Cardno ENTRIX

Shaping the Future



Snow Creek Estuary Restoration

Final Design Report

January 2013

Prepared For

North Olympic Salmon Coalition

Snow Creek Restoration

Final Design Report

January 2013

Prepared for

North Olympic Salmon Coalition
205 W. Patison St. Suite B
Port Hadlock, WA 98339
360-379-8051

Prepared by

Cardno ENTRIX
200 First Avenue West, Suite 500, Seattle WA 98119
Tel 206 269 0104 Fax 206 269 0098
www.cardnoentrix.com

Table of Contents

Executive Summary v

Chapter 1 Introduction 11

Chapter 2 Background 12

2.1 Watershed Characteristics 12

2.2 Human Modification to the Watershed 16

2.3 Endangered Salmonids 17

2.4 Project Objectives and Constraints 18

Chapter 3 Snow Creek Hydrology 19

3.1 Peak Flood Recurrence Analysis 19

3.2 Watershed Regression Analysis 19

3.3 Tidal Hydrology 21

Chapter 4 Geomorphic Assessment 22

4.1 Historical Channel Alignment of Snow and Salmon Creeks 22

4.2 Historical Changes to the Snow Creek Delta 24

4.3 Snow Creek Channel Geometry Change 28

4.4 Bank Erosion and Avulsion Potential 30

4.5 Salt Marsh Vegetation Zones 36

Chapter 5 Risks Associated with 60 Percent Design 41

5.1 Project Description 41

5.2 Methods for Assigning Level of Risk 41

5.3 Flooding 42

5.4 Sedimentation 49

5.5 Channel Avulsion 50

5.6 Construction Activities 50

5.7 Public Safety and Recreation 51

5.8 Conclusions 51

Chapter 6 Conclusions and Recommendations 52

Chapter 7 References 53

Appendices

Appendix A Snow Creek Tidal Hydrology Memorandum

Appendix B Historical Maps and Aerial Photographs

Appendix C Channel Survey Cross Sections

Appendix D Site Photographs

Appendix E Two-Dimensional Hydraulic Model Memorandum

Tables

Table 3-1: Estimated annual peak flows in Snow Creek adjusted to the estuary outlet 19

Table 3-2: Estimated annual peak flows in Snow Creek based on USGS regional regression equations.....20

Table 4-1: Linear distance of delta progradation from the historical aerial photo record. 25

Table 4-2: Material of eroding banks and corresponding critical shear stress (from ASCE 1992) required for transport. 33

Table 4-3: Critical shear stress for the Project area, upstream and downstream of the SR 20 bridge. 33

Table 4-4: Area distribution of biogeomorphic salt marsh zones. 39

Table 4-5: Elevation ranges for observed salt marsh species. Elevation include ranges in which each species was dominant and where each occurred as an associate species. 40

Figures

Figure 1-1: Snow Creek Restoration Project area at the head of Discovery Bay in the Olympic Peninsula. 11

Figure 2-1: Snow Creek watershed above the Project area (USGS 2011). 13

Figure 3-1. Comparison of Estimated Annual Peak Flows at the Snow Creek outlet to Discovery Bay.....20

Figure 4-1: Approximate alignment of Snow and Salmon creeks prior to relocation at the edges of the valley for agricultural use. 23

Figure 4-2: Changes to the salt marsh vegetated surface in the Snow and Salmon delta from 1870 to 2009.....26

Figure 4-3: The present day Snow Creek profile and the future delta profiles, extrapolated using the rate of delta progradation seen from 1950 to 2009 of 12 feet per year. This extrapolation assumes that Snow Creek retains its present day alignment and does not rejoin Salmon Creek. 27

Figure 4-4: Cross section survey locations established by JCCD.....29

Figure 4-5: Bank erosion areas recorded in the September 2011 survey. 32

Figure 4-6: Potential avulsion locations in lower Snow Creek.....34

Figure 4-7: Stratigraphy of right bank indicating channel dynamics in Snow Creek. 35

Figure 4-8: Location of vegetation transects surveyed September 28, 2011. 37

Figure 4-9: Biogeomorphic salt marsh zones of the Snow-Salmon delta. 38

Figure 5-1: A graphical definition of risk, R = P(H)*C, where P(H) is the probability of some hazard (e.g., flooding, erosion) and C is the consequence (e.g., monetary damages). 42

Figure 5-2. River 2D model water depth results for the 2-year flow event (443 cfs) at MHHW (6.38 ft NAVD 88) for existing conditions. 45

Figure 5-3. River 2D model water depth results for the 2-year flow event (443 cfs) at MHHW (6.38 ft NAVD 88) for proposed conditions. 46

Figure 5-4. River 2D model water depth results for the 100-year flow event (1909 cfs) at MHHW (6.38 ft NAVD 88) for existing conditions. 47

Figure 5-5. River 2D model water depth results for the 100-year flow event (1909 cfs) at MHHW (6.38 ft NAVD 88) for proposed conditions. 48

This Page Intentionally Left Blank

Executive Summary

Introduction

The North Olympic Salmon Coalition (NOSC) has retained Cardno ENTRIX for the Snow Creek Estuary Restoration Project with the purpose of reconnection and restoration of altered habitats in the Snow Creek estuary. This document presents the hydrologic, hydraulic and geomorphic site assessments and the design considerations for the 60 percent restoration plans.

The Snow Creek watershed drains an area of 24 square miles ranging from its sea level outlet at the southeast end of Discovery Bay on the Strait of Juan de Fuca to its headwaters at 4250 feet elevation on the northeastern slope of Mount Zion. The climate is characterized by cool, dry summers and mild, wet winters. Precipitation within the basin falls primarily as rainfall with some snow at high elevations. Land use within the basin draining to the Project Area consists of commercial forestry with residential properties and agricultural land located in the lower basin.

The Snow and Salmon Creek estuary system has been manipulated by human development for over a hundred years. Snow Creek was historically a right (east) bank tributary to Salmon Creek. In 1873 the channel in the current location of Snow Creek was a blind tidal slough and the historical Snow Creek flowed down the center of the valley. After 1873, Snow Creek was relocated to the east side of the valley to flow directly into Discovery Bay. Though separated, Snow Creek has been seen to flood into the pasture on the left (west) bank during flood flows and to jump its bank in the intertidal zones, reconnecting with Salmon Creek (Correa 2002). In addition to the relocation of the creek, a railroad grade was built across the estuary, which effectively cut off tidal and stream exchange processes and filled in tidal habitat. US Highway 101 was built in the 1930s and State Route 20 was built on fill near the upstream extent of the Project site. Tidal marshes in the Project have been filled for residential development; infrastructure includes a septic tank and its drainfield, a 2-inch water line within the railroad grade, French drains in the hillslope above the tidal marsh and a discharge ditch for an artesian well located outside the Project boundaries. Channelization of Snow Creek and draining of associated wetlands has further reduced habitat in the estuary.

The Washington Department of Fish and Wildlife (WDFW) salmonid monitoring weir at approximately River Mile (RM) 0.3 blocks the movement of some sediment and large woody debris (LWD). The screens are removed during high flows and LWD is passed downstream. Sediment accumulating behind the weir is removed every few years and disposed at an upland site (Randy Cooper, personal communication). Restoration actions in 1995 and 1996 included the addition of LWD and removal of two to three feet of sediment (20,000 CY) from the channel in the reach below the weir (Ames et al. 2000).

Under the Endangered Species Act (ESA), the Hood Canal/Eastern Strait of Juan de Fuca summer-run chum (*Oncorhynchus keta*) were listed as threatened in 1999, and steelhead (*O. mykiss*) were listed as threatened in 2007 (NOAA 2011). Snow Creek remains one of the “core sources” of the ESA listed Strait of Juan de Fuca summer chum population (Brewer et al. 2007). Estuaries serve as critical habitat for juvenile fish (Novakowski et al. 2004). Pacific salmonids

use estuaries for foraging, refugia and physiological transition as juveniles and for staging and physiological transition as adults (Beamer et al. 2005; Simenstad 2000). The summer chum of the Eastern Strait of Juan de Fuca Conservation Unit are likely from the Salmon/Snow Creek and Jimmycomelately watersheds, hence these are the stocks targeted for recovery (Ames et al. 2000). The priority for natal subestuary restoration is rearing area, habitat diversity and food sources; the Discovery Bay shoreline is high ranking in restoration priorities for the region.

The Project objectives were selected to rehabilitate estuarine habitat based on the results of the site assessment and the key limiting factors for salmon population recovery identified in the chum recovery implementation plan (Ames et al. 2000). These objectives are as follows:

1. Re-establish hydraulic connectivity between Snow Creek and the surrounding salt marsh through removal of dikes and the railroad grade;

2. Maximize the tidal prism by removing fill from potential salt marsh areas;

3. Increase the amount of tidal channel habitat in the estuary;

4. Create and maintain in-stream complexity with large woody debris (LWD); and

5. Improve water quality through relocation of the septic system to an upland site.

The primary constraint identified for the Project is that restoration actions cannot result in additional flooding to adjacent properties and infrastructure, including roadways and the artesian well.

Creek and Tidal Hydrology

Annual peak flows were estimated from the U.S. Geological Survey (USGS) flow gauge on Snow Creek near Maynard, WA. Using the USGS Bulletin 17b peak flood recurrence analysis method (USGS 1981). Cardno ENTRIX adjusted the basin drainage area and ran the USGS computer program PeakFQ on streamflow data. As a check, Cardno ENTRIX also employed regression computations that relate watershed area to return interval discharge based on regional characteristics. The USGS Bulletin 17b peak flood flow values were selected for use on this project because they are based on 27 years of actual flow measurements in Snow Creek near the Project area. The regression equation estimates were significantly lower and were not used. The estimated annual peak flows are as follows:

Recurrence Interval (USGS Bulletin 17B)	2--Year	10--Year	25-Year	50-Year	100-Year
Flow (cfs)	443	1017	1356	1627	1909

The results of a tidal study performed by Cardno ENTRIX are summarized in a technical memorandum presented in Appendix A. Water surfaces within the Project area are either directly influenced by an influx of sea water or indirectly influenced by the fluctuating downstream water surface. Accurate estimates of site specific tidal elevations are essential for predicting the location of salt marsh habitat and assessing inundation extents. Because no site specific tidal elevation statistics were available for the Project area, four water level pressure transducers were

installed in Snow Creek and in Discovery Bay in the Project area from September 3, 2011 to November 15, 2011.

Calculations to determine the Mean Higher High Water (MHHW) and Mean High Water (MHW) at the Snow Creek Project site followed published NOAA methodology. The estimated MHHW and MHW tidal statistics at the Snow Creek Project site (all NAVD 88 datum) are 6.38 feet and 5.76 feet, respectively. The maximum tide recorded during this period was 7.68 ft, but this is not necessarily the highest tide possible here. No determination of Mean Lower Low Water (MLLW) or Mean Low Water (MLW) could be made because the water surface elevation of the low tide was below the elevation of 0.43 foot that the monitoring devices could be installed.

Geomorphic Assessment

Historic changes to the Snow and Salmon Creek estuary were assessed using remote sensing data in a geographic information system (GIS). Reconstruction of the historical channel alignment of Snow and Salmon creeks was based on an 1873 General Land Office (GLO) plat map, with topographic features in a 1939 aerial photograph and 2002 LiDAR used to further refine the location of the historic channels. Although the exact date of the relocation is not known, the Snow Creek channel was in the current location by the time of the 1939 aerial photograph.

The seaward edge of the vegetated salt marsh has steadily prograded into Discovery Bay since 1870. The overall rate of delta progradation from 1870 to 2009 was 15 feet per year, totaling 2,070 feet of change in the location of the seaward edge of the vegetated salt marsh. Volume accumulation from 1870 to 2009 was 535 cubic yards (CY) per year, equivalent to a total of 74,000 CY of material. These values conservatively assume that all areas beyond the vegetated surface in 1873 and 1950 were at the mudflat elevation because the elevations beyond the salt marsh are not readily determined from the available data. If the elevations outside the vegetated marsh ranged from mudflat near the marsh to an elevation of 2 feet below mudflat further out into the bay, the volumes of accumulation would be the volumes of accumulation would be 1,020 CY per year from 1870 to 2009. This corresponds to a total volume of 142,000 CY.

Changes to the bed elevation of the Snow Creek channel were analyzed using cross sections surveyed by the Jefferson County Conservation District (JCCD) between 1995 and 2009 as part of the Quilcene-Snow Restoration Team project to lower and widen the channel and install LWD. The total channel volume change was about 6,750 CY (about 500 CY per year). This change occurred for the most part as an increase in channel bed elevation rather than channel narrowing. The processes of aggradation and channel geometry change will likely continue into the future as long as Snow Creek remains in its current alignment. If the average volume change from 1996 to 1998 is projected into the future, it would correspond to an average bed elevation change of about 1 feet after 20 years. This matches the scope of the dredging operation, which removed 2 to 3 feet of sediment.

Avulsion is a natural process in a delta and the presence of multiple distributary channels is typical for these types of geomorphic systems. Distributaries serve important functions in the delta: they distribute river flows, sediment, nutrients, wood, and aquatic organisms into the wetlands and marshes of the delta (Hood 2010). The field assessment identified several areas

with evidence of over-bank flood flows that are likely avulsion pathways. One site was located upstream of the WDFW weir on the left bank. Downstream of SR 20, two sites were identified as low areas in the right bank. Splay deposits, or areas of high ground, were seen on the tidal plain where upland vegetation has established in isolated areas within surrounding salt marsh vegetation.

Salt Marsh Vegetation

In order to determine the optimal configuration and depth of salt marsh excavation, we conducted a survey of existing salt marsh vegetation on September 28 and 29, 2011. The primary activities were to map vegetation species presence and abundance cover along surveyed cross sections and characterize the vegetation communities by dominant and associate species. The analysis of the vegetation data in conjunction with the topographic survey data suggests the following ranges of elevation in feet (NAVD 88) for salt marsh zones:

	Elevation (feet NAVD 88)	Percentage of Study Area
Low Marsh Mosaic	5.6 to 7.3	22
Middle Marsh Mosaic	6.8 to 7.6	17
High Marsh Mosaic	7.0 to 8.6	20
Upland	8.0 to 10.9	41

The zones exhibit concurrence in range and boundaries between zones are not necessarily distinct. In addition, each zone is more accurately described as a mosaic, with patches of varying topography and species associations. This pattern is indicative of a dynamic system, where the sediment regime is rapidly changing the topography and the salt marsh vegetation is responding to these sediment fluxes. In addition, much of the site has been directly altered by activities in the estuary, leading to patchy conditions of vegetation colonization. Within the roughly 40-acre study area, 16 acres or 41 percent was at upland elevations not supporting salt marsh vegetation.

Risk Assessment

A risk assessment is systematic evaluation of potential adverse effects from hazardous events, processes, actions or substances. Risk is defined as the probability that a hazard (or source of harm) will result in a negative consequence (harm or loss). The level of risk is the product of the probability of a hazard occurring and the magnitude of the consequence of that event. If an event has little or no consequence than the associated risk would be relatively low. If the probability of a hazard occurring is certain and the level of consequence severe, then the risk is high.

The hazards identified for the Project include the following:

1. Sedimentation, flooding and channel avulsion damaging infrastructure, adjacent property or habitat;

2. Construction activities impacting habitat and ecological function; and

3. Threats to public safety or obstructions to recreational users.

To assess any potential increase in flooding risk as a result of project activities, a two-dimensional hydraulic model was performed using the University of Alberta River 2D model. The model was run for existing conditions and the proposed conditions of the 30 percent design assuming a static bed geometry. The results of this analysis indicate that flooding conditions are likely to remain unchanged on the private properties upstream and adjacent to the Project area under proposed conditions. Within the delta and Project area, the Snow Creek channel and the reconnected tidal plain and slough channels may experience more frequent and deeper levels of inundation. Because the increase in water depths were limited to Project areas having no infrastructure concerns, the consequences of the Project actions are considered low in terms of potential flooding. The low probability of high-magnitude events (p=0.01) combined with relatively low consequences results in a low risk to a properties and infrastructure from increased flooding due to the Project.

Sedimentation in the Project site takes the form of channel bed aggradation and delta surface accretion and progradation. While the deposition of sediment is a natural process inherent to delta formation, this was considered a potential indirect hazard to infrastructure where it increases water surface elevations and hence, the potential for flooding or channel avulsion. Sedimentation can also be a hazard to habitat if existing or restored salt marsh is converted to upland and potential non-native invasive vegetation such as reed canary grass (*Phalaris arundinacea*).

