FINLEY CREEK ALLUVIAL FAN GEOMORPHIC AND HYDRAULIC ANALYSES AND IMPLICATIONS FOR RESTORATION

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INTRODUCTION

Finley Creek, located on the Olympic Peninsula in western Washington, is a tributary of the Quinault River upstream of Lake Quinault. Previous observers have noted recent progressive lateral movement of the channel toward the eastern side of the Finley Creek alluvial fan, and aggradation and perching of the channel in the vicinity of the North Shore Road Bridge. The relationship between Finley Creek and the Quinault River is one of a long-term dynamic interaction between a large alluvial fan and mainstem river. The current sediment production from Finley Creek is of critical concern due to ongoing dredging at North Shore Road Bridge and the potential environmental effects of the dredging both upstream and downstream of the bridge (NPS, 2005) and sediment deposition and lateral Quinault River channel migration (GeoEngineers, 2011). Previous studies on Finley Creek have documented historical channel change using rectified aerial photography (Bountry et al. 2005) and the problems associated with aggradation and erosion on sections of Finley Creek (Kennard, 2009; Smillie, 2001; Jackson and Smillie, 1994).

The objectives of this study are to (1) provide a geomorphic analysis of conditions on Finley Creek in order to place current conditions into a long term context and to identify areas of potential avulsion and lateral erosion; and (2) conduct hydraulic modeling of various scenarios to guide the evaluation of alternatives for addressing aggradation near the North Shore Road Bridge and improvement of aquatic habitat on Finley Creek.

SETTING

Finley Creek flows from its headwaters in Olympic National Park to the south through a steep and narrow canyon with step-pool channel morphology. The stream emerges onto the Finley Creek alluvial fan, where channel morphology is braided at intermediate to high flows. Finley Creek joins the Quinault River just upstream of Quinault Lake near Quinault, Washington (Figure 1). Kestner Creek and Canoe Creek flow onto the Finley Creek alluvial fan on its western edge. The tributaries currently do not have a surface connection with Finley Creek but contain groundwater flow which is likely partially sourced from Finley Creek.

Flood frequency flows calculated indirectly by National Stream Statistics (Knowles and Sumioka, 2001) indicate a high-end 2-year event for Finley Creek is on the order of 2,500 ft^3/s while a 100-year flow is approximately 6,150 ft^3/s. A recently installed staff gage with time-lapse photography at the canyon mouth has continuously recorded stage. Flows of 1,557 and 1,240 ft^3/s through 2013 and 2014 have been measured at the Finley Creek Bridge—these flows are on the order of annual to 1.25-yr events and have been contained within the main channel of

Finley Creek. High flows mainly occur during the rainy season which on the Olympic Peninsula spans the months of October through March.

The Finley Creek alluvial fan is a moderate gradient, humid fan with a seasonally fluctuating discharge. Fluvial processes dominate on the fan and within its main channels; debris flow processes are dominant in the headwaters where steep tributaries join the main stem. The Finley Creek alluvial fan can be divided into an upper fan and lower fan based on changes in gradient and fan morphology (Figure 1). The upper fan is a higher gradient fan with one or two main channels that flow between interfluves stabilized by vegetation and soil development. These interfluves are young alluvial fan terraces, which have been abandoned by Finley Creek through avulsion and minor incision. The fan terraces consist of interbedded sand and gravel fluvial units. The upper fan is bounded by Pleistocene glaciofluvial deposits on the eastern edge and bedrock with steep gradient tributaries on the western edge. The lower fan is a lower gradient system with distributary channels that diverge from the main channel, some of which dissipate on the fan surface and others which deliver sediment to the Quinault River.

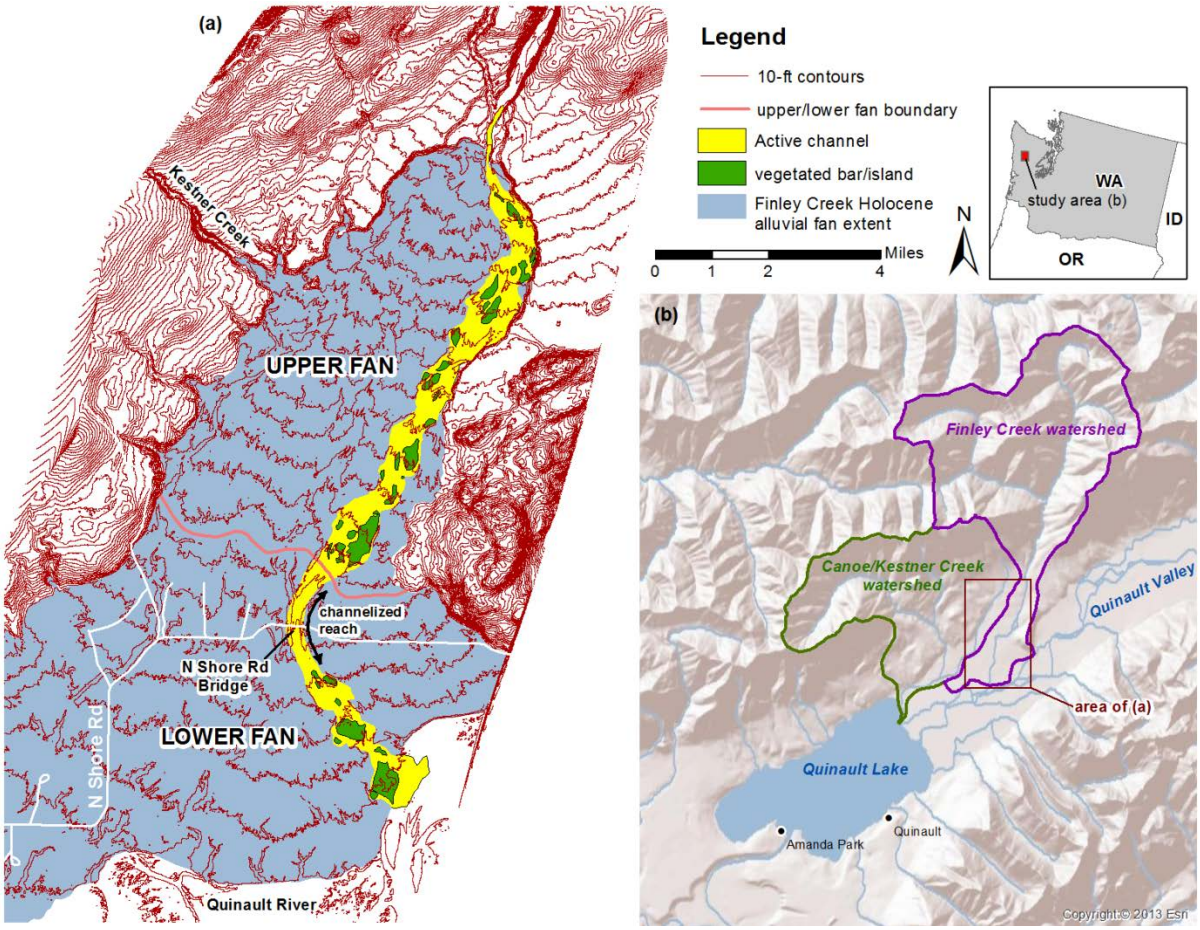

Figure 1 Location map showing (a) Finley Creek alluvial fan and (b) physiographic setting of study area.

Channel morphology of Finley Creek varies based on position within the alluvial fan and the amount of manipulation, and can be characterized in three segments: upper fan, lower fan and a channelized reach at the upstream part of the lower fan. On the upper fan, the main channel of Finley Creek is braided with high relief between the thalweg and top of unvegetated bars (Figure 2). Channel complexity is high with small pool and riffle areas during low flow. During high flow, the channel transitions to a braided morphology with abundant large woody debris and gravel bars. Mid-channel islands with immature vegetation such as alders and conifers occupy portions of the main channel and are transient features that are modified during high magnitude flows.

On the lower fan, the main channel is composed of a single braided channel that conveys the majority of flow to the Quinault River. Several large mid-channel islands exist with immature to mature vegetation (Figure 2). Many of these islands have been formed as the channel has scoured around older landscape features and isolated areas of the older alluvial surfaces as islands. Therefore the older character of the islands is in contrast to the immature islands in the active channel of the upper fan. In many locations, lacustrine sediment is exposed under the younger alluvium now contained on the islands in the lower fan. Prior to channel manipulation, the lower fan was largely a distributary system, where smaller channels branched from the main channel issuing from the upper fan. Blockage of many of the distributary channels by man-made berms or levees on the lower fan has prevented surface flow into many of the historical distributary channels, although several of these channels continue to convey baseflow from shallow groundwater. In the channelized reach in the vicinity of the North Shore Road Bridge, where the channel is constrained by levees, the channel is single thread with low relief and low complexity, and is a much narrower channel than the other reaches (Figure 2). Large woody debris is not abundant, partially due to clearing during gravel excavation.

Figure 2 Ground photos showing channel morphology in (a) upper fan; (b) channelized reach; (c) lower fan.

METHODS AND RESULTS

Various methods are employed to answer the study questions. Geomorphic and hydraulic analysis methods used in this study are:

- surficial mapping
- geomorphic change detection (Wheaton et al., 2010)
- mapping of potential sites of lateral erosion and channel avulsions
- numerical hydraulic modeling

Surficial mapping: The mapping for this project focuses on surficial deposits on the Finley Creek alluvial fan and highlights how recently surfaces have been activated by Finley Creek. Each map unit is a complex of ages; for instance, areas that have been active historically may include areas of older alluvium that have not been completely overprinted by historical lateral channel erosion or deposition. On the lower fan, deposits may also include underlying lacustrine sediment that is related to higher stages of Quinault Lake during the early to middle Holocene (~10-6ka). Mapping was performed remotely using historical channel mapping from Bountry et al. (2005), post-2005 channel mapping, 2011 LiDAR surface morphology and 2011 NAIP digital photography. Areas along the active channel were field checked; limited field checking was performed in areas away from the active channel. Where possible, exposures of the different alluvial deposits were described and photographed.

The youngest map units include the Finley Creek active channel and vegetated gravel bars and the Kestner Creek active channel and bars (Figure 3). The active channel map unit includes the area on Finley Creek alluvial fan that was actively being reworked by fluvial processes in 2011, the dates of the aerial photography and LiDAR. This includes the low flow and high flow channels, and unvegetated gravel bars. Vegetated bars or islands occur as mid-channel features with irregular surface morphology. The Kestner Creek active channel contains alluvium primarily derived from the Kestner Creek drainage, but may contain alluvium derived from Finley Creek as well, as it appears that the two drainages merged on the west side of the fan prior to the time covered by the historical channel mapping.

Historical alluvium includes areas on the Finley Creek alluvial fan that have been occupied historically since the late 1800s by either the main channel or distributary channels of Finley Creek (Bountry et al. 2005). The map units may include areas of older alluvium that have not been completely modified by historical channel activity. The historical alluvium is grouped into four main units based on the time period over which the area was actively being reworked by the main channel or distributary channels of Finley Creek (Figure 3): Historical alluvium III (post-1960), Historical alluvium II (1939-2002), and Historical alluvium IB (pre-1960) and IA (~1890s). Historical alluvium II contains overlapping time periods with III and IB because the time in which this area was occupied spans both units. The general pattern in historical alluviation has been a progressive shift of the active Finley Creek channel to the west on the fan, which was initiated by the log jams constructed by homesteaders in the late 1800s and into the 1930s at the canyon mouth on the upper fan to block flow from entering the western channels (Historical alluvium 1A and 1B). On the lower fan, levees were built near North Shore Road

Bridge in more recent decades to block flow from entering the western distributary channels (Historical alluvium II).

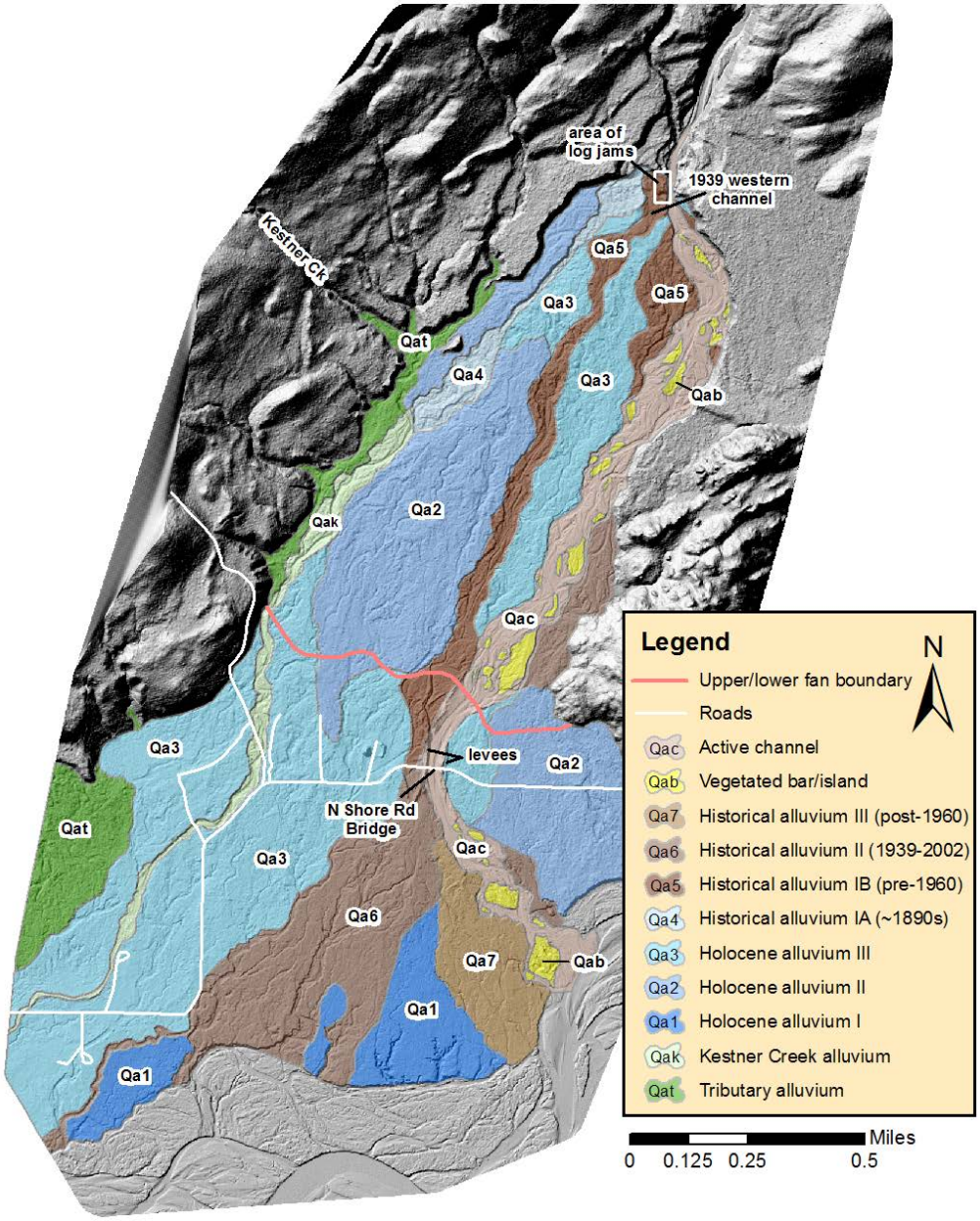

Figure 3 Surficial geologic map of Holocene units, Finley Creek alluvial fan. Basemap is a hillshade derived from 2011 LiDAR.

Holocene alluvium is mapped as three separate units based on surface morphology, soils and relative height above the active channel of Finley Creek. The units are numbered I, II and III in order of relative decreasing age. These units generally predate historical aerial photography and historical maps and therefore reflect areas of the fan that were active prior to the late 1800's. Based on limited radiocarbon data, these units appear to span the Late to Middle Holocene if underlying lacustrine units are included in the age estimate (<6ka) (Bountry et al., 2005).

Geomorphic Change Detection, patterns of erosion and deposition: Geomorphic Change Detection (GCD) software (V5.0, https://sites.google.com/a/joewheaton.org/gcd/home), which is based on the theory presented in Wheaton et al. (2010) was used to detect changes in erosion and deposition using changes in elevation between the 2002 and 2011, the dates of the LiDAR datasets (Figure 4). GCD was also used to develop a sediment budget along Finley Creek. Once the two datasets were converted into orthogonal and concurrent rasters, a threshold of 20 cm was applied to the DEM of difference, which was generated by taking the differences in the grid point elevations in 2002 and 2011. For the entire active channel area (active channel and vegetated islands map units), results show the alluvial fan had net deposition of more than 300,000 yd^3 in the 9 years between 2002 and 2011.

Areas of interest were further delineated in ArcGIS (Figure 4). Upstream of the North Shore Road Bridge (upper fan and upstream portion of lower fan), net deposition was 215,000 yd^3, in which 244,000 yd^3 of deposition and 29,700 yd^3 of erosion were calculated between the two datasets. There has been net erosion from the glacial terrace (labeled glacial terrace area, Figure 4) of -40,000 yd^3 based on 79,900 yd^3 of erosion and 39,900 yd^3 of deposition. The sediment budget calculations during this time period (2002-2011) show that the majority of sediment deposition is from headwater sources (e.g. landslides) since there is no sediment source within the fan (such as bank erosion) that shows net erosion similar to the net deposition in the active channel. The active channel in the channelized reach experienced net erosion (-7,000 yd^3) over the 9 year span, although this area was actively managed during this time period. In 2002 LiDAR (Oct 30th), the channel had just been excavated and in 2011 LiDAR (Nov-Dec), some deposition had already occurred following excavation. An increase in the volume of the berms or levees is also detected, with the river right levee gaining 14,000 yd^3, and the river left levee gaining 3,600 yd^3. Deposition in the western distributary area (labeled lower fan distributary area) is detected, with net erosion in the active channel downstream of North Shore Road Bridge to Quinault River (10,000 yd^3). In all areas downstream from North Shore Road Bridge (lower fan), net deposition (128,000 yd^3) is detected between 2002 and 2011.

Potential for future channel change, lateral erosion and channel avulsion: Finley Creek alluvial fan is a dynamic system, and has continued to evolve throughout the historical period. Channel change is a natural part of the Finley Creek system and will need to be considered in any recommendations for future management alternatives. The identification of areas most prone to lateral erosion and avulsion are important to identify and evaluate as part of identifying restoration alternatives. Areas of lateral erosion were identified on the basis of vertical stream banks observed and mapped during 2013 fieldwork (Figure 5). Vertical banks of unvegetated sediment are indicative of actively eroding areas and are typically located along outer bends in the channel where shear stress on banks is the highest. These areas are likely to continue to erode as long as the active channel is located in a similar position. Most areas of Finley Creek that are prone to lateral erosion are located along the western side of the active channel, where the channel is actively eroding. Areas prone to toppling are located along the eastern side of the upper fan active channel where fluvioglacial deposits crop out in the glacial terrace. This area has been eroding laterally since about 1952; however, undercutting at the channel level has caused toppling of the surface soil, depositing underlying sediment and large trees at the base of

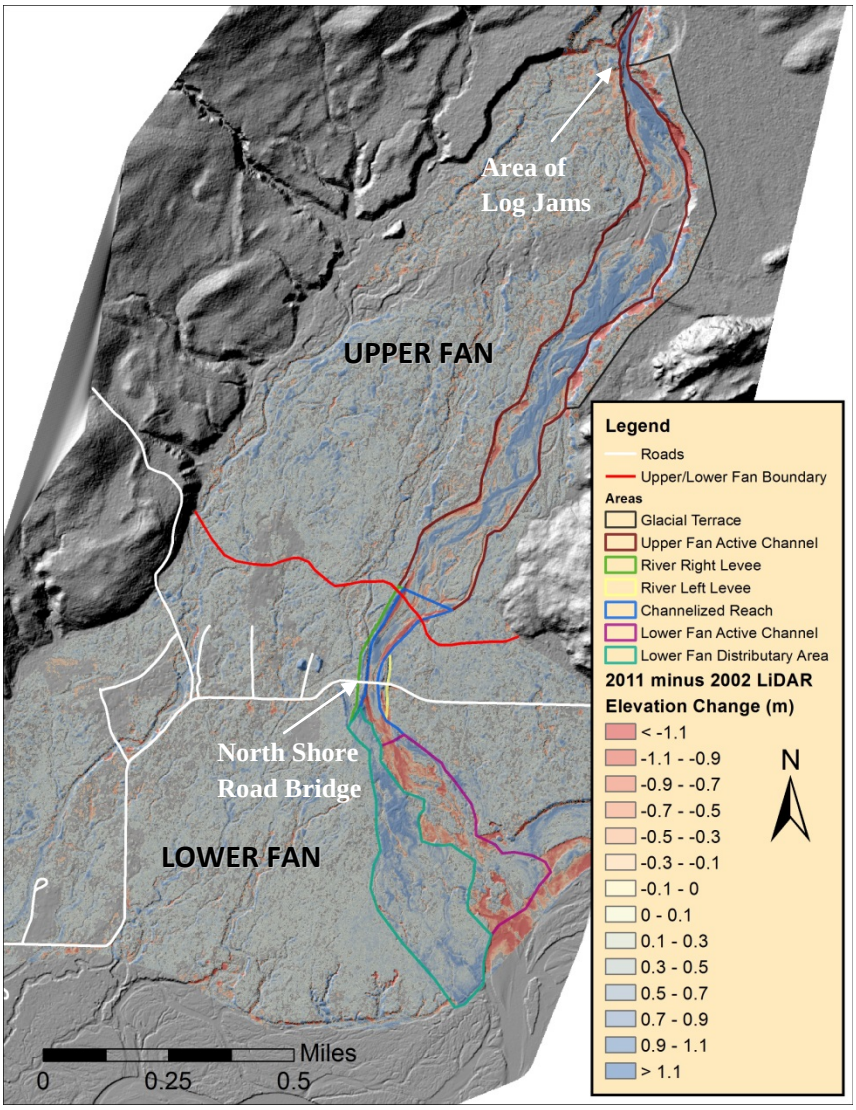

Figure 4 Erosion and deposition patterns of Finley Creek between 2002 and 2011 identified using Geomorphic Change Detection software.

the bluff. In addition, unraveling of the mostly unconsolidated glacial sediments has also generated a large amount of debris in the channel that provides some measure of bank protection along the eastern side of the channel on the upper fan. However, retreat of the bluff could continue through physical weathering and detachment of unconsolidated materials at the base of the bluff.

Channel avulsions could promote abandonment of some areas along the stream in which case the lateral erosion would shift to different areas than those shown in Figure 5. Areas of potential avulsion are located where the channel is most likely to shift position by abandoning its present channel for a new course (black circles in Figure 5). A channel avulsion could also occur where the distribution of flow and sediment shifts to a new location without completely abandoning, but leaving much less flow in, the old channel.

Potential avulsions areas were defined based on:

- Areas of low elevation adjacent to the active channel, especially those located along outer bends in the channel
- Presence of geologically recent or historical channels in overbank areas that have flow only in larger floods, but could be accessed by main channel flow
- Channels inundated in overbank areas as shown by the hydraulic model results
- Evidence for splays of the main channel, which indicate overbank inundation and preferred flow paths during high flows

Other areas of potential avulsion were identified that were not adjacent to the active channel in order to identify low elevation areas where the main channel could avulse if human constructs such as berms or levees were removed (white circles in Figure 5). These areas could also be avulsion areas even if human constructs are maintained, but the avulsion may take considerably longer to occur.

The area with the most potential for channel avulsion is located along the western side of the active channel upstream from the North Shore Road Bridge (area # 4, 5 and 10). This is an extensive area of low elevation where the current Finley Creek channel is perched above its surrounding floodplain, and held in place by man-made berms (area #10). When compared to surficial mapping (Figure 3), the avulsion areas are located mostly in areas that are mapped as historical alluvium.

Numerical hydraulic modeling: A fixed-bed two-dimensional (2D) numerical hydraulic model, SRH-2D (Lai, 2008), was employed to capture the inundation extent and hydraulic properties of flood flows experienced on the Finley Creek alluvial fan. Over the entire alluvial fan, only surface hydraulics are simulated, although observations indicate that there is significant surface water and groundwater interaction on the alluvial fan. Six different steady flows from the 1.5- to the 100-year discharge are simulated on the 2011 LiDAR surface, with the downstream stage-discharge boundary condition based on a modified HEC-RAS model of the Quinault River used in Bountry et al (2005). Manning roughness values were assigned to various areas including the channel (0.025-0.035), densely vegetated floodplain (0.1), sparsely vegetated floodplain (0.04), road prism (0.02), and structure footprints (0.08).

Lacking gaged discharge and measured water surface elevations for model calibration, a sensitivity test of the assumed water surface elevation was performed varying channel roughness and flood frequency. Modeling results of existing conditions for the 2- and 100-year events indicate that these flows are confined primarily to the active channel (Figure 6). Various restoration ideas developed with the consensus of the stakeholders can be simulated with the 2D numerical hydraulic model, such as the removal of various anthropogenic features (e.g. levees and log jams), which reduces the confinement of flows across the alluvial fan (Figure 6). Restoration ideas include removal of the historical log jams on the west side at the canyon mouth (Figure 3), removal of a portion of the western levee upstream of North Shore Road Bridge, construction of 7 to 8 road crossings through the road prism and raise of the road prism above the 100-year water surface elevation.

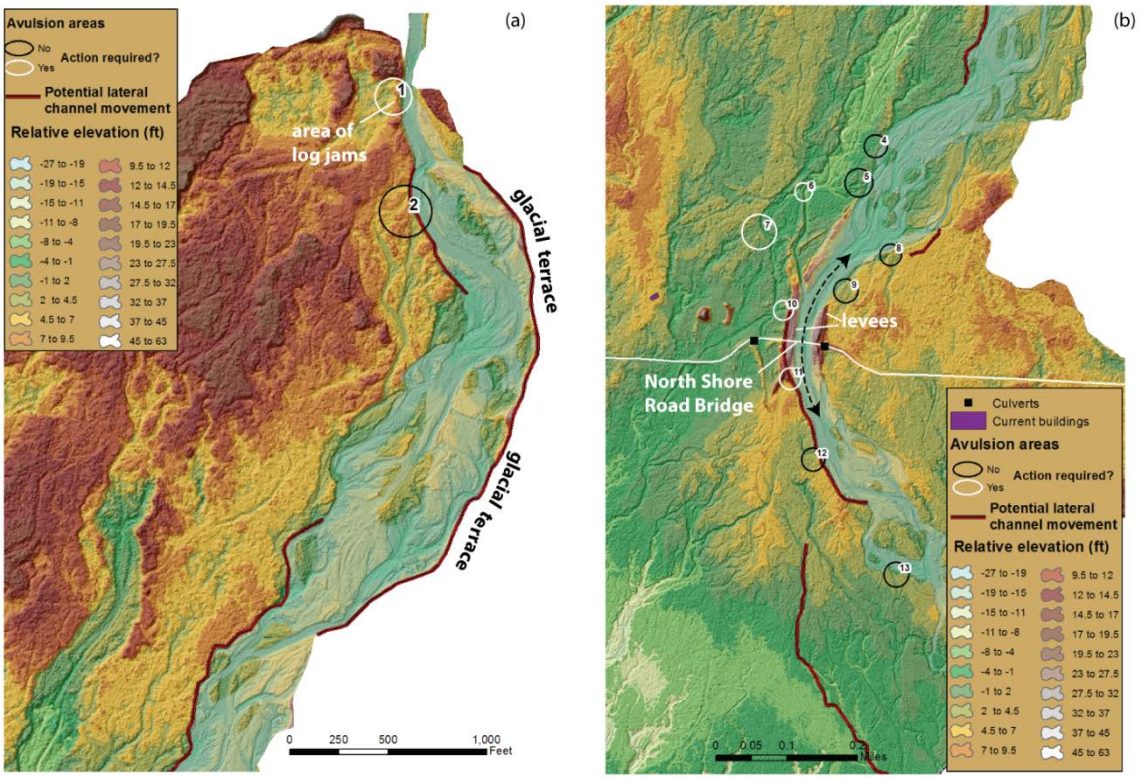

Figure 5 Finley Creek potential avulsion and lateral erosion areas. (a) upper fan; (b) lower fan. The avulsion areas are based on 2011 relative elevation map and field verification in 2014. The areas of potential lateral erosion were identified during field work in 2013. Avulsion areas are shown as circles; black circles show areas where man-made features do not block the channel from avulsing. White circles show areas where man-made features would either need to be removed or eroded before an avulsion could occur. Dashed line with arrows shows the channelized reach. The 2011 active channel is shown in light blue overlaid on the relative elevation map.

SUMMARY OF PRESENT CONDITIONS

Prior to human manipulation, Finley Creek existed as a multi-thread system that flowed through islands of alluvium with weakly developed soils and mature vegetation. With a natural decrease in gradient on the lower fan, flows became more distributary, depositing sediment on the fan surface and delivering sediment to the Quinault River. With the help of human constructs such as levees, repeated excavation of the channel, log structures and berms, the Finley Creek channel on both the upper and lower fan has been restricted to one main channel with intermittent mid-channel islands and immature vegetation and has shifted progressively to the east beginning in the late 1800s. In recent years (2002-2011), the main channel of Finley Creek on the upper fan has been dominated by deposition; the channel on the lower fan has been dominated by erosion. Landslides in the form of large debris avalanches appear to occur every few decades in the canyon upstream of the alluvial fan and are a periodic but persistent sediment source to the Finley Creek channel on the upper fan. Streambank erosion of the glacial terrace along the east

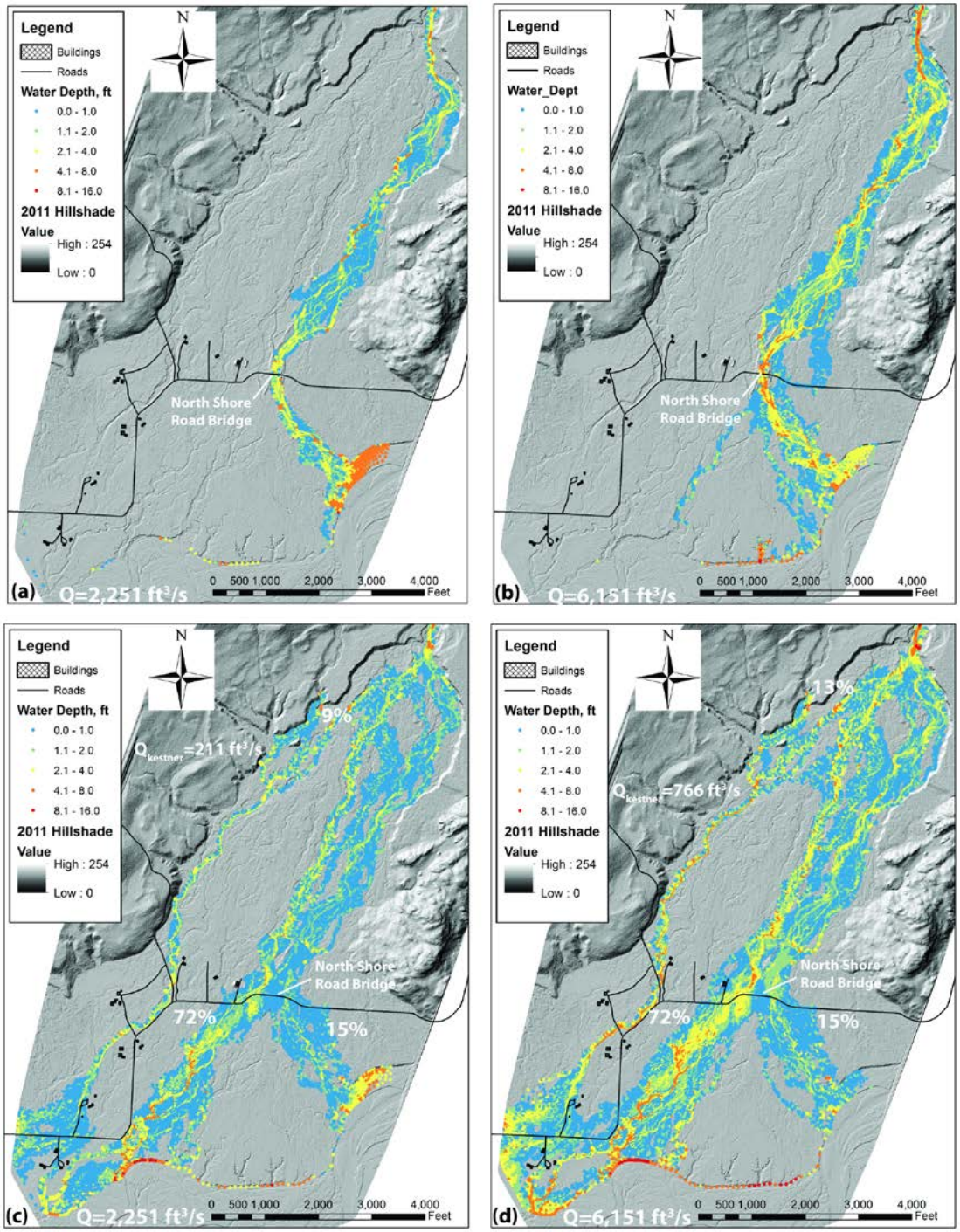

Figure 6 Hydraulic modeling results. (a) Existing condition (2011) 2-year discharge; (b) Existing condition (2011) 100-year discharge; (c) Example restoration condition, 2-year discharge and (d) Example restoration condition, 100-year discharge. Both restoration conditions (c) and (d) show modeling results with the removal of western levee at the North Shore Bridge and the log jam at canyon mouth and construction of channel crossings through North Shore road prism and raise of the road prism above the 100-year water surface elevation. Percentages show the distribution of flow among the various flow paths.

boundary of the upper fan and alluvial fan materials along the channel in the upper and lower fan area also provide sediment but total volume from these sources is not as large as the sediment contributions from the landslides. The area in the vicinity of the North Shore Road Bridge (the channelized section) has experienced net erosion likely because the channel has been excavated on an annual basis to increase channel conveyance under the bridge, however, sediment quickly refills the excavated area during the rainy season from November through February. Areas of potential avulsion are located mostly along the west side of the active channel on both the upper and lower fan at pre-existing historical channel paths. The 1939 western channel branch near the canyon mouth is not as likely to be an avulsion path even if the historical log jam is removed because the active channel appears to have incised in this location following the abandonment of the western channel. A major upstream landslide with large wood and a large sediment pulse would be necessary to cause an avulsion in this area.

IMPLICATIONS FOR RESTORATION

Hydraulic modeling of existing conditions shows that flows up to the 100-year magnitude are largely contained within the existing Finley Creek channel. Therefore, restoration alternatives will need to include active or passive removal of levees that block flow from entering former distributary areas on the lower fan. Restoration alternatives are currently being explored with coordination with local stakeholders. As an example, modeling of the 2-year and 100-year discharges show that if the western levee at the North Shore Bridge is removed and the channel aggrades 3 ft based on previous depths of channel filling following excavation, the following changes occur:

- Increased inundation in North Shore Road area primarily east of the current channel location and potential for flow on lower fan in west channel.
- Additional flow in western historical channels (Historical alluvium IA and IB) as a result of aggradation and west levee erosion/removal in which flow spreads across lower fan (50/50 split). Flow remains east of North Shore Road north-south trending section and there is no flooding of current structures.

Allowing flow onto the western part of the fan should reduce aggradation in the vicinity of the North Shore Road Bridge and also increase flow into historical channels and therefore habitat availability for various aquatic species. To accommodate flow and sediment across the North Shore Road in order to allow for year round road usage, the construction of seven to eight stream crossings in the road prism, with possibility of a road prism raise above the water surface elevation of the modeled 100-year discharge are included in the model (Figure 6c and 6d). Forded crossings, temporary bridges, and/or permanent bridge crossings are also potential alternatives that will be further investigated.

Active restoration by means of removing the log jam blocking the prehistorical channel at the canyon mouth would allow flows into 1890's, 1939, and current channels, increasing flows into nearby Kestner Creek and reducing flow in Finley Creek at North Shore Road Bridge. Flow is mostly in western channel on the lower fan (70%+). With this scenario, some flow connectivity with Kestner Creek and the western part of alluvial fan causes possible overtopping of the North

Shore Road near known free-standing structures. Options for either protecting this area with structures or relocating structures would need to be considered for this restoration alternative.

Analyses that were key to the investigation of the alluvial fan are the surficial mapping and relative elevation mapping of the fan to define prehistoric and historic channels, and also to identify trends in lateral migration and potential avulsion areas. 2D numerical hydraulic modeling is key to identifying existing active flow paths during higher flows and for developing a snapshot of future active flow paths given various future actions on the alluvial fan. Challenges in developing a more sustainable road crossing across an alluvial fan requires the implementation of multiple crossings which allow for migration of the active channel across the fan with enough capacity to pass large flows that transport woody material and sediment. A better understanding of the surface water and groundwater interactions on the alluvial fan through coupled hydraulic modeling would be desirable for future analyses and would aid in the evaluation of aquatic habitat on Finley Creek and associated tributaries.

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