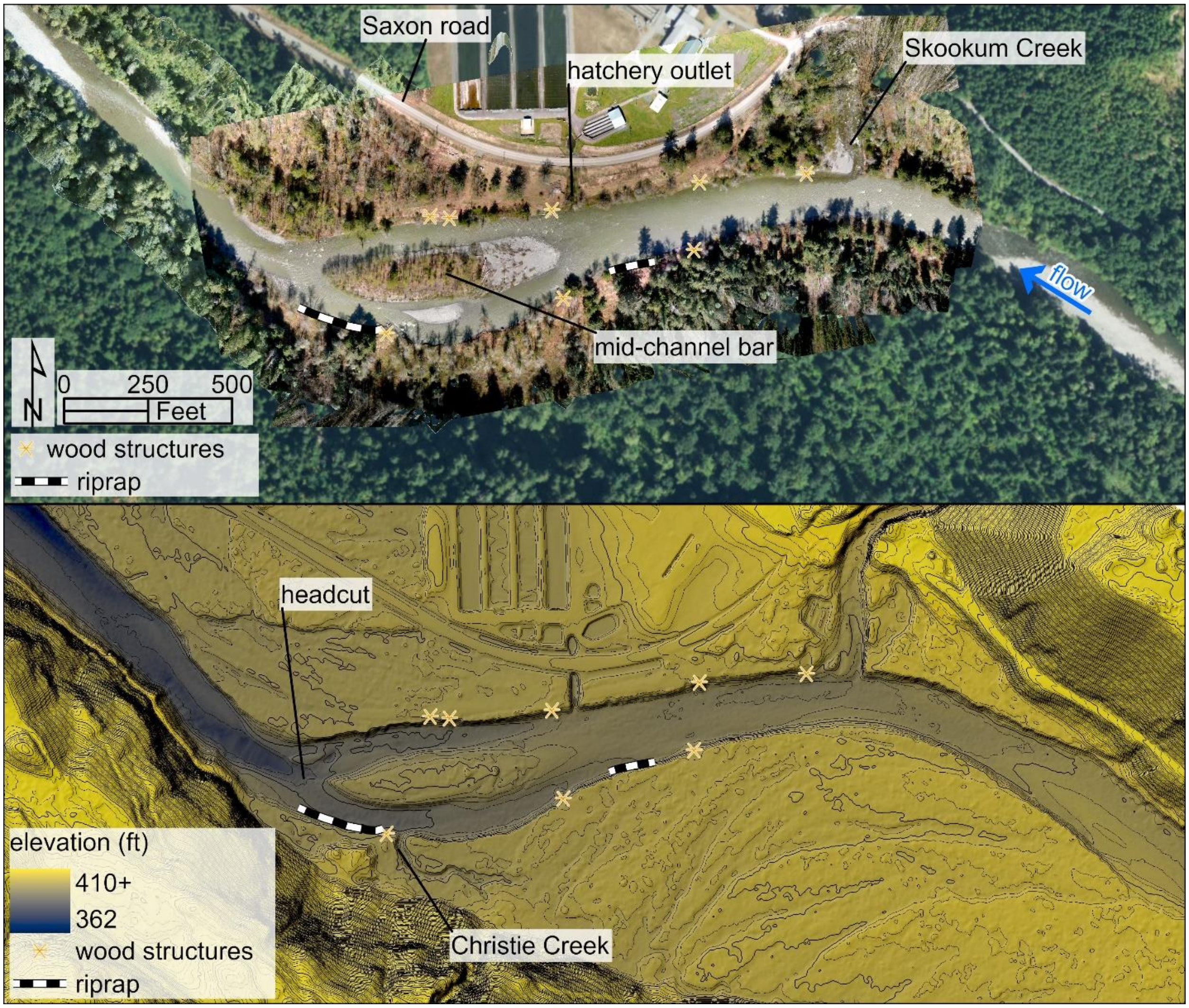

Figure 1: Site map showing a composite of imagery from 2023 (center), 2022 (downstream), and 2017 (background) (top), and LiDAR topobathymetry from 2017 (bottom). Contour interval is 2 ft.

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 it during low flows.
- Bank armoring and, to a more limited extent, wood structures, within the project 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: summer low flows are getting lower due to climate change (Tohver et al., 2014), and the channel along the southern side of the mid-channel bar 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 the mid-channel bar began growing and banks began eroding in the mid-1950s. The right bank of the northern channel eroded slightly as the mid-channel bar grew in the 1990 to 2010 period; however, most of the erosion has occurred along the left bank of the southern channel. In response, the southern 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 impacted the reach:

- Between 1966 and 1986, a road and cabin were built on the left bank of the southern channel along the mid-channel bar. 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 from its previous position along the right (north) bank further inland. A series of large wood structures were also constructed along the right bank to create pool habitat. Shallow probing conducted by LNNR of the right bank confirmed a lack of riprap along this bank near the surface.
- In 2017, a series of habitat wood structures were built along the left bank of the Southern channel and some of the riprap revetment was removed. At the same time, the right bank wood structures were augmented to extend further into the flow.

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

As the mid-channel bar grows and the channel widens and migrates via bank erosion, the left (south) channel is growing faster than the right (north) channel, leading to flow diversion down the left channel and away from the hatchery outlet and sediment deposition at the head of the bar near the outlet. While the right 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 wood structures built in 2010 to create pool habitat likely reduce bank erosion in the immediate vicinity of each structure.
- Flow diversion down the left channel along the mid-channel bar may be depriving the right 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 Figure 2: notice that clearer Skookum Creek water doesn't fully mix with the turbid water of the South Fork Nooksack for approximately 300 ft downstream of the confluence at a 1,700 cfs South Fork Nooksack flow. Examination of the two-dimensional hydraulic model of the existing condition showed a significant reduction in velocity near the bank extending down to the second 2010 wood structure (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 side channel continues to erode (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 left side channel has diverted flow away from the right side channel and the hatchery outlet channel. The bank erosion shows no sign of slowing (Figure 4), nor of restarting along the right side channel. Therefore, we predict that under existing conditions, the left bank will continue to erode and the left channel will continue to widen, further depriving the right channel and hatchery outlet of flow and exacerbating the existing fish passage problem. As the channel migrates south, the right (north) channel may eventually infill with sediment, vegetate, and stop conveying low flows entirely.

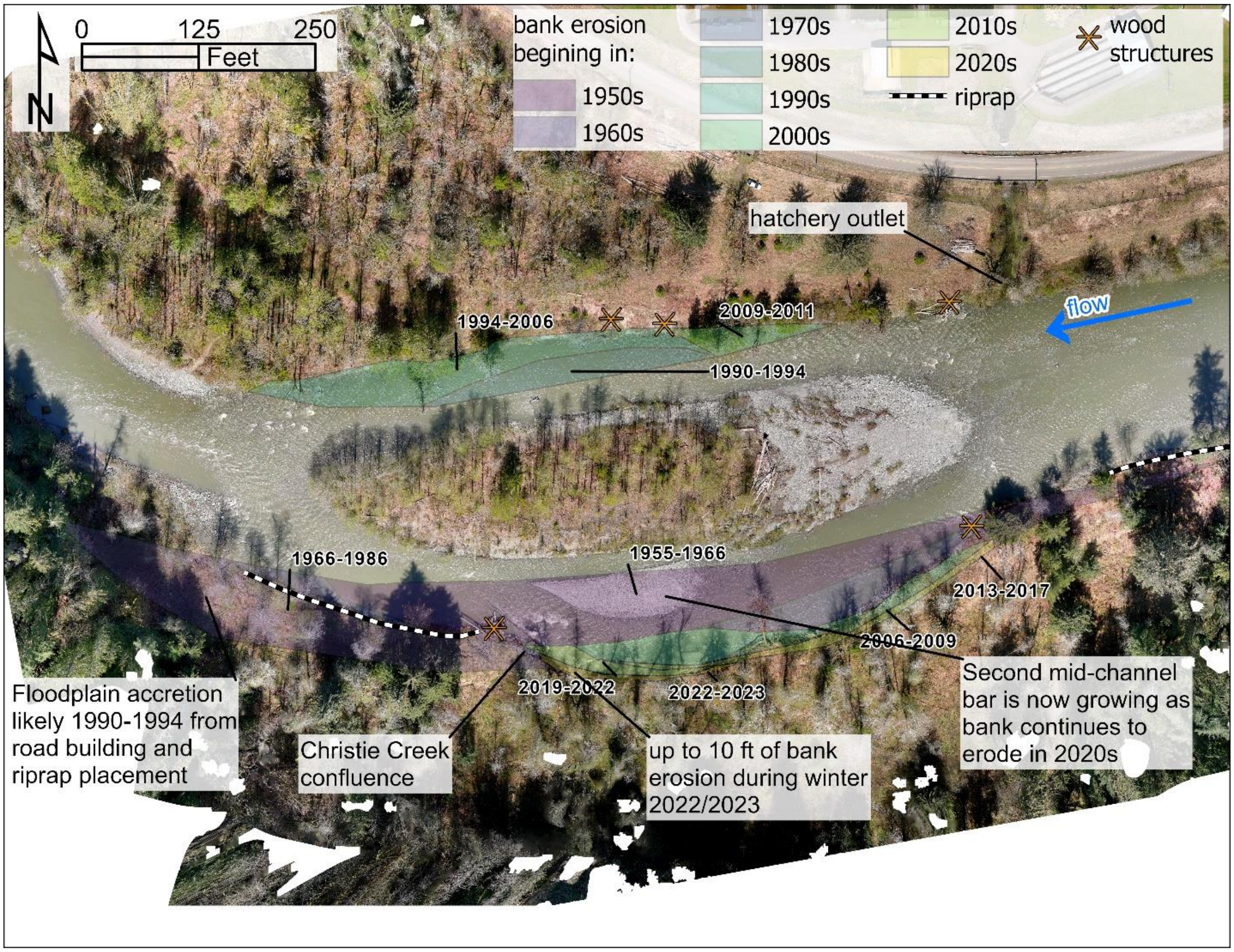

Figure 3: Bank erosion around the mid-channel bar just downstream of the hatchery outlet.

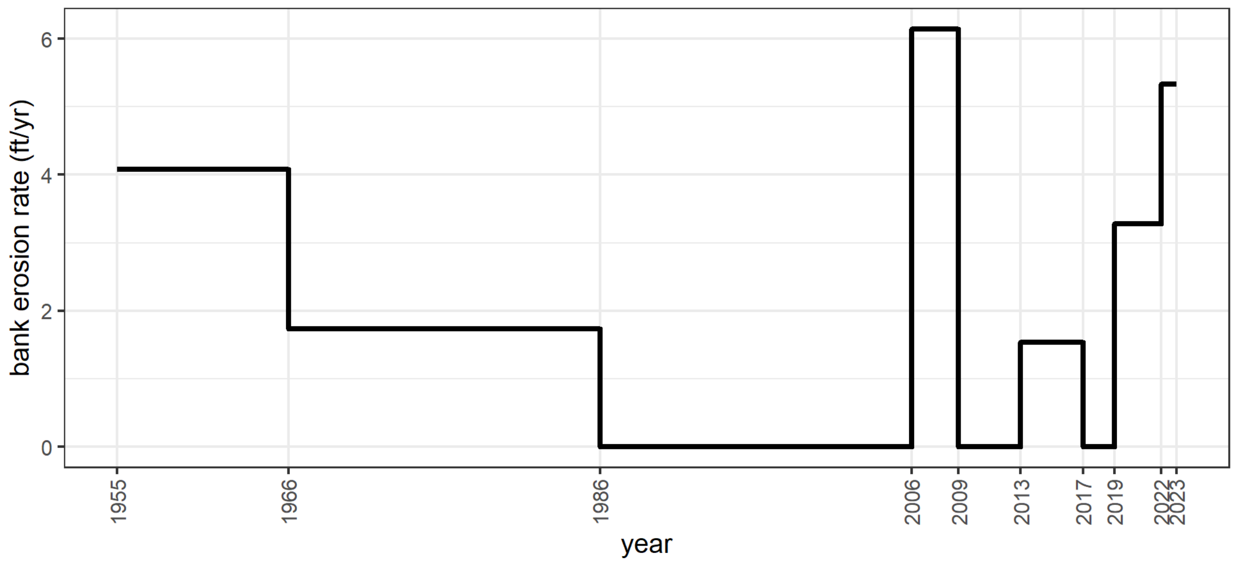

Figure 4: Bank erosion rate averaged along the length of the portion of bank that was eroding in each period of observation for the left bank.

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 Nooksack.
- The downstream end of the mid-channel bar is the upper step of the headcut. In the event that it moves upstream, it will divert more flow into whichever channel conveys more flow, currently the left channel, which would divert more flow away from the hatchery outlet.

LiDAR topography and historical imagery and maps indicate that prior to the 1884 General Land Office mapping of this area, the South Fork Nooksack cut off a large meander bend about 3000 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. Headcuts typically cause channel incision (elevation loss) upstream because they elevate sediment transport capacity.

In the South Fork Nooksack'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 3000 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 the mid-channel bar. 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 not to 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. The mid-channel bar reduces flow energy and may have kept the headcut from migrating upstream or slowed its migration in the past. However, as the left 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 left channel becomes more dominant, it could further exacerbate the current fish passage problem.

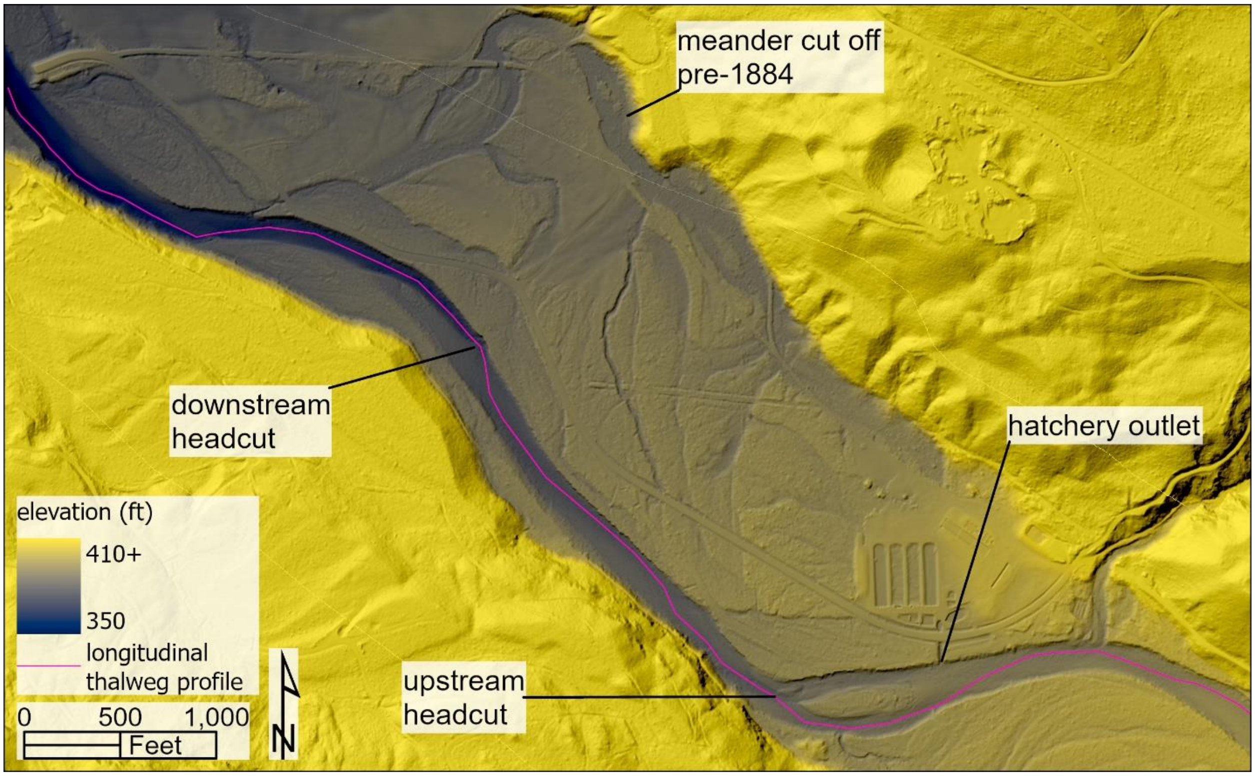

Figure 5: 2017 LiDAR topography showing the cutoff meander and resulting headcut locations.

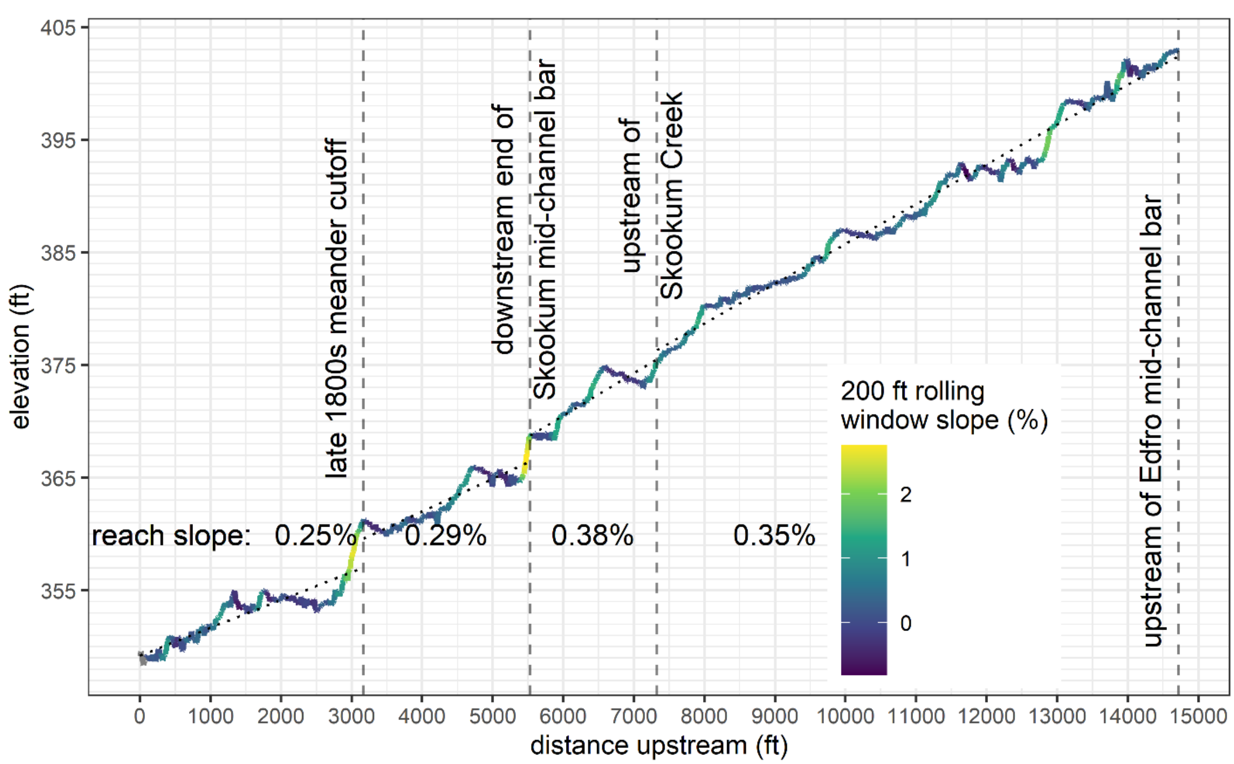

Figure 6: Longitudinal thalweg profile (alignment shown in Figure 5) from Saxon Bridge (downstream) to the upstream end of the Edfro mid-channel bar. Reach-average slopes are shown as dotted lines for each reach.

5 GEOMORPHIC DESIGN CONSIDERATIONS

To ensure that salmonids can access the outlet, it is crucial for the hatchery outlet channel to sustainably connect with the South Fork Nooksack 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 complimentary ways to reach this solution:

A) Rearrange the South Fork Nooksack River 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 solve the fish passage barrier problem, the consultant team identified three potential alternatives. Alternative 1 relies entirely on option A - rearranging the South Fork Nooksack 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 Nooksack. Finally, Alternative 3 relies entirely on option B, moving the hatchery outlet channel while only minimally changing the South Fork Nooksack.

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 wood structures decay, the river could resume its current trajectory of expanding the left channel and diverting flow away from the hatchery outlet, which would require adaptive management in the form of wood 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 wood structures to increase flow depth near the outlet channel, it is more likely to remain sustainable as wood structures decay, and 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 the mid-channel bar. 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. There is a small gravel bar where the outlet channel would enter the South Fork, which may block the end of the outlet channel; however, the flows from the outlet channel may keep sediment from depositing or scour it away after it deposits, or wood 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. 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 wood structures to have long-lasting geomorphic effects, they must induce sediment and wood deposition, and promote vegetation growth to replace the impact of the decaying wood 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.

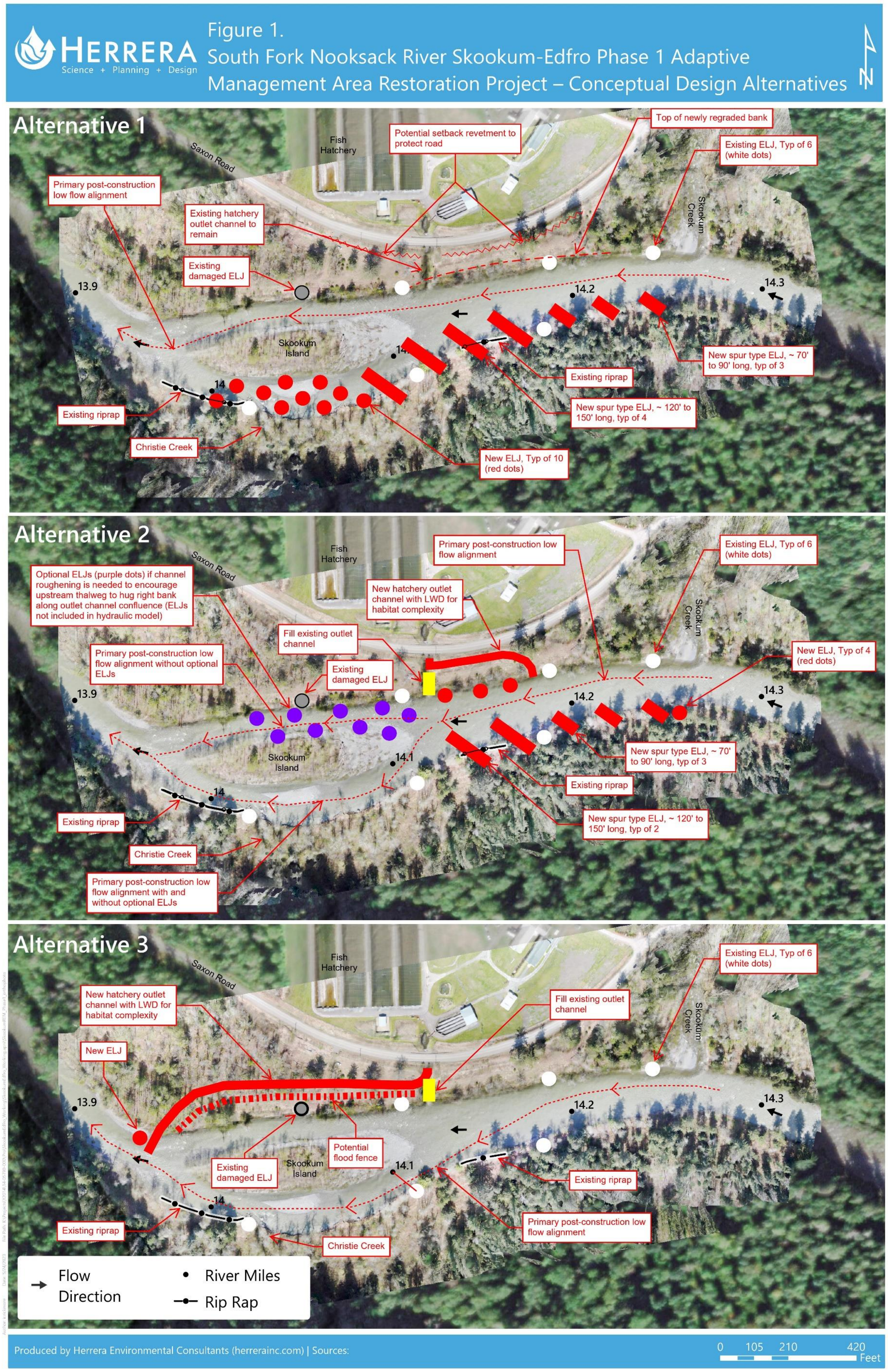

Figure 7: Design alternatives. Note that features shown are approximately located.

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 left 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 ft upstream away from the sediment deposition occurring around the mid-channel bar. • Roughen left bank opposite outlet channel to constrict flow against the new outlet channel and right bank. • (Optional) Roughen right side channel to constrict most of high flows to left channel but allow flushing flows and create a low flow pathway down right 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). • Right side 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 the mid-channel bar. • 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 CONCLUSIONS AND NEXT STEPS

The South Fork Nooksack River has been migrating via bank erosion and mid-channel bar growth away from the Skookum Fish Hatchery outlet (salmonid inlet), creating a low flow depth fish passage barrier. Solving this issue could be done by some combination of realigning the hatchery outlet channel to meet the South Fork Nooksack at a deeper portion of the channel or rearranging the South Fork Nooksack to deepen the channel around the outlet. Here, we present and discuss three design alternatives that span this spectrum, ranging from solely moving the South Fork Nooksack (alternative 1) to solely moving the hatchery outlet (alternative 3), with an intermediate alternative 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.

This draft geomorphic memo will be revised after the 3 alternatives have been evaluated using a 2-dimensional hydraulic model. That revision will reflect hydraulic model analysis and a revised comparison of the three alternatives.

REFERENCES

Anderson, S. W., Konrad, C. P., Grossman, E. E., & Curran, C. A. (2019). *Sediment Storage and Transport in the Nooksack River Basin, Northwestern Washington, 2006–15. Prepared in cooperation with the Whatcom County Flood Control Zone District* (Scientific Investigations Report No. 2019–5008; Scientific Investigations Report, p. 43). U.S. Department of the Interior U.S. Geological Survey. https://doi.org/10.3133/sir20195008.

Brown, M., & Maudlin, M. (2007). *Upper South Fork Nooksack River Habitat Assessment* [Submitted to Salmon Recovery Funding Board]. Lummi Nation Natural Resources Department.

Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, *139–140*, 460–470. https://doi.org/10.1016/j.geomorph.2011.11.011

Collins, B. D., & Sheikh, A. (2004). *Historical Channel Locations of the Nooksack River* [Report to Whatcom County Public Works Department]. Department of Earth and Space Sciences, University of Washington.

Element Solutions. (2015). *South Fork Nooksack – Skookum Edfro Reach Geomorphic Analyses for Salmon Restoration Project Designs*. Prepared for Lummi Natural Resources and Herrera Environmental Consultants.

Hyatt, T. L., & Naiman, R. J. (2001). The Residence Time of Large Woody Debris in the Queets River, Washington, Usa. *Ecological Applications*, *11*(1), 191–202. https://doi.org/10.1890/1051-0761(2001)011[0191:TRTOLW]2.0.CO;2

Lapen, T. J. (2000). *Geologic Map of the Bellingham 1:100,000 Quadrangle, Washington* (Open File Report No. 2000–5). Washington Division of.

Merten, E., Vaz, P. G., Decker-Fritz, J. A., Finlay, J. C., & Stefan, H. G. (2013). Relative importance of breakage and decay as processes depleting large wood from streams. *Geomorphology*, *190*, 40–47. https://doi.org/10.1016/j.geomorph.2013.02.006

Sass, G. G. (2009). Coarse Woody Debris in Lakes and Streams. In *Encyclopedia of Inland Waters* (pp. 60–69). Elsevier. https://doi.org/10.1016/B978-012370626-3.00221-0

Scherer, R. (2004). Decomposition and Longevity of In-Stream Woody Debris: A Review of Literature From North America. In G. J. Scrimgeour, B. Eisler, B. McCulloch, U. Silins, & M. Monita (Eds.), *Forest Land–Fish Conference II – Ecosystem Stewardship through Collaboration*.

Stein, O. R., & Julien, P. Y. (1993). Criterion Delineating the Mode of Headcut Migration. *Journal of Hydraulic Engineering*, *119*(1), 37–50. https://doi.org/10.1061/(ASCE)0733-9429(1993)119:1(37)

Tohver, I. M., Hamlet, A. F., & Lee, S.-Y. (2014). Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America. *Journal of the American Water Resources Association*, *50*(6), 1461–1476. https://doi.org/10.1111/jawr.12199