The results of the Cardno ENTRIX two-dimensional model of potential sediment movement in the Swan Creek estuary are presented in a technical memorandum included as Appendix E. If sediment supply and watershed hydrology remain constant in the future, sediment transport conditions are likely to remain unchanged on the private properties upstream and adjacent to the Project area under proposed conditions. The Snow Creek channel bed substrate is likely to become finer, while the estuary and slough channels may see an influx of coarser sediments. Because the non-tidal section of the channel is likely to undergo periods of aggradation and substrate fining during small events followed by scouring and flushing during larger, less frequent flows, no increase in flooding is anticipated. The risk from conversion to upland would be mitigated by early identification and removal of invasive vegetation and replacement with fast-growing upland native species, such as willow (*Salix* spp.). The low level of change to sedimentation patterns from existing to proposed conditions combined with the low consequence to the undeveloped Project reach results in a designation of low risk to habitat and flooding. While the probability of an avulsion downstream of SR 20 is high, there are no negative consequences to habitat from the return to natural delta dynamics. The risk of an avulsion upstream of SR 20 and US 101 is not changed from existing conditions, so the risk level from restoration actions in the Project reach is also low.

There are several components to the construction of the proposed restoration Project that have the potential of posing hazards to existing habitat. These hazards would be short-term in nature and only be present during the construction of the Project. Construction activities will comply with the National Pollutant Discharge Elimination System (NPDES) permit issued by the Washington State Department of Ecology and would constitute a low level of risk to fish and other aquatic species.

Snow Creek is not considered a navigable waterway by the United States Army Corps of Engineers. While part of the Project site is publicly owned by WDFW, it is not heavily used for recreation. The construction of the Project will not introduce any additional hazard beyond what already exists in all dynamic estuarine systems. When we combine the low probability of interactions between public users and the proposed Project and the low potential to impact recreational users of the creek relative to existing conditions, the resulting level of risk is low.

The overall risk associated with the elements of the Snow Creek Estuary Restoration Project is equivalent to that expected in naturally functioning estuarine systems. Restoring ecological, geomorphic and hydraulic processes will result in some unavoidable risks when compared to the existing conditions. The nature of the goals of restoration— increasing dynamic characteristics and encouraging hydraulic and geomorphic habitat-forming processes—will promote changes in delta morphology. Water surface elevations, flow depth and velocity, and shear stress can change with installation of the Project. However the changes are either beneficial to the Project and have low associated risk, or the risk is not changed when compared to the existing conditions.

Conclusions

Partial restoration of the Snow Creek estuary can enhance ecological function and meet Project goals within current constraints. Excavation of fill in the salt marsh and creation of tidal channels will maximize habitat for salmon populations that are in decline and are highly dependent on estuaries for viability. Cardno ENTRIX recommends the removal of dredge spoils and fill from the Snow Creek delta and banks within the Project area to an elevation of approximately 7 feet (NAVD 88). The removal of fill would maximize the amount of estuarine habitat available to salmonids during key phases of their life histories. These elevations will allow for the natural colonization of salt marsh vegetation from the existing salt marsh sources on site. Upland areas where excavation materials are stored should be permanently vegetated with Pacific Northwest native trees and shrubs to enhance marine riparian function and prevent the spread of non-native invasive vegetation. The septic system on the east floodplain between the railroad grade and SR 20 must be removed before work can be completed in this area. As the upland septic relocation site is still under consideration, work could be completed in this area during a second Project phase if needed.

Chapter 1 Introduction

The North Olympic Salmon Coalition (NOSC) has contracted with Cardno ENTRIX for the Snow Creek Estuary Restoration Project with the purpose of reconnection and restoration of altered habitats in the Snow Creek estuary, located at the head of Discovery Bay in Jefferson County, Washington (Figure 1-1). This document presents the hydrologic, hydraulic and geomorphic site assessments and the design considerations for the 60 percent restoration plans for the Snow Creek estuary. The historic estuary has been modified by relocation of the Snow Creek channel, the filling of estuary habitats, and the development of infrastructure, including State Route 20 and US Highway 101. NOSC intends to use these plans to restore tidal connection, increase the tidal prism, and improve habitat-forming processes in the Snow Creek estuarine ecosystem.

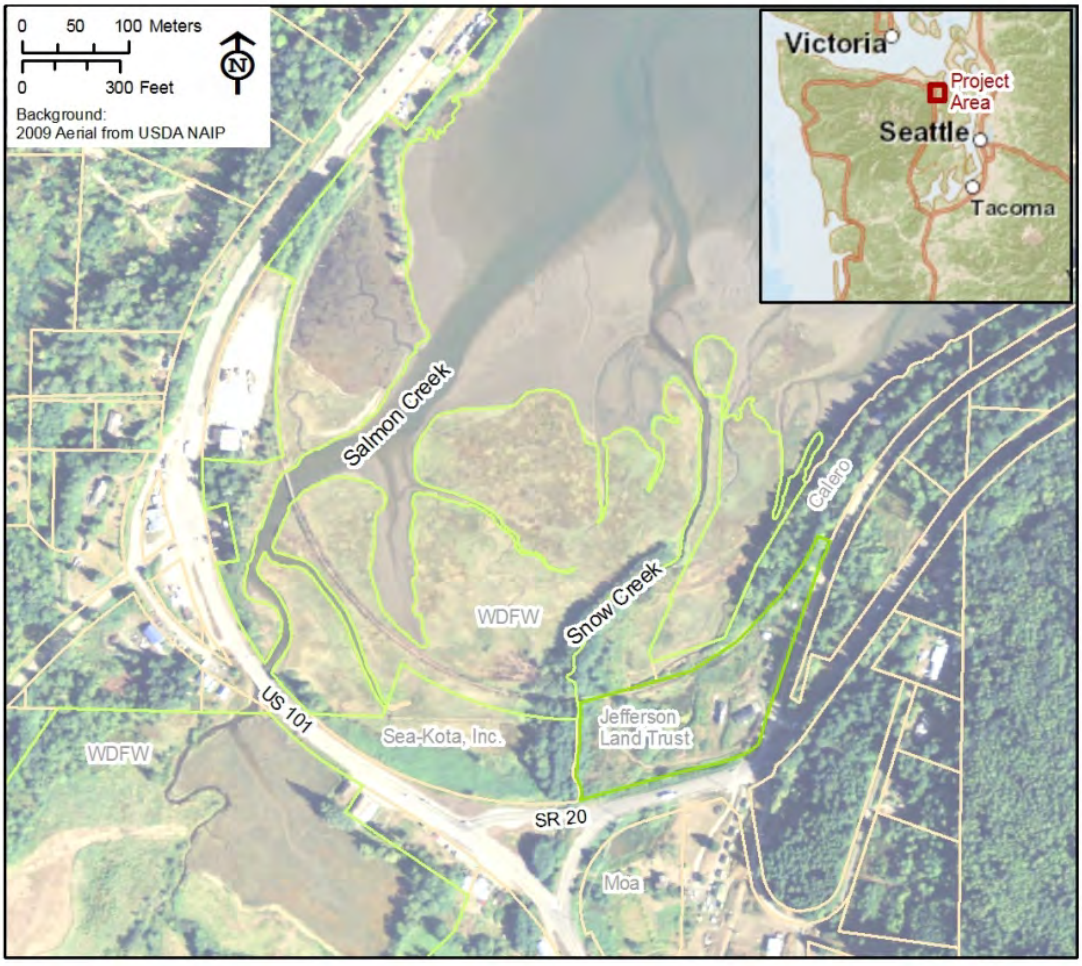


Figure 1-1: Snow Creek Restoration Project area at the head of Discovery Bay in the Olympic Peninsula.

Chapter 2 Background

2.1 Watershed Characteristics

The Snow Creek watershed drains 24 square miles ranging from its sea level outlet at the southeast end of Discovery Bay on the Strait of Juan de Fuca to its headwaters at 4250 feet elevation on the northeastern slope of Mount Zion. Figure 2-1 shows the Project Area and a delineation of the Snow Creek basin. With a 30-mile stream network, Snow Creek has its headwaters in Clallam County and its estuarine outlet in Jefferson County. Trapper, Rixon, and Andrews Creek contribute to Snow Creek flows. The basin has a mean slope of 21 percent with 22.5 percent of its area having slopes greater than 30 percent. A mean annual precipitation of 39.3 inches falls on the Snow Creek watershed. An area-weighted forest canopy covers 72 percent of the basin based on the National Land Cover Database (NLCD) 2001 canopy dataset (USGS 2011).

The climate is characterized by cool, dry summers and mild, wet winters. Due to the varied relief within the watershed, temperature and precipitation varies with elevation. In the lowlands, winter temperatures range from 30 ºF to 52 ºF while summers range from 60 ºF to 80 ºF. Precipitation within the basin falls primarily as rainfall with some snow at high elevations. Monthly averaged precipitation ranges from near zero to 6.8 inches per month in the lower areas of the basin (USHCN 2011). Though average annual precipitation is 39.3 inches, precipitation does vary significantly depending on location in the watershed as shown in Figure 2-4 from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system (PRISM Climate Group 2011). The southern end of Discovery Bay and the Snow Creek basin receive more annual rainfall than both Sequim and Port Townsend.

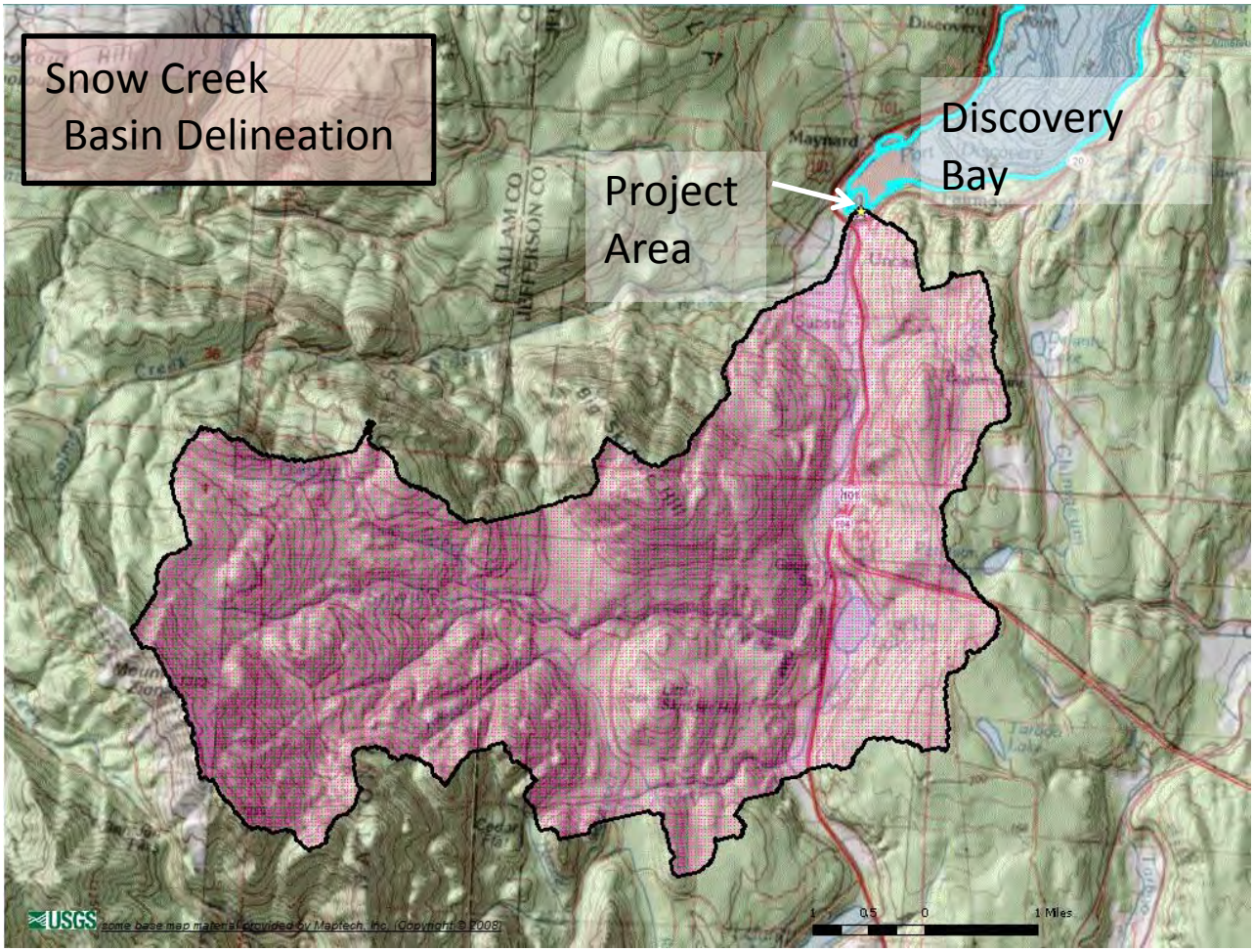


Figure 2-1: Snow Creek watershed above the Project area (USGS 2011).

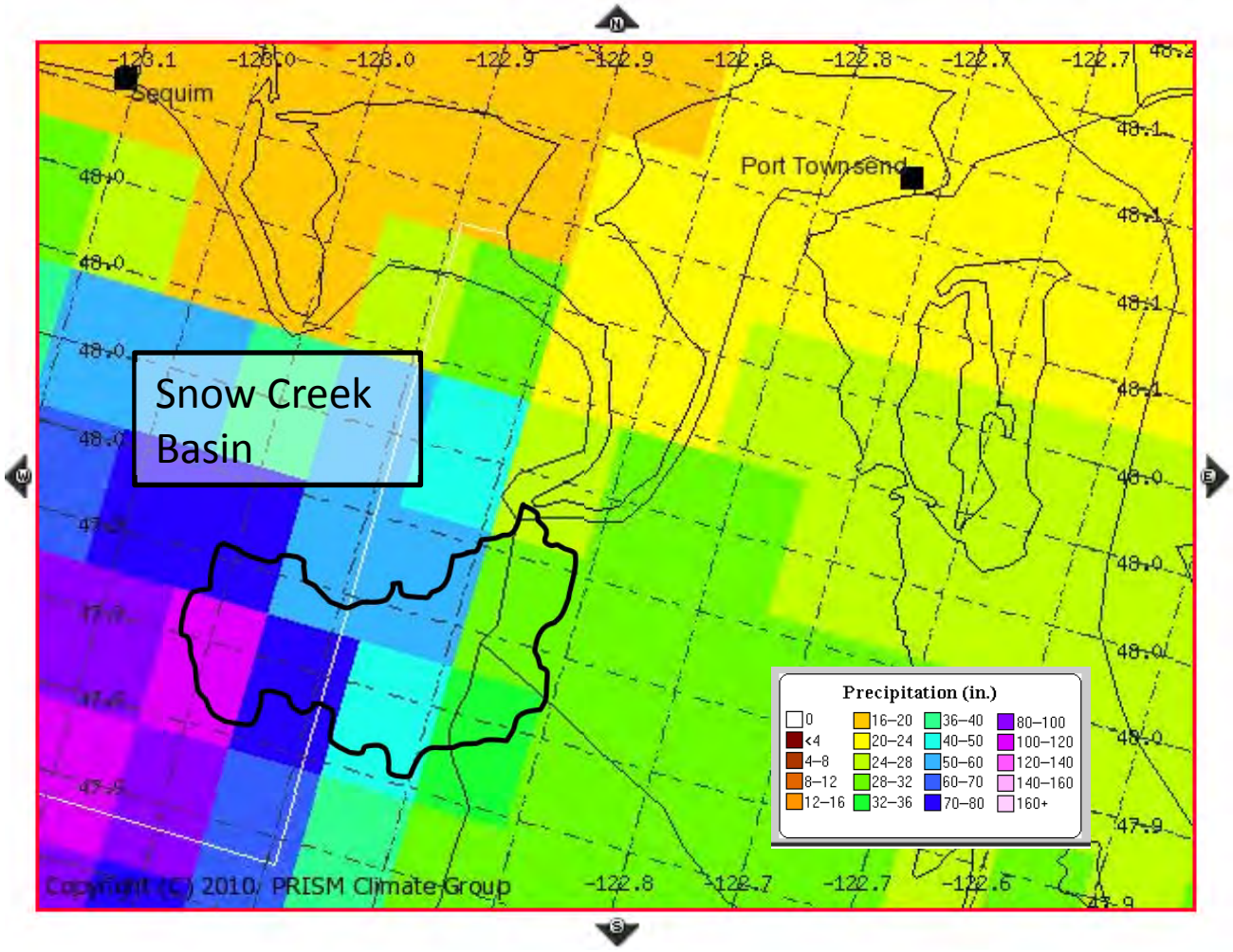


Figure 2-2: Mean annual precipitation from the PRISM data set 1971 to 2000 (PRISM 2011).

The geology of the Discovery Bay region consists of Pleistocene continental glacial drift: clay, silt, sand, gravel, cobbles, and boulders deposited by continental ice sheets as till and outwash between 1.8 million years ago (Ma) to 16,000 years ago (Schuster 2005). Recent alluvial deposits occur at the head of the bay at the Salmon/Snow outlet. Volcanic rocks of the Crescent Formation and marine sedimentary rocks are found immediately inland, dating from the Tertiary period (which ranges from 66 to 2 million years ago) (Schuster 2005). During the most recent continental ice-sheet advance, the region was covered with thousands of feet of ice and meltwaters from the retreat of the Puget Lobe created drainages, including the spillway that connected Dabob Bay to Discovery Bay via the Leland Creek and Snow/Salmon Creek valleys (Thorson 1980). That drainageway is still evident today in the modern topography.

Land use within the basin draining to the Project Area consists of commercial forestry with residential properties and agricultural land located in the lower basin. NOAA's Coastal Change Analysis Program (C-CAP) Land Cover Atlas provides data of land use change (Figure 2-2) and forest fragmentation with forest losses (Figure 2-3) from 1996 to 2006. The basin has seen considerable change due to commercial forestry and development (NOAA C-CAP 2011). This may contribute to increased flow and sediment discharge within the watershed.

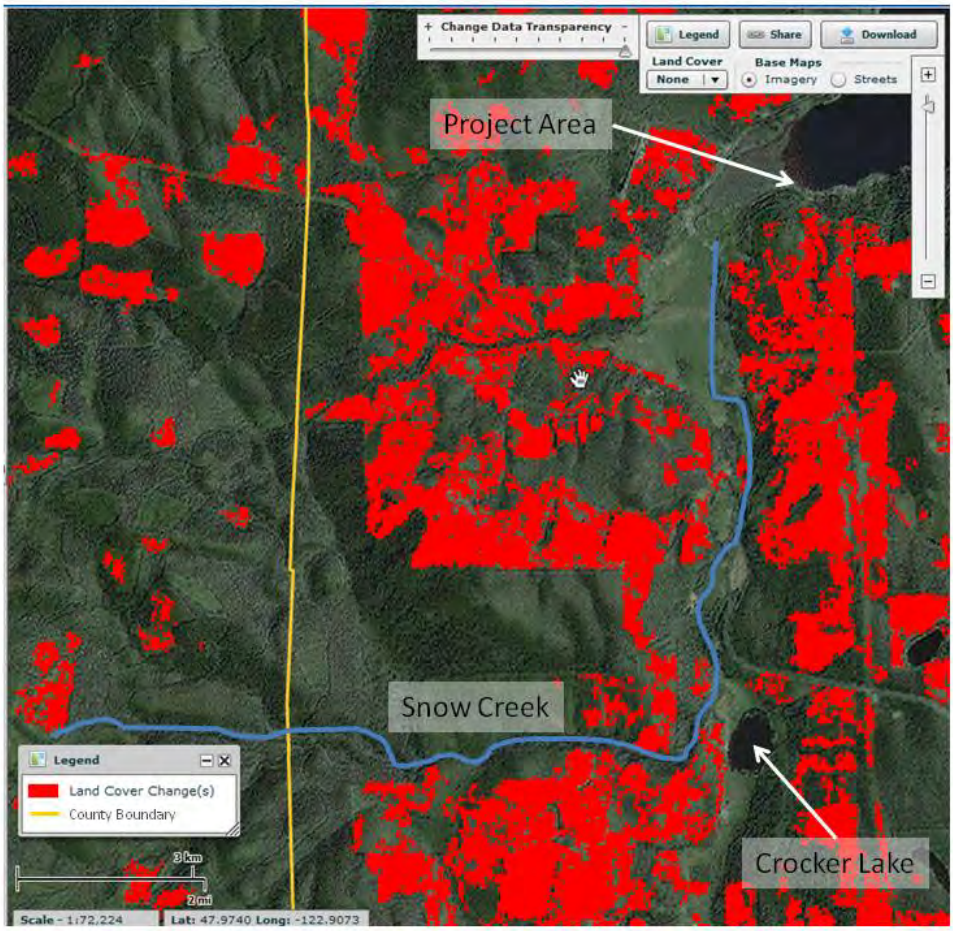


Figure 2-3. NOAA C-CAP land cover change analysis for Snow Creek area.

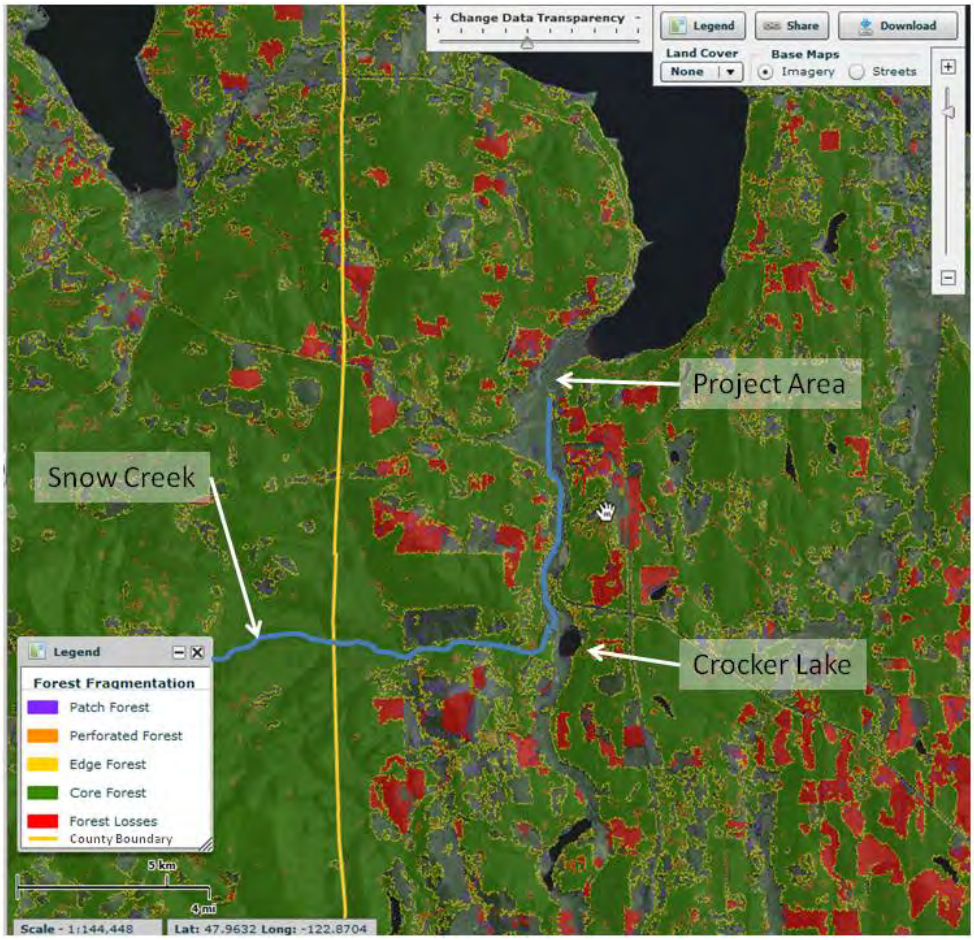


Figure 2-4. NOAA C-CAP forest fragmentation analysis for Snow Creek area.

2.2 Human Modification to the Watershed

The Snow and Salmon Creek estuary system has been manipulated by human development for over a hundred years. Snow Creek was historically a right (east) bank tributary to Salmon Creek. After 1873, Snow Creek was relocated from the center of the valley to the east side to flow directly into Discovery Bay. Though separated from Salmon Creek, Snow Creek has been seen to flood into the pasture on the left (west) bank during flood flows and to jump its bank in the intertidal zones, reconnecting with Salmon Creek (Correa 2002). Other modifications in the watershed include the diversion of Andrews Creek into Snow Creek from its historical outlet into Leland Lake (Correa 2002).

In addition to the relocation of the creek, 1,100 feet of the Chicago, Milwaukee, and St. Paul railroad grade was built across the estuary in 1914, which effectively cut off tidal and stream exchange processes and filled in tidal habitat. US Highway 101 was built in the 1930s as the Olympic Loop Highway (Montgomery and Hartmann 2011) and has had similar effects. State Route 20 was also built on fill in the estuary; it meets US 101 near the upstream extent of the Project site. In addition to impacts from transportation infrastructure, tidal marshes in the Project Area have been filled for residential development; other infrastructure includes a septic tank and its drainfield, a 2-inch water line within the railroad grade, French drains in the hillslope above

the tidal marsh, and a discharge ditch for an artesian well located outside the Project boundaries. Channelization of Snow Creek and draining of associated wetlands has further reduced habitat in the estuary. Overall, tidal exchange and habitat connectivity have been substantially diminished in the last century.

The existing riparian buffer of Snow Creek below RM 3 is narrow—76 percent is less than 66 feet wide—and is deciduous dominant although historical evidence indicates conifer presence (Ames et al. 2000). Logging in the basin began as early as 1870, when a logging railroad ran east of Snow Creek and terminated at a logging chute that brought the timber to the water (Montgomery and Hartmann 2011).

The Washington Department of Fish and Wildlife (WDFW) salmonid monitoring weir at approximately River Mile (RM) 0.3 has been tracking populations of summer chum, coho, steelhead and cutthroat since 1977 (Correa 2002). The weir blocks the movement of some sediment and large woody debris (LWD). Screens with fine mesh are installed in March that can catch steelhead and coho but allow juvenile chum to pass through. The screens are removed during high flows (Randy Cooper, personal communication). LWD is passed downstream and sediment accumulating behind the weir is removed every few years for disposal at an upland site (Randy Cooper, personal communication).

As part of their actions to enhance habitat and reduce flooding to neighboring properties in 1995 and 1996, the Quilcene-Snow Restoration Team lowered the channel bed two to three feet, widened the channel and installed LWD in the reach below the weir. They removed 20,000 CY of sediment, creating 33 pools. In these pools, 66 tree stumps and 42 logs were placed while 540 trees were planted in the riparian corridor. In addition, 150 feet of dike was removed from the high marsh (Ames et al. 2000).

2.3 Endangered Salmonids

Under the Endangered Species Act (ESA), the Hood Canal/Eastern Strait of Juan de Fuca summer-run chum *(Oncorhynchus keta)* were listed as threatened in 1999 and steelhead *(O. mykiss*) were listed as threatened in 2007 (NOAA 2011). Snow Creek remains one of the "core sources" of the ESA listed Strait of Juan de Fuca summer chum population (Brewer et al. 2007). Coho (*O. kisutch)* were listed as a species of concern in 2004 (NOAA 2011).

Chum salmon spawn in lower Snow Creek, mainly below RM 1.5 but extending up to RM 3.0. They move into the estuary after less than 30 days and rear in the nearshore and estuary until migrating to the ocean, returning after three to five years (Correa 2002). Chum are highly dependent on estuaries, and the estuarine rearing phase of their life history is a major factor in the size of the adult population (Johnson et al. 1997). Chum fry may remain in complex subestuaries for longer because of their favorable conditions: dendritic channels, better sources of food, and lower water velocities in marshes (Brewer et al. 2007). Chum fry also move into tidal marshes as they migrate through the nearshore, coming in on the high tide and departing on the ebb tide (Brewer et al. 2007).

The summer chum of the Eastern Strait of Juan de Fuca Conservation Unit are likely from the Salmon/Snow Creek and Jimmycomelately watersheds, hence these are the stocks targeted for recovery (Ames et al. 2000). The priority for natal subestuary restoration is rearing area, habitat

diversity and food sources; the Discovery Bay shoreline is high ranking in restoration priorities in the region.

The limiting factors for Snow Creek identified in the chum recovery implementation plan (Ames et al. 2000) are as follows:

- Lack of channel complexity, including stable log jams, riparian buffers, and channel stability;
- Loss of estuarine habitat due to diking and roads;
- Sediment grain size and channel bed aggradation;
- Altered hydrological regimes resulting in higher peak flows and lower summer low flows; and
- Inadequate riparian buffers, including forest species composition, age and extent.

2.4 Project Objectives and Constraints

The Project objectives were selected to rehabilitate estuarine habitat based on the results of the site assessment and the key limiting factors for salmon population recovery identified in the chum recovery implementation plan (Ames et al. 2000). These objectives are as follows:

1. Re-establish hydraulic connectivity between Snow Creek and the surrounding salt marsh through removal of dikes and the railroad grade;
2. Maximize the tidal prism by removing fill from potential salt marsh areas;
3. Increase the amount of tidal channel habitat in the estuary by excavating channels in the delta plain;
4. Create and maintain in-stream complexity with LWD installations; and
5. Improve water quality in the estuary through relocation of the septic system to an upland site.

The primary constraint identified for the Project is that restoration actions cannot result in additional flooding to adjacent properties and infrastructure, including roadways and the artesian well.

Chapter 3 Snow Creek Hydrology

3.1 Peak Flood Recurrence Analysis

The U.S. Geological Survey (USGS) maintained a flow gauge on Snow Creek near Maynard, WA adjacent to Crocker Lake at approximate RM 3.7 (USGS 12050500) with an 11.2 square mile drainage. It has streamflow data available from 1953 to 1979 (27 years). The Washington Department of Ecology (WDOE) has a telemetry flow monitoring station at the Snow Creek WDFW Weir (RM 0.3). The WDOE data begin in 2007 with additional data from 2002 to 2006 that were extrapolated from other stations (WDOE 2011). These data do not meet the minimum 10-year requirement for the USGS Bulletin 17b peak flood recurrence analysis (USGS 1981). Thus, for peak flood recurrence analysis, Cardno ENTRIX utilized data from USGS 12050500 with adjustments to actual basin drainage area (from 11.2 square miles at the gauge to 24.1 square miles at the creek estuary) (Table 3-1). Cardno ENTRIX ran the USGS computer program PeakFQ on all 27 years of available USGS peak streamflow data, as adjusted for the increase in drainage area by making use of the following equation to extrapolate flows (Knowles 2001):

$$Q_u = Q_g(\frac{Au}{Ag})^x$$

Where
Q_u is flow at the ungauged site (cubic feet per second, cfs)
Q_g is flow at the gauged site (cfs)
Au is the area of the ungauged basin (square miles)
Ag is the area of the gauged basin (square miles)
x is an exponent for the particular region in Washington (x = 0.98 for Region 2)

Table 3-1 presents the results of the Cardno ENTRIX flood recurrence analysis.

Table 3-1: Estimated annual peak flows in Snow Creek adjusted to the estuary outlet .

Recurrence Interval	2-Year	10-Year	25-Year	50-Year	100-Year
Flow (cfs)	443	1017	1356	1627	1909

3.2 Watershed Regression Analysis

As a check, Cardno ENTRIX also employed regression computations in order to estimate peak discharge flow rates on Snow Creek at the Project area using the USGS method that relates watershed area to return interval discharge based on regional characteristics. This analysis employed the regional regressions developed by Knowles and Sumioka (2001) based on mean annual precipitation (P), watershed area (A) and gauge data from over 200 stations in the region. The Region 2 regional regression equations used in this analysis are as follows:

$$Q_2 = 0.090A^{0.877}P^{1.51}$$

$$Q_{10} = 0.129A^{0.868}P^{1.57}$$

$$Q_{25} = 0.148A^{0.864}P^{1.59}$$

$$Q_{50} = 0.161A^{0.862}P^{1.61}$$

$$Q_{100} = 0.174A^{0.861}P^{1.62}$$

Table 3-2 summarizes the predicted discharges for Snow Creek using the regional regression equations with a mean annual precipitation of 39.3 inches (USGS StreamStats 2011) and a watershed area of 24.1 square miles. Figure 3-1 provides a side-by-side comparison of estimated annual peak flows from this Cardno ENTRIX analysis and a prior WDFW analysis (Barnard 2007).

Table 3-2: Estimated annual peak flows in Snow Creek based on USGS regional regression equations

Recurrence Interval	2-Year	10-Year	25-Year	50-Year	100-Year
Flow (cfs)	375	652	794	924	1030
Standard error (%)	56	53	53	53	54

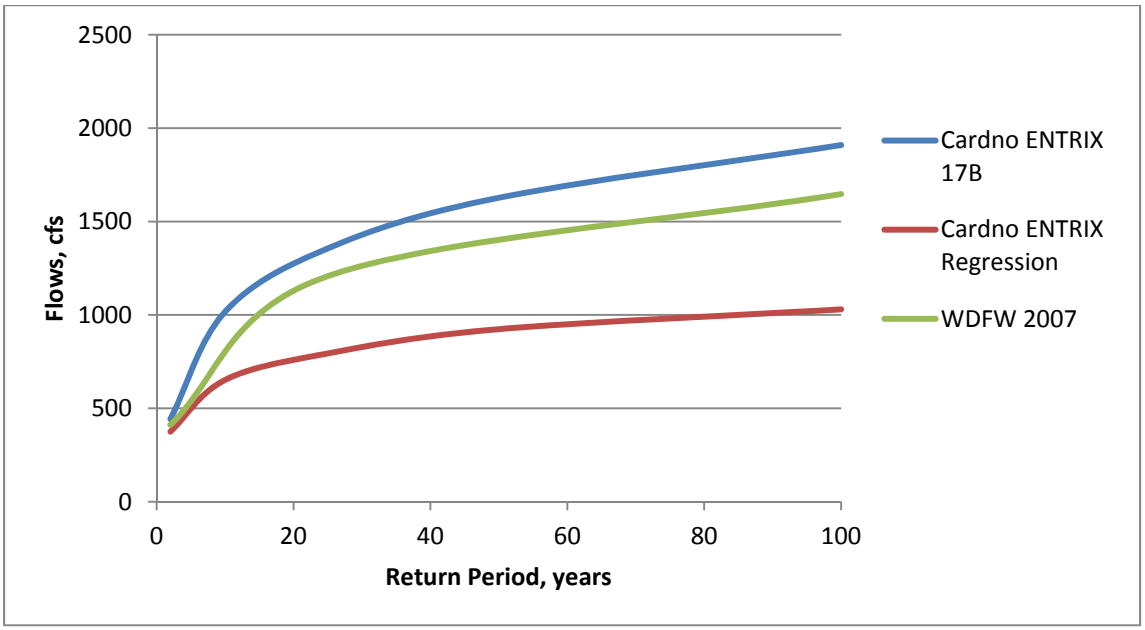


Figure 3-1. Comparison of Estimated Annual Peak Flows at the Snow Creek outlet to Discovery Bay

Based on the review of calculated flood recurrences described above, the USGS Bulletin 17b peak flood flow values have been selected for use on this project. These estimates are based on 27 years of actual flow measurements in Snow Creek near the Project area and are significantly higher than the regression equation estimates. These values are based on the data currently available for this watershed; therefore, they should only be used in conjunction with a good understanding of the assumptions and limitations guiding this analysis.

3.3 Tidal Hydrology

The results of a tidal study performed by Cardno ENTRIX are summarized in a technical memorandum presented in Appendix A. Water surfaces within the Project area are either directly influenced by an influx of sea water or indirectly influenced by the fluctuating downstream water surface. Accurate estimates of site specific tidal elevations are essential for predicting the location of salt marsh habitat and assessing inundation extents. Cardno ENTRIX was not aware of any data that provide site-specific tidal elevation statistics for the Project area, so two approaches were considered to develop local tidal statistics. The first method utilized existing National Oceanic and Atmospheric Administration (NOAA) tidal gages at Port Angeles, Port Townsend and Gardiner Bay as surrogates for the Snow Creek site. As described in Appendix A, it was determined that existing tide gages do not provide sufficient data for this project and could not be used as a surrogate. Therefore, a more detailed, site-specific approach was applied, using data obtained from four water-level pressure transducers installed in Snow Creek and in Discovery Bay in the Project area that collected data from September 3, 2011 to November 15, 2011.

Calculations to determine the Mean Higher High Water (MHHW) and Mean High Water (MHW) at the Snow Creek Project site followed published NOAA methodology. The estimated MHHW and MHW tidal statistics at the Snow Creek Project site (all using NAVD 88) are 6.38 feet and 5.76 feet, respectively. The maximum tide recorded during this period was 7.68 ft, but this is not necessarily the maximum tide that could occur here. No determination of Mean Lower Low Water (MLLW) or Mean Low Water (MLW) could be made because the water-surface elevation of the low tide was below the elevation that the monitoring devices could be installed at 0.43 feet elevation.

Chapter 4 Geomorphic Assessment

4.1 Historical Channel Alignment of Snow and Salmon Creeks

Historic changes to the Snow and Salmon Creek estuary were assessed using remote sensing data in a geographic information system (GIS). The earliest data were historic maps: the 1870 topographic map (also known as a T-sheet) from the US Coast and Geodetic Survey and the 1873 US General Land Office (GLO) plat map. Historical aerial photographs from 1939, 1950 and 1993 were georeferenced in GIS using a 2009 US Department of Agriculture National Agricultural Inventory Program (USDA NAIP) orthophoto. All historical maps and aerials are presented in Appendix B. In addition, 2002 LiDAR was used in the form of a bare earth Digital Elevation Model (DEM).

Reconstruction of the historical channel alignments of Snow and Salmon creeks were based on the 1873 plat map, which is less detailed than the 1870 T-sheet but extends inland into the watershed. Because the 1873 map was not spatially accurate enough to be precisely georectified, topographic features in the 1939 aerial and the 2002 LiDAR DEM were used to further refine the location of the historic channels. Note that in 1873 the channel in the current location of Snow Creek was a blind tidal slough and the historical Snow Creek flowed down the center of the valley (Figure 4-1).

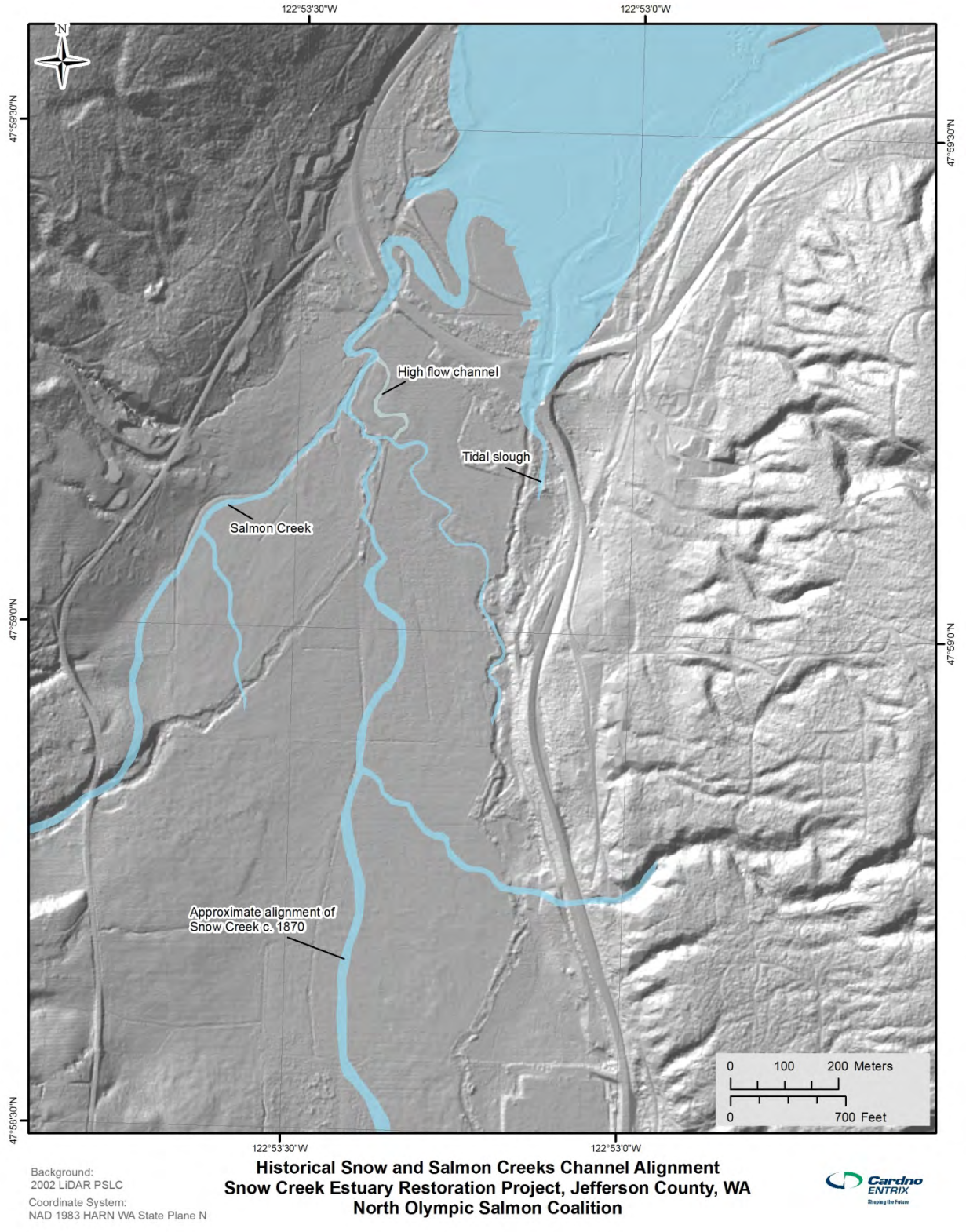


Figure 4-1: Approximate alignment of Snow and Salmon creeks prior to relocation at the edges of the valley for agricultural use.

4.2 Historical Changes to the Snow Creek Delta

The analysis of historical delta changes was based on quantifying the extent of vegetated salt marsh from the 1870 T-Sheet and the 1939, 1950, 1993 and 2009 orthophotos. The 1873 plat map was not detailed or high resolution enough in the region of the delta for use in this analysis.

The seaward edge of the delta has steadily prograded into Discovery Bay since 1870 (Table 4-1). This has occurred despite the dredging of material at the WDFW weir and in the channel below SR 20. When averaged over each time step, the overall rate of delta progradation from 1870 to 2009 was 15 feet per year, totaling 2,070 feet of change in the location of the seaward edge of the vegetated salt marsh (Table 4-1). The annual rates of progradation were greatest in the period between 1870 and 1939 and between 1980 and 1990, averaging 19 and 21 feet per year, respectively. The lowest rate occurred after 1990, when the delta prograded 56 feet or 3 feet per year. This time period includes the dredging of about 20,000 CY from the channel, approximately twice the amount that would have accumulated in that 19-year period based on analysis of the aerial photos.

With the digitized extents of the delta, the volumes of sediment required for progradation could be calculated in GIS. The area of change between each time step (14 acres from 1870 to 2009) was multiplied by the change in elevation. This assumed that the non-vegetated areas in the early maps were at least at the elevation of the mudflats in the 2002 LiDAR: approximately 6 feet with nearly no slope. The vegetated salt marsh surface was taken from the 2011 topographical survey and vegetation study. The upper extent is the average high-marsh elevation (7.8 feet) and the lower extent is lowest low-marsh elevation (6.4 feet). The vegetated marsh was assumed to have a consistent slope as seen from the topographic survey. The volumes did not include the railroad grade, highways, dredge spoils or other fill in the estuary.

Total volume accumulation from 1870 to 2009 was 535 cubic yards (CY) per year, equivalent to a total of 74,000 CY of material retained in the delta between 1870 and 2009 (Figure 4-2). These values conservatively assume that all areas beyond the vegetated surface in 1870 and 1950 were at the mudflat elevation because the elevations beyond the salt marsh are not readily determined from the available data. If the elevations outside the vegetated marsh ranged from mudflat near the marsh to an elevation of 2 feet below mudflat farther out into the bay, the volumes of accumulation would be 1,020 CY per year from 1870 to 2009. This corresponds to a total volume of 142,000 CY.

Table 4-1: Linear distance of delta progradation from the historical aerial photo record.

Time Period	Distance prograded (ft)	Annual rate (ft/yr)
1870-1939	1,297	19
1939-1950	137	13
1950-1965	208	14
1965-1980	191	13
WDFW weir installed 1977—approx. 600 CY dredged every 3 years since		
1980-1990	212	21
Channel dredged 1995-1996, 20,000 CY removed		
1990-2009	56	3
Overall 1870-2009	2,070	15

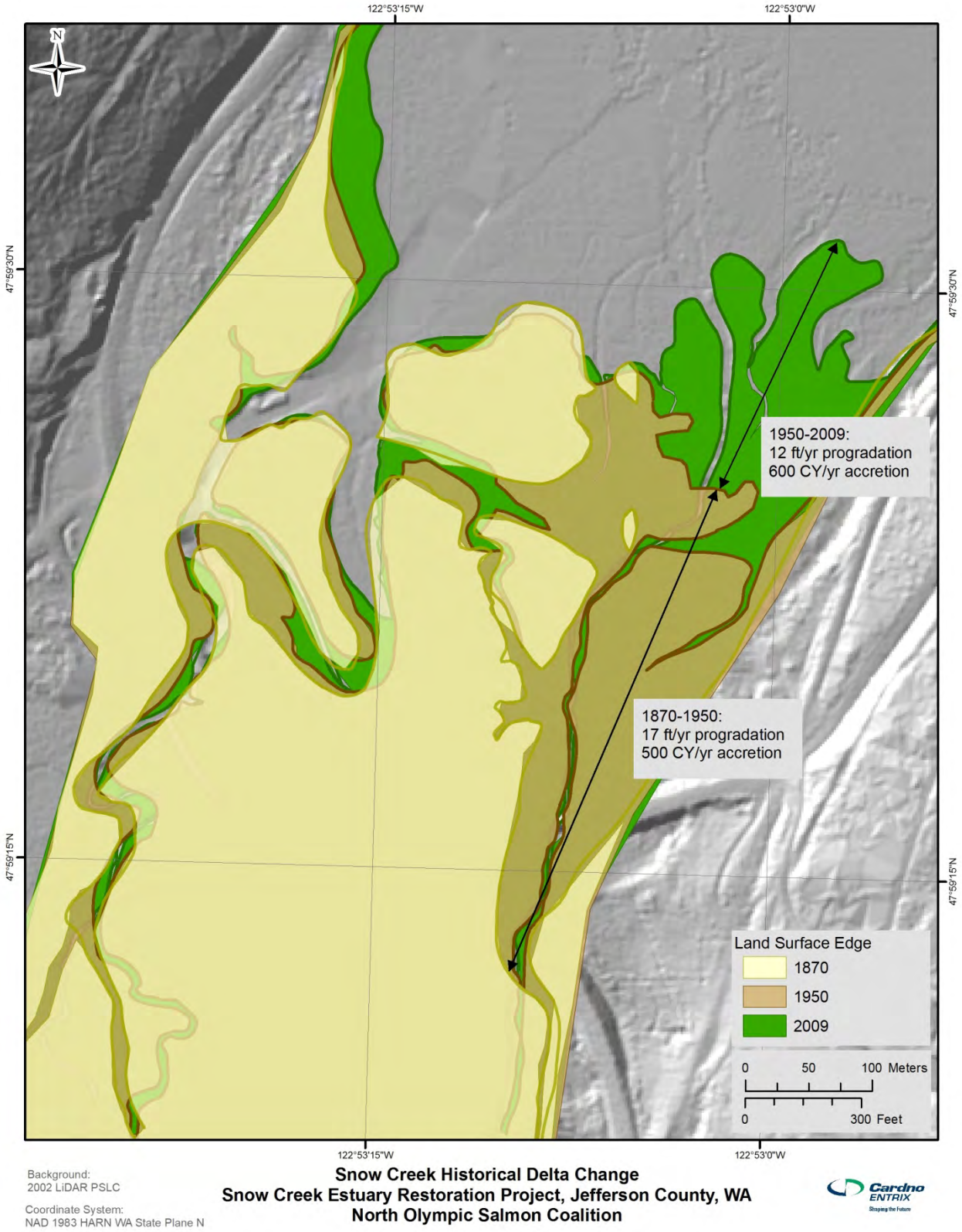


Figure 4-2: Changes to the salt marsh vegetated surface in the Snow and Salmon delta from 1870 to 2009.

The 14 acres of salt marsh newly created since 1870 is a result of the relocation of Snow Creek from a tributary of Salmon Creek to its direct delivery into Discovery Bay. Along with building out the salt marsh into bay, the process of delta progradation also is increasing the elevation of the tidal plain surface. As Snow Creek reaches the outlet into the bay, the sediment carried drops out and slopes decrease. As more sediment is brought into the delta by the creek, the delta will extend farther out as it increases in elevation to maintain the equilibrium slope required for sediment transport to continue. In this way, the creek will maintain the slopes seen today (0.0017 in the lower 1,000 feet, 0.0039 below the SR 20 bridge, and 0.0054 from US 101 to the WDFW weir) even as the delta continues to prograde (Figure 4-3). This equates to roughly 2 to 3 feet of channel aggradation at the SR 20 and US 101 locations over the next 50 years. This process will continue into the future as long as the same supply of sediment from Snow Creek is delivered directly to the delta.

If Snow Creek remains in its current alignment flowing into Discovery Bay, progradation will continue to occur with both positive and negative consequences for salmonid habitat. The new creation of salt marsh that has offset much of the salt marsh loss in the estuary (Todd et al. 2006) will continue to form the type of estuarine habitat that chum require for viable populations. The processes that build out the salt marsh are gradual; if they continue to occur at the same rate seen in the historical record, a significant increase in salt marsh area will take decades. Simultaneously, the accretion of sediment on the tidal plain may convert currently productive salt marsh farthest from the water's edge into upland habitat, particularly in locations where the tidal exchange that could redistribute sediment has been reduced due to estuary modifications.

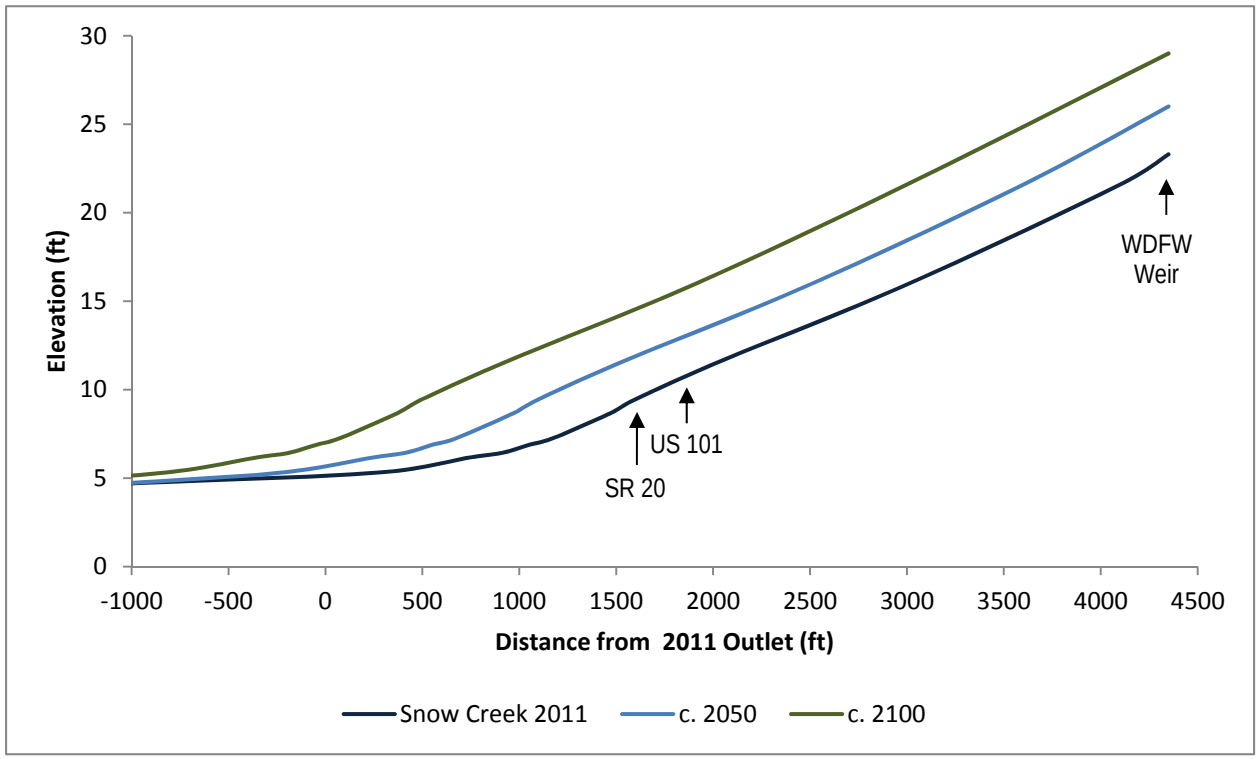


Figure 4-3: The present day Snow Creek profile and the future delta profiles, extrapolated from the rate of delta progradation, assuming Snow Creek retains its present day alignment separate from Salmon Creek.

4.3 Snow Creek Channel Geometry Change

Changes to the Snow Creek channel were analyzed using cross sections surveyed by the Jefferson County Conservation District (JCCD) between 1995 and 2009 as part of the Quilcene-Snow Restoration Team project to lower and widen the channel and install LWD. JCCD surveyed the channel in 25 locations, each roughly 100 to 200 feet apart (Figure 4-4). The channel survey data are presented in Appendix C. Because the surveys occurred in the location and during the time frame of the channel dredging, we examined the channel profiles and eliminated from consideration those surveys that represented the disturbances and not the background channel evolution. In the period immediately after channel dredging, the low areas created by the excavation of pools would preferentially fill in with sediment and the decrease in average channel slope after removal of material would enhance sediment deposition. After consideration of all data, the surveys from August 1996 and December 2009 from Cross Section -520 to Cross Section 505 were selected for analysis (Figure 4-4). Although aggradation rates should lessen toward the seaward edge of the delta as slope decreases toward the bay and this data set includes channel response to the disturbance period of dredging, the 1996 to 2009 data set represents overall aggradation rates in the greatest geographic area and over the longest time period.

Changes in the channel between time steps at each location were analyzed using a trapezoidal numerical integration of the curves representing each cross section. The difference between the numerical integrations produced the area change between each time step; the area change was then converted to a volume change by interpolating the change over the distance represented by each cross section. The length of each volume cell was the sum of the distance to each midpoint between cells (e.g., the area change at Cross Section 360 was multiplied over the distance from Cross Section 360 to the midpoint between Cross Sections 360 and 505 plus the distance to the midpoint between Cross Sections 260 and 360). Note that the volume change does not only represent vertical aggradation or degradation of the channel; it also includes a horizontal component, e.g. scour that results in a new thalweg location or depositions of bars.

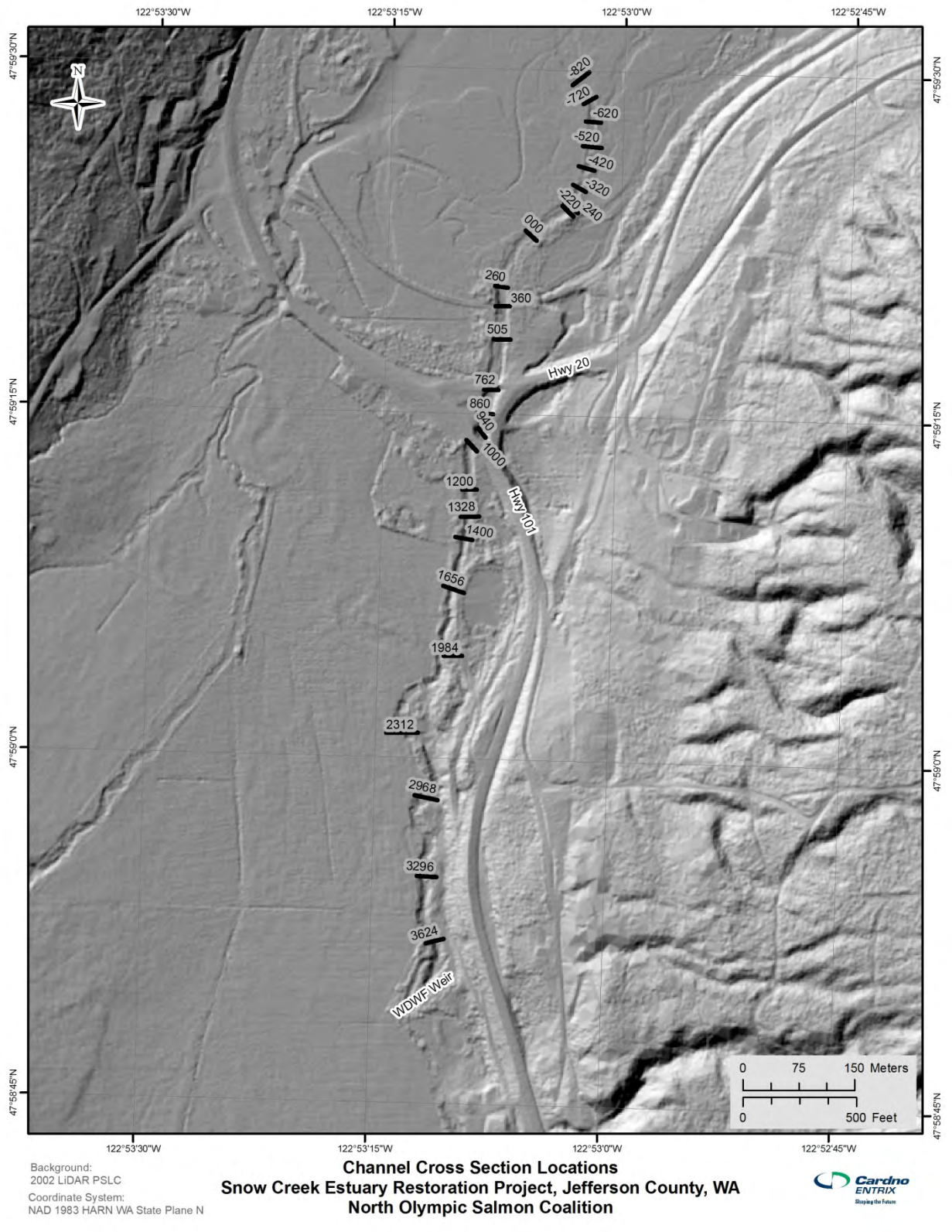


Figure 4-4: Cross section survey locations established by JCCD.

The total channel volume change between Cross Section -520 and Cross Section 505 from 1996 to 2009 was about 6,750 CY (about 500 CY per year). This change occurred for the most part as an increase in channel bed elevation rather than channel narrowing. The sediment accumulating in the Snow Creek channel is from sources upstream in the watershed. The WDFW weir allows some of the sediment load to pass along the creek, especially during high flows when the screens are removed. While improved forestry practices will reduce sediment delivery into Snow Creek, the processes of aggradation and channel geometry change will likely continue into the future as long as Snow Creek remains in its current alignment. The consistent progradation of the delta since 1870 suggests that magnitude of sediment delivery into the stream is not solely related to recent logging activity in the watershed. If the average volume change from 1996 to 1998 is projected into the future, it would correspond to an average bed elevation change of about 1 feet after 20 years. This matches the scope of the dredging operation, which removed 2 to 3 feet of sediment.

Although the limited temporal and geographic scope of the channel survey data do not result in absolute values for channel aggradation outside the influence of dredging, the analysis does confirm overall trends of sediment accumulation and the order of magnitude of change seen in the historical analysis of the delta

4.4 Bank Erosion and Avulsion Potential

Avulsion is a natural process in a delta, and the presence of multiple distributary channels is typical for these types of geomorphic systems. Distributaries naturally form though avulsion or through splitting of the channel as the delta progrades and mouth bars form (Hood 2010). Distributaries serve important functions in the delta: they distribute river flows, sediment, nutrients, wood, and aquatic organisms into the wetlands and marshes of the delta (Hood 2010). As the channel bed elevation increases, the potential for avulsion also increases. This is due to the decrease in channel capacity and the loss of gradient advantage in the mainstem. The ratios of the water surface slopes of the mainstem channel and potential avulsion channel predict whether a complete or partial avulsion will occur or whether the avulsion will fail and the new channel fill in (Slingerland and Smith 1998). In addition to water surface gradient, the erodibilty of the substrates of the banks and floodplain and the floodplain gradient also control the avulsion process (Makaske 2001). In order to assess the processes and potential avulsion pathways of Snow Creek, an analysis of channel conditions was conducted during a geomorphic field assessment on September 28 and 29, 2011. The assessment included the collection of the following data:

- Bank material, height and extent of actively eroding areas;
- Channel bed materials;
- Evidence of sediment accumulation and aggradation in the channel;
- Presence of natural splay deposits in the floodplain;
- Potential avulsion sites;
- Presence of LWD; and
- Wolman pebble counts (Wolman 1954) at three locations to evaluate the grain size distribution of the channel bed materials.

In addition to recording the location of these features using a geographical positioning system (GPS), site conditions were documented in GPS-linked photographs presented in Appendix D. Because of limited landowner access, the assessment was restricted to the channel from the outlet into Discovery Bay to the US 101 bridge, and from approximately 1,270 feet downstream of the WDFW weir to 400 feet upstream of the weir (Figure 4-5).

The field assessment recorded active bank erosion locations (Figure 4-5), which involved bank materials that ranged from silty sand to a mix of sand and gravel. These observations were correlated with calculations of local *shear stress* (τ) on the channel bank, defined as the component of the force exerted by flowing water that is parallel to the bank. The *critical shear stress* (τ_c) is the force required to mobilize a particle and initiate erosion of the bank. Critical shear stress is defined as follows in imperial units:

$$\tau_c = \gamma\, R\, S$$

Where

τ_c = critical boundary shear stress (lbs/ft^2)
g = specific weight of water (62.4 lbs/ft^3 at 40 °F)
R = hydraulic radius (channel area divided by wetted perimeter, ft)
S = slope of the energy gradient of the flow (dimensionless)

The area of bank erosion seen in the field and the corresponding values of critical shear stress for the material observed are shown in Table 4-2. Making common assumptions (the slope of the channel is equal to the slope of the energy gradient and the hydraulic radius is roughly the same as the water depth) , critical shear stress for the bank materials is reached when water depths reach 1.75 feet in the reach below the railroad grade and 0.75 foot in the reach between the railroad grade and SR 20 (Table 4-3). According to the hydraulic model described above, these depths are met or exceeded during the 2-year flows of 443 cfs during MHHW tide levels. These results indicate that avulsion of the channel is probably common and is likely to continue to occur under the current hydrological and sediment regimes.

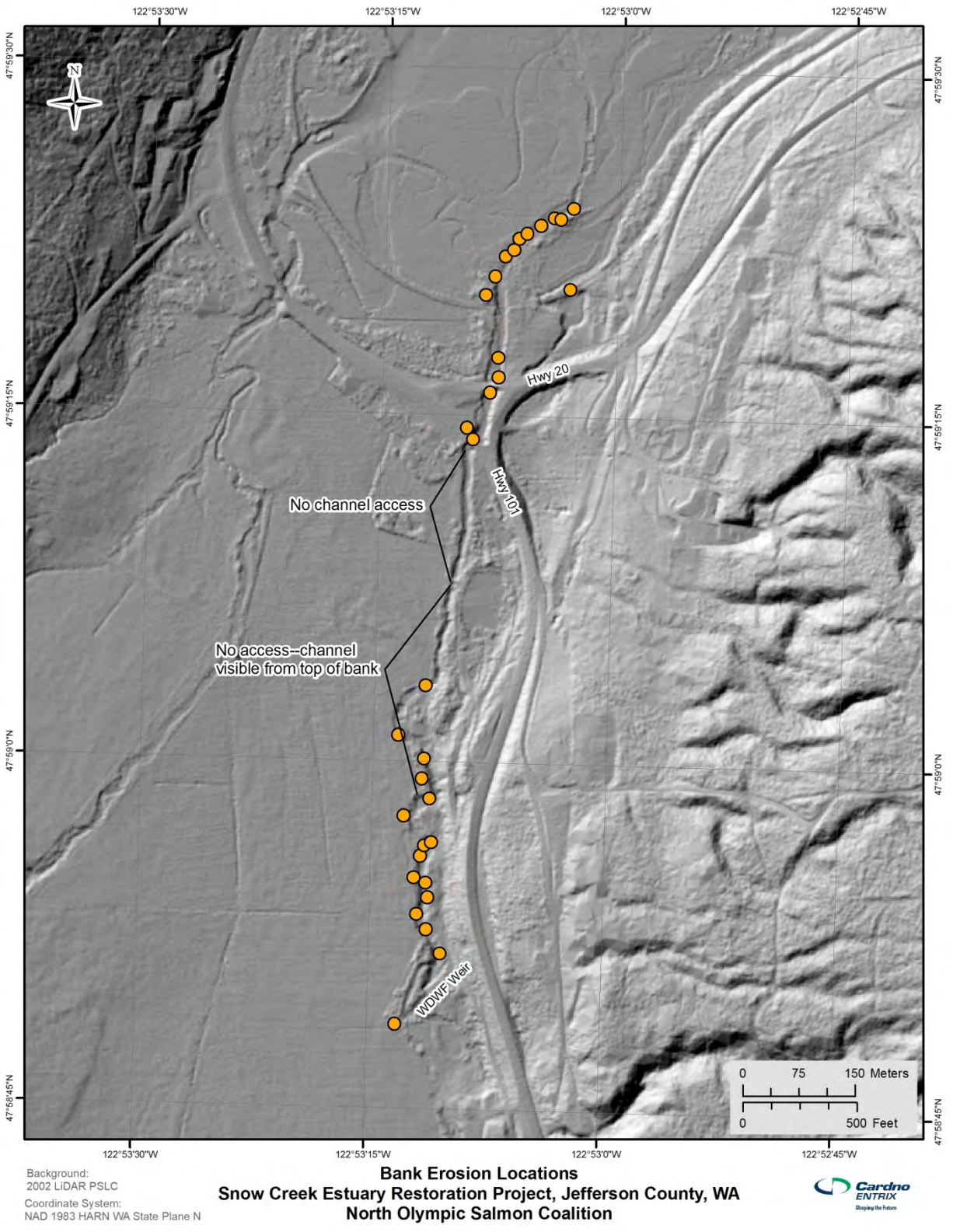


Figure 4-5: Bank erosion areas recorded in the September 2011 survey.

Table 4-2: Material of eroding banks and corresponding critical shear stress (from ASCE 1992) required for transport.

Bank Material	τ_c Critical Shear Stress (lbs/ft^2)
Silt-sand	0.12 – 0.17
Sand-gravel	0.075 - 0.12

Table 4-3: Critical shear stress for the Project area, upstream and downstream of the SR 20 bridge.

	Below Railroad Grade	Between Railroad Grade and SR 20
Slope	0.0017	0.0039
Water Depth	1.75	0.75
Critical Shear Stress	0.19	0.18

The field assessment identified several areas with evidence for probable avulsion pathways (Figure 4-6). The site upstream of the WDFW weir on the left bank was identified by a low area in the bank. Whereas banks averaged about 6 feet high in the study reach above of the weir, the potential avulsion site had only a 3-foot-high bank. Accumulations of LWD were observed in the area; these jams could help initiate an avulsion by deflecting flows into the bank or by creating a backwater effect that elevates water surface elevations.

Downstream of SR 20, two potential sites were identified on the right bank. In both cases, low areas were observed in the berm that runs along the banks. In addition, splay deposits, or areas of high ground, were seen on the tidal plain in the path that overland flows have taken. Upland vegetation has established on these splay deposits: Scotch broom (*Cytisus scoparius*) and Himalayan blackberry (*Rubus discolor*), whereas the surrounding surface supports salt marsh vegetation.

The dynamic nature of the lower Snow Creek channel has been noted by long-time residents (Walter Moa, personal communication) and was visible in the stratigraphy of the banks near the outlet into Discovery Bay (Figure 4-7). The repeating sequence of layers of gravel alternating with layers of organic root material over silt indicates this process of channel switching. The silt and roots represent the gradual accumulation of fine grained material deposited slowly enough to allow salt marsh surface vegetation to adapt and survive. The layer of gravel indicates a period when the active channel of Snow Creek was at this location, with flows and sediment supply sufficient to bring coarse material to the delta. This process can be seen in the coarse material accumulating at the present day outlet of Snow Creek.

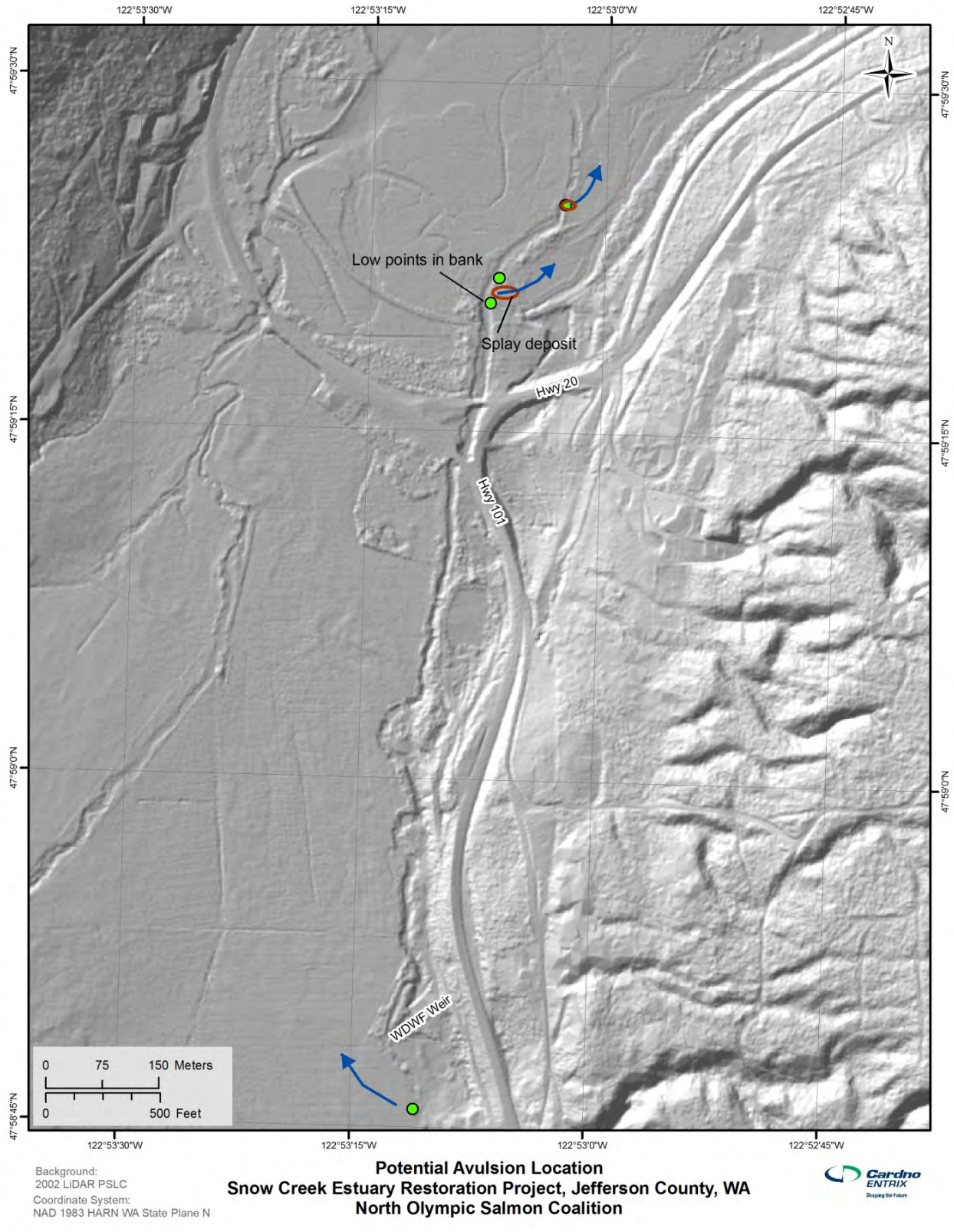


Figure 4-6: Potential avulsion locations in lower Snow Creek.



Figure 4-7: Stratigraphy of right bank indicating channel dynamics in Snow Creek. The upper photo shows stratigraphy indicating channel dynamics in Snow Creek with the sequence of horizons as follows: (A) Roots, (B) Silt, (C) Coarse gravel, (D) Roots, (E) Silt. The sequence of roots over silt seen in layers A and B and again in D and E indicate gradual accumulation of fine grained material through slow moving tidal and overbank flows. The silt accumulated slowly enough to allow salt marsh surface vegetation to survive. The C layer of gravel indicates a period when the active channel of Snow Creek was at this location, with flows and sediment supply sufficient to bring coarse material to the delta. This process can be seen at the present-day outlet of Snow Creek (lower left photo), where coarse material is accumulating (lower right, with pen for scale).

4.5 Salt Marsh Vegetation Zones

Understanding the existing vegetation patterns and the overall geomorphic context of the Project site will help determine the restoration actions that will most likely result in successful colonization of salt marsh vegetation and enhancement of ecological function. In order to determine the optimal configuration and depth of excavation in removal of the dredge spoils, we conducted a survey of existing salt marsh vegetation on September 28 and 29, 2011. The primary activity was to map the vegetation species presence and abundance cover along surveyed cross sections and in fill areas of the Project site using a global positioning system (GPS) (Figure 4-8). We also characterized the vegetation communities by dominant and associate species and mapped the extent of upland vegetation, particularly the edge of reed canary grass (*Phalaris arundinacea*) infestation along the banks of Snow Creek in the Project area.

The community composition of the salt marsh vegetation combined with topographic survey data, LiDAR imagery, and aerial photographs allowed us to map the salt marsh zones present in the study area (Figure 4-9). Species ranges and the overall community composition were used to determine the elevation ranges presented above. Lyngbey's sedge (*Carex lyngbyei*) and pickleweed (*Salicornia virginica*) indicated a low marsh community. The presence of Pacific silverweed (*Potentilla anserina ssp. Pacifica*), spearscale (*Atriplex prostrata*) and Douglas aster (*Aster subspicatusi*) denoted high marsh. A number of the species observed during the survey show broad ranges of elevations where they occur. These include common rush (*Juncus effusus*) and saltgrass (*Distichlis spicata*). Because these species could be found in a wide range of elevation, they were used in association with the narrow range species to distinguish middle marsh zones.

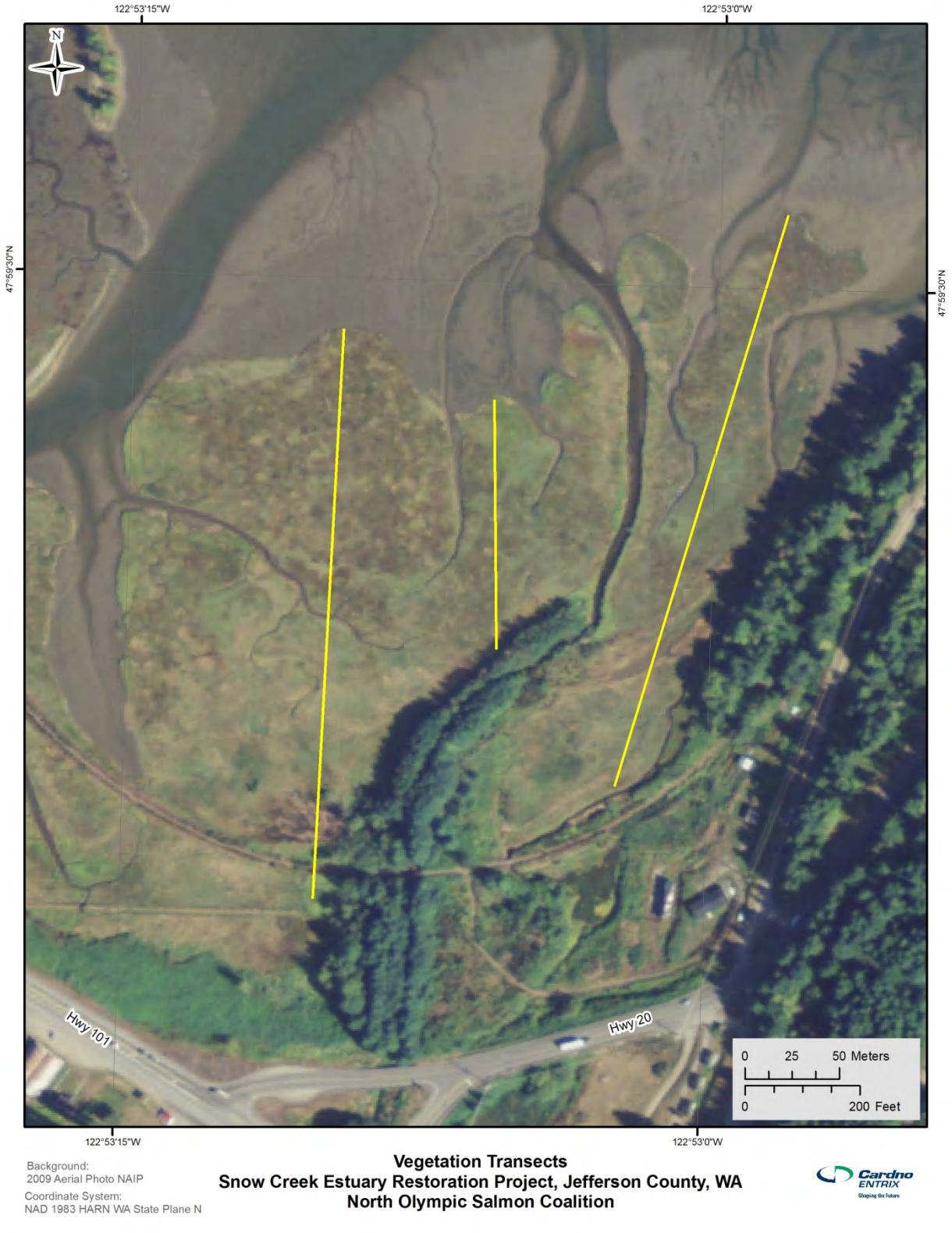


Figure 4-8: Location of vegetation transects surveyed September 28, 2011.

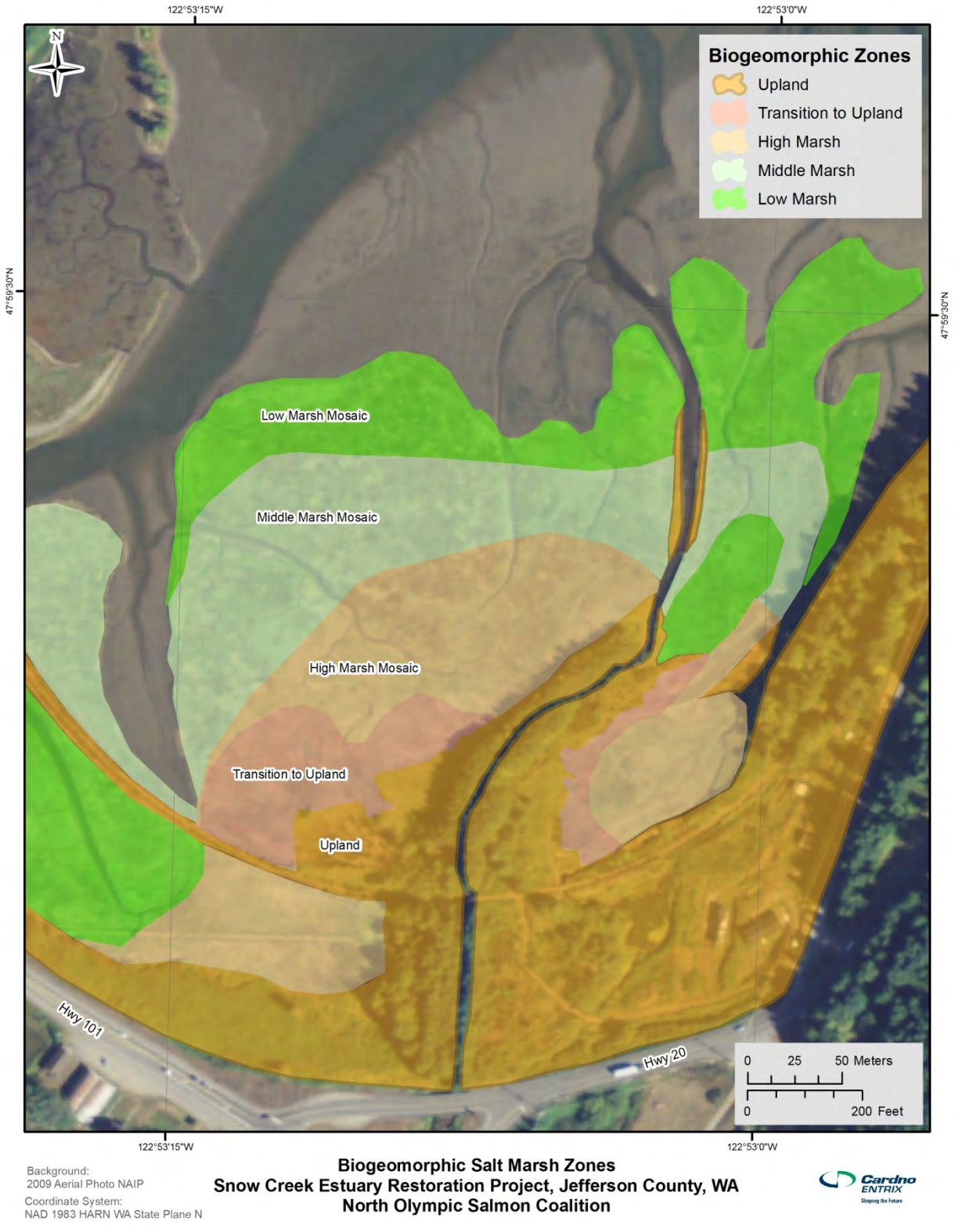


Figure 4-9: Biogeomorphic salt marsh zones of the Snow-Salmon delta.

The analysis of the vegetation data in conjunction with the topographic survey data suggests the following ranges of elevation in feet (NAVD 88) for salt marsh zones:

- Low marsh: 5.6 to 7.3
- Middle marsh: 6.8 to 7.6
- High marsh: 7.0 to 8.6
- Upland: 8.0 to 10.9

The elevation ranges for the vegetation based on the topographic survey are shown in Table 4-5, and they define zones that overlap in range and boundaries between zones are not entirely distinct. Overall elevation differences in most of the salt marsh are subtle. In addition, each zone is more accurately described as a mosaic, with patches of varying topography and species associations. This pattern is indicative of a dynamic system, where the sediment regime is rapidly changing the topography and the salt marsh vegetation is responding to these sediment fluxes. In addition, much of the site has been directly altered by activities in the estuary, leading to patchy conditions of vegetation colonization.

The tidal datums presented in Section 3 place the low marsh zone between MHW at 5.76 feet and MHHW at 6.38 feet (NAVD 88). The middle and high marsh zones are above MHHW and the transition into upland communities occurs at least 2 feet above MHHW. Within the roughly 40-acre study area, 16 acres was at upland elevations not capable of supporting salt marsh vegetation (Table 4-4). The removal of fill in these areas, where possible, would maximize the amount of new estuarine habitat available to salmonids during key phases of their life histories. The existing areas of intact salt marsh would provide propagule sources for vegetation colonization of restored areas.

Table 4-4: Area distribution of biogeomorphic salt marsh zones.

	Area (ac)	Percentage of Study Area
Low Marsh Mosaic	9	22
Middle Marsh Mosaic	7	17
High Marsh Mosaic	8	20
Upland	16	41
Total	39.5	

Overall numbers of non-native invasive species found during the survey were low. Nonetheless, noxious weeds such as reed canary grass, Scotch broom *(Cytisus scoparius*), Himalayan blackberry *(Rubus discolor*), Japanese knotweed (*Polygonum cuspidatum*) and Canada thistle (*Cirsium arvense*) were found on the site. Restoration actions should include management strategies for invasive species, particularly because the disturbance caused by removal of fill will provide an opportunity for non-native species to become established on available bare ground.

Table 4-5: Elevation ranges for observed salt marsh species. Elevation include ranges in which each species was dominant and where each occurred as an associate species.

Binomial	Common name	Elevation Range-Dominant (Ft NAVD 88)	Elevation Range-Associate (Ft NAVD 88)
Salt Marsh Species			
Aster subspicatus	Douglas aster	8.0 - 8.6	7.7
Atriplex prostrata	Orache, fat hen, spearscale	7.0 - 7.4	6.6 - 7.9
Carex lyngbyei	Lyngbye's sedge	6.2 - 7.1	7
Deschampsia cespitosa	Tufted hairgrass	Seen on site, but not in survey transect	
Distichlis spicata	Saltgrass	6.6 - 7.5	6.4 - 7.9
Grindelia integrifolia	Gumweed	--	6.6
Juncus effusus	Common rush	6.8 - 7.6	6.6 - 7.3
Juncus gerardii	Mud rush	--	6.6 - 7.0
Potentilla anserina ssp. pacifica	Pacific silverweed	--	6.8 - 7.9
Salicornia virginica	Pickleweed	6.4 - 7.3	6.8 - 7.9
Scirpus maritimus	Salt marsh bulrush	--	6.6
Spergularia macrotheca	Sandspurry	--	6.6 - 7.5
Triglochin maritimum	Seaside Arrow-grass	--	6.4 - 7.5
Upland Species			
Achillea millefolium	Common yarrow	--	7.6 - 8.6
Alnus rubra	Red alder	8.9 - 9.6	--
Salix scouleriana	Scouler's willow	--	8.6
Typha latifolia	Cattail	10.4	--
Non-Native Upland Species			
Cirsium arvense	Canada thistle	--	7.9
Cytisus scoparius	Scotch broom	8.2 - 8.8	7.6 - 7.9
Lolium perenne	Perennial ryegrass	7.1 - 7.9	7.3 - 7.5
Phalaris arundinacea	Reed canary grass	8.0 - 10.9	--
Rubus discolor	Blackberry	8.8 - 10.0	--
Polygonum cuspidatum	Japanese knotweed	Seen on site, but not in survey transect	

Chapter 5 Risks Associated with 60 Percent Design

A risk assessment is systematic evaluation of potential adverse effects from hazardous events, processes, actions or substances. In this risk assessment, risk is defined as the probability that a hazard (or source of harm) will result in a negative consequence (harm or loss). The goal of this risk assessment is to identify hazards and characterize risks under existing and proposed Project conditions. If there are measures to address hazards, then mitigating actions can be taken to minimize or eliminate any risks.

5.1 Project Description

The restoration approach will address the habitat degradation occurring since historic disturbance. The Project consists of the following elements, also shown in the final design plans:

1. Excavation of dredge spoils and fill from the Snow Creek banks downstream of SR 20, excluding the Sea-Kota property on the left (west) bank;
2. Excavation of the upland portions of delta surface downstream of SR 20 to a salt marsh elevation of 6.5 to 7 feet (NAVD 88);
3. Excavation of a tidal slough network in the newly re-created salt marsh;
4. Removal of the railroad grade and two creosote timber bridges over Snow and Salmon creeks;
5. Installation of LWD habitat structures along Snow Creek; and
6. Permanent storage of excavated materials at an adjacent upland site outside of the salt marsh area.

5.2 Methods for Assigning Level of Risk

The level of risk is the product of the probability of a hazard occurring and the magnitude of the consequence of that event. If an event has little or no consequence than the associated risk would be relatively low. If the probability of a hazard occurring is certain and the level of consequence severe, than the risk is high. A high negative consequence combined with a high probability of occurrence results in a *high* level of risk (Figure 5-1). A high negative consequence combined with a low probability of occurrence results in a *medium* level of risk. A low negative consequence combined with a low probability of occurrence results in a *low* risk.

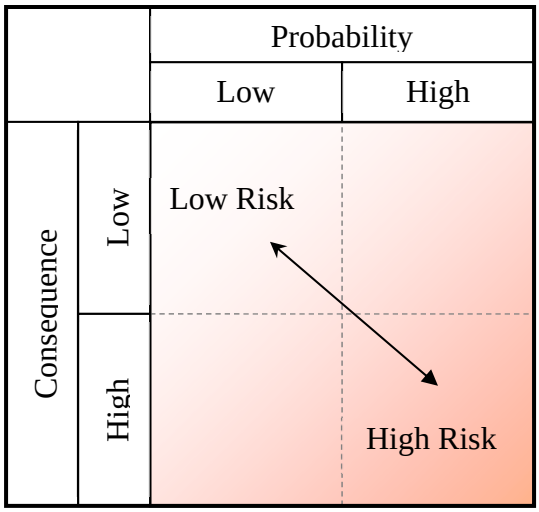


Figure 5-1: A graphical definition of risk, R = P(H)*C, where P(H) is the probability of some hazard (e.g., flooding, erosion) and C is the consequence (e.g., monetary damages).

Re-establishing natural processes is vital to enhancing and maintaining ecological function. Project goals that take into account natural processes can minimize risk by adapting the Project to the site context. The dynamic nature of estuarine systems is desirable for optimal ecological function; however, it also presents challenges to property owners and resource managers in protecting and maintaining infrastructure, and to public and private users. It is the responsibility of program mangers and participating agencies to notify the public, property owners, recreational users and other stakeholders of the hazards associated with changing estuarine systems, especially when they are modified as part of Project plans.

The hazards (and the resulting risks) identified for the Project include the following:

4. Risk to infrastructure, adjacent property or habitat from sedimentation, flooding and channel avulsion;

5. Risk to habitat and ecological function from construction activities; and

6. Risk to public safety or obstructions to recreational users.

5.3 Flooding

Flooding was considered as a potential hazard to the infrastructure in the vicinity of the Project: SR 20, US 101, residences, commercial buildings, the septic tank and its drainfield. The artesian well located outside the Project boundaries was also considered an item of concern because of the potential for backwatering of the discharge ditch for this public drinking water supply.

A two-dimensional hydraulic model was performed using the University of Alberta River 2D model. River 2D is a two-dimensional depth averaged finite element model used for river hydrodynamic and fish habitat modeling (Steffler and Blackburn 2001). Inputs needed for the model include bed topography, bed roughness, and boundary conditions that include discharge and downstream stage (water surface elevation). The model consists of two streams, Snow Creek and Salmon Creek. Both creeks enter the tidal mudflats near the downstream boundary of the

model and the model extended 728.5 m (2,390 feet) upstream. Salmon Creek was not analyzed for this Project but its estimated flow conditions were included in the model based on data from Barnard (2007).

The foundation for the 2D model is the topography: the 2002 LiDAR and the 2011 Cardno ENTRIX topographic survey data merged into a DEM. Because channel topography was not surveyed above the US 101 bridge due to lack of landowner cooperation, the average offset between the in-channel LiDAR data and the in-channel survey was applied to the LiDAR data above the US 101 bridge. This created a reasonable estimation for the in-stream topography. A ten-meter computational mesh was created in River2D for the entire site. The mesh was then refined to 1.9 meters in and around Snow Creek. River2D uses a hydraulic roughness dimension assigned to each node in the mesh. For this model the three roughness dimensions used were as follows:

- Snow Creek Instream (gravel/cobble): 0.152 m;
- Out of Stream Rough Vegetation: 1.26 m; and
- Mudflats: 0.005 m.

Two flow events were selected for analysis under existing conditions: the 2-year and 100-year flood events. Values for Snow Creek were obtained from the hydrological analysis using the USGS Bulletin 17b method, while values for Salmon Creek were obtained from Barnard (2007). For the 100-year flow 54.06 cubic meters per second (cms) (1909 cfs) was used for Snow Creek and 36.33 cms (1283 cfs) for Salmon Creek. For the 2-year event, a flow of 12.54 cms (443 cfs) was used for Snow Creek and 9.1 cms (321 cfs) for Salmon Creek. MHHW (1.94 m / 6.38 ft) was used as the downstream boundary condition. The model could not be calibrated due to a lack of stage and discharge data; however, there was a stage point for 2 cfs taken at the Snow Creek gage just downstream of the railroad bridge which was used to validate the low-flow results.

The model was run under existing conditions and under the 30 percent design proposed condition. The existing conditions topography utilized the combined 2002 LiDAR and 2011 Cardno ENTRIX ground survey DEM. The proposed conditions model incorporated the following features of the 30 percent design:

1) Dredge spoil/fill soil removal along the channel banks downstream of SR 20 (with the exception of the Sea-Kota property on the left bank);

2) Removal of the railroad grade up to the Calero property line; and

3) Removal of dredge spoil/fill soil on the delta surface within the existing estuary to an average of 7 feet elevation (NAVD 88).

Figures 5-2 to 5-5 illustrate the results of the modeled water depths for existing and proposed conditions at the 2-year and 100-year flows. Within the floodplain and delta downstream of SR 20, the results generally show increased inundation throughout the Project area. The removal of dredge spoils and fill from the right bank of Snow Creek downstream of SR 20 to an appropriate salt marsh elevation of 7 feet (NAVD88) would eliminate the defined stream channel. The lack of a defined stream channel causes even low flows to fan out into the marsh surface after passing

under the SR 20 bridge, and also results in decreased inundation of the Sea-Kota property. The increased flood inundation of the Project site indicates that the goal of improved hydraulic connectivity between Snow Creek and the marsh surface will be met at the modeled flows. The model results also show some lowering of the 100-year flood elevation upstream of US 101, owing to reduced backwater effects from the less constrained channel after berm removal downstream. There is no indication of increased backwatering into the artesian well drainage ditch upstream of SR 20.

The results of this analysis indicate that flooding conditions are likely to remain unchanged on the private properties upstream and adjacent to the Project area under proposed conditions. Within the delta and Project area, the Snow Creek channel and the re-connected tidal plain and slough channels may experience more frequent and deeper levels of inundation. Because the increase in water depths were limited to Project areas with no infrastructure concerns, the consequences of the Project actions are considered low in terms of potential flooding. The low probability of high-magnitude events ($p=0.01$) combined with low consequence results in a low risk to a properties and infrastructure from increased flooding due to the Project.

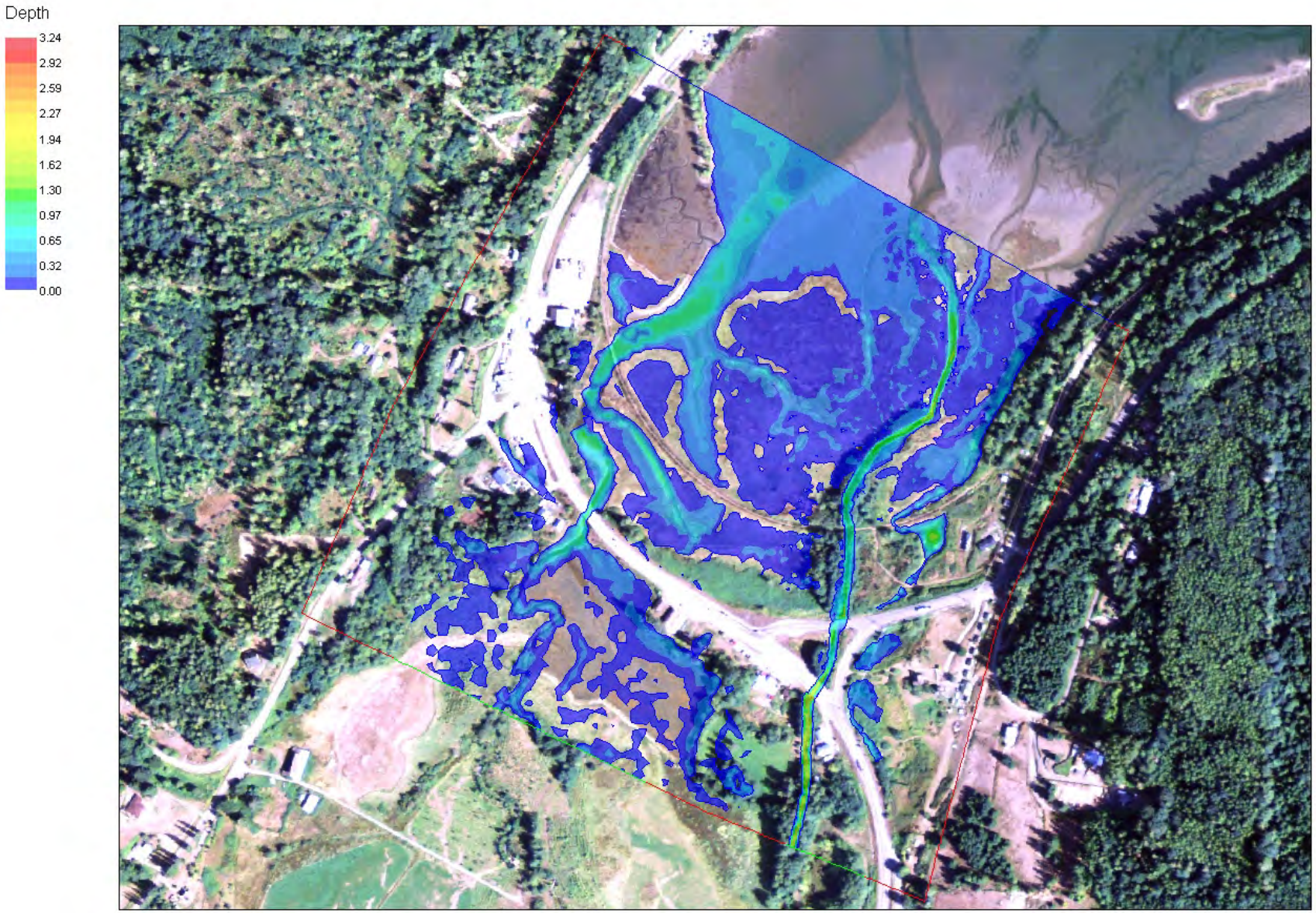


Figure 5-2: River 2D model water depth results for the 2-year flow event (443 cfs) at MHHW (6.38 ft NAVD 88) for existing conditions.

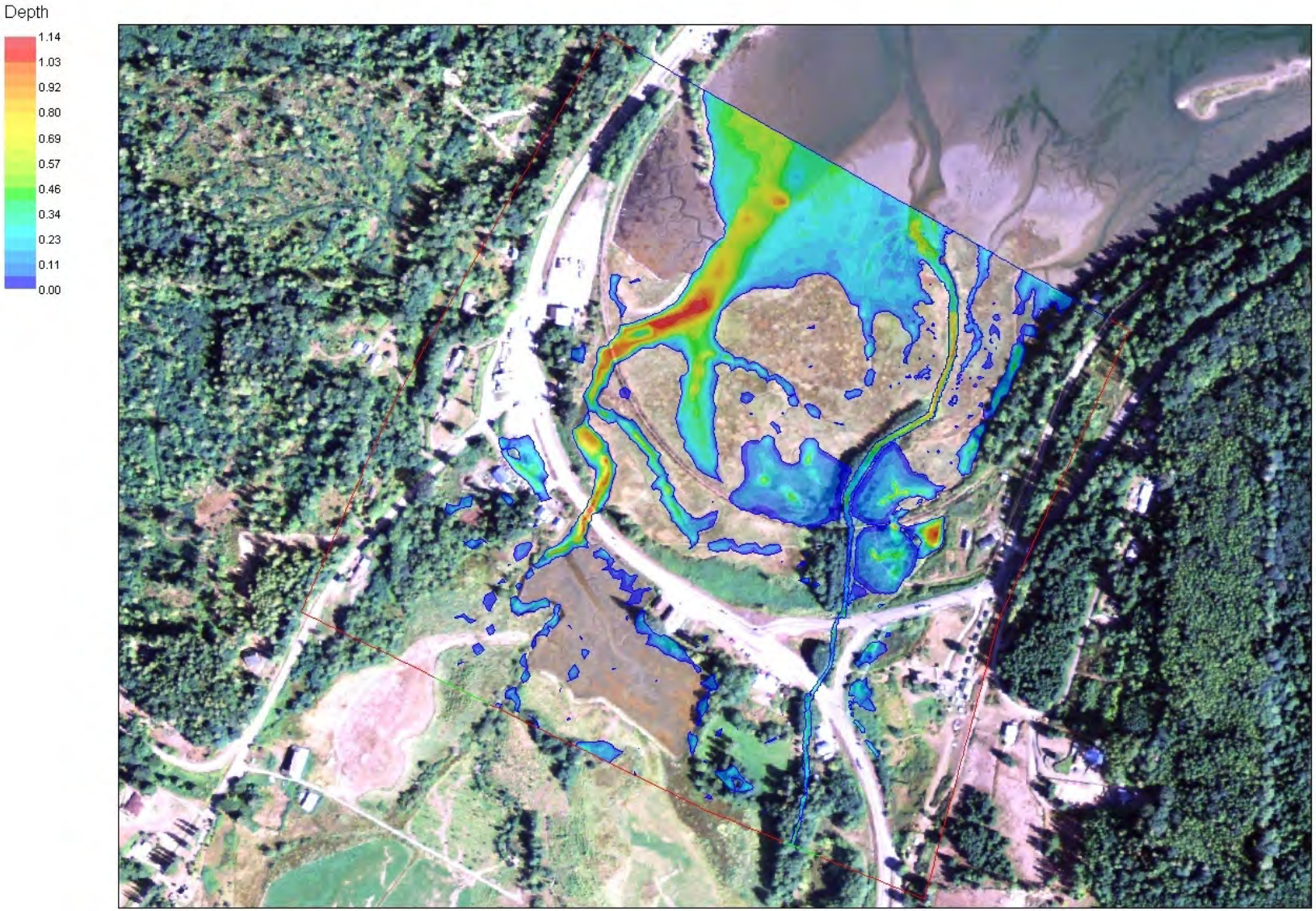


Figure 5-3: River 2D model water depth results for the 2-year flow event (443 cfs) at MHHW (6.38 ft NAVD 88) for proposed conditions.

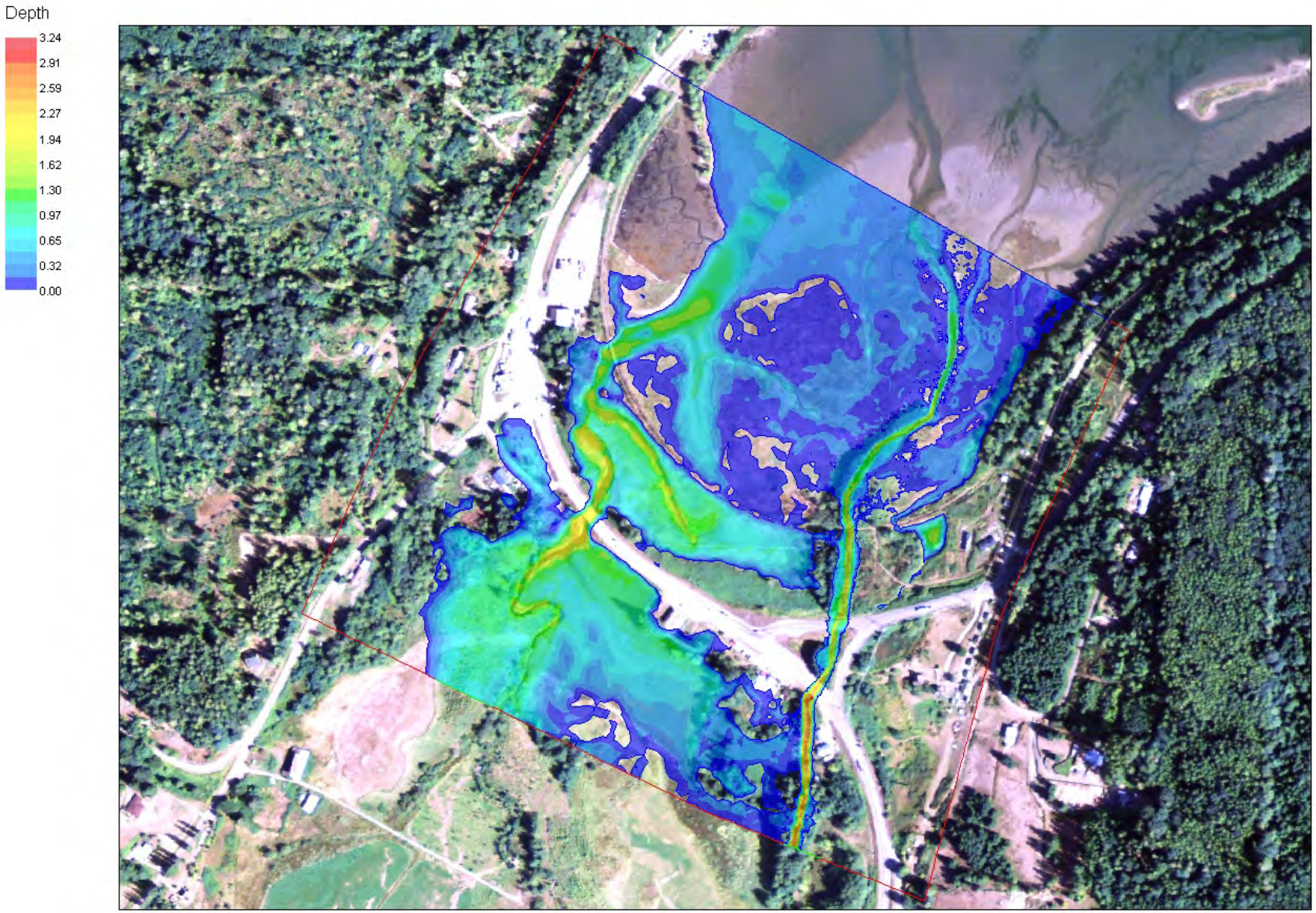


Figure 5-4: River 2D model water depth results for the 100-year flow event (1909 cfs) at MHHW (6.38 ft NAVD 88) for existing conditions.

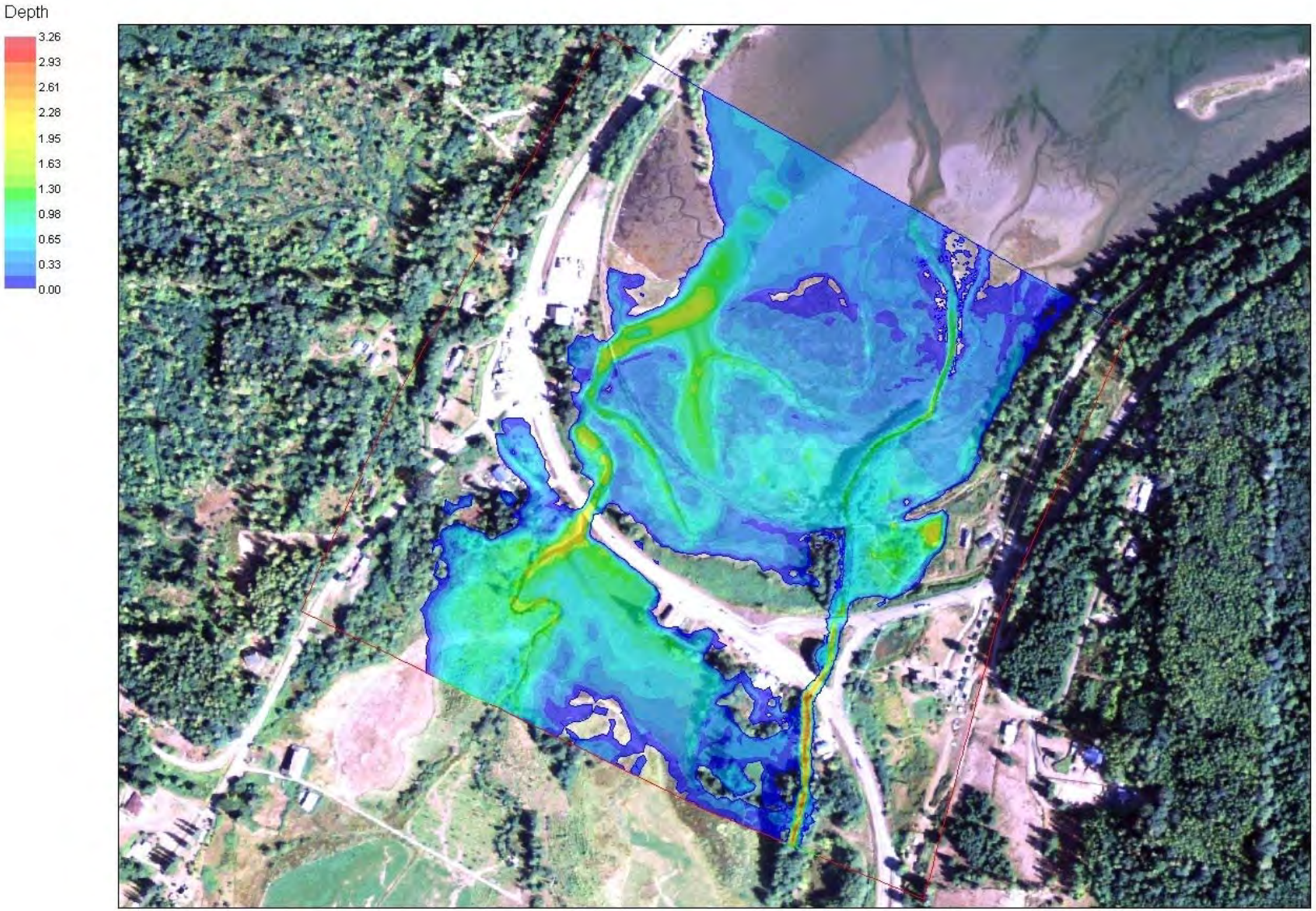


Figure 5-5: River 2D model water depth results for the 100-year flow event (1909 cfs) at MHHW (6.38 ft NAVD 88) for proposed conditions.

5.4 Sedimentation

Sedimentation in the Project site takes the form of channel bed aggradation and delta surface accretion and progradation. While the deposition of sediment is a natural process inherent to delta formation, this was considered a potential hazard to infrastructure and habitat. Sedimentation can result in an indirect hazard to infrastructure where it increases water surface elevations and hence, the potential for flooding or channel avulsion. Sedimentation can also be a hazard to habitat if existing or restored salt marsh is converted to upland, opening the area to the spread of non-native invasive vegetation such as reed canary grass. This would reduce productive habitat and worsen existing invasive plant problems already present in the delta. Shallower flow associated with channel bed aggradation may also increase low-flow water temperatures, reduce bed complexity, and reduce the aeration of spawning gravels within the Project reach.

The results of the Cardno ENTRIX two-dimensional model of potential sediment movement in the Snow Creek estuary are presented in a technical memorandum included as Appendix E. The sediment-transporting ability of the flow can be represented by the *shear velocity*, which scales with rates of bedload sediment transport. For each model run, the shear velocity output was classified in ArcGIS using the values found in the U.S. Army Corps of Engineers empirical measurements of the critical shear velocities required to initiate motion for a given particle size. While these shear velocity classes indicate the particle sizes that would be entrained at a given value, sediment transport will also be influenced by flow variability (pulses of higher velocity which may occur), suspended sediments (which can dampen turbulence), and particle interactions. The output is most useful in comparing the spatial patterns of predicted sediment mobilization, and any differences between current and future scenarios.

The lack of a defined Snow Creek channel downstream of SR 20 under the proposed conditions model reduced sediment transport capacity of both freshwater and tidal flows and expanded the area of sediment deposition, resulting in an increased potential for fine sand to coarse gravel to accumulate on the marsh surface and within tidal slough channels. The area presently occupied by the Snow Creek channel downstream of SR 20 experienced aggradation and fining of sediments under 2-year and 100-year flow models. Sediment transport capacity within the Snow Creek channel upstream of SR 20 decreased for the 2-year flow but was maintained during the 100-year flow. Although dynamic tidal modeling has not been completed for the Project area, it is expected that higher freshwater flows and ebbing tides will flush some of these finer sediments from the channel, salt marsh and slough channels, including the artesian well drainage ditch.

The results of this analysis indicate that if sediment supply and watershed hydrology remain constant in the future, sediment transport conditions are likely to remain unchanged on the private properties upstream and adjacent to the Project area under proposed conditions. The Snow Creek channel bed substrate is likely to become finer, while the estuary and slough channels may see an influx of coarser sediments. Because the non-tidal section of the channel is likely to undergo periods of aggradation and substrate fining during small events followed by scouring and flushing during larger, less frequent flows, no increase in flooding is anticipated. Monitoring of delta evolution after restoration should include vegetation colonization. The risk from conversion to upland would be mitigated by early identification and removal of invasive vegetation and replacement with fast-growing upland native species, such as willow (*Salix* spp.).

The low level of change to sedimentation patterns from existing to proposed conditions combined with the low consequence to the undeveloped Project reach results in a designation of low risk to habitat and flooding. This low risk can be further mitigated through a monitoring and revegetation plan for parts of the delta subject to sedimentation.

5.5 Channel Avulsion

The Snow Creek channel response to bed aggradation may be avulsion to new paths within the estuary and/or the formation of multiple distributary channels on the delta. This would represent the resumption of natural delta channel dynamics that had been limited by artificial constraints. Frequent switching of channel location and multiple distributaries are natural features of delta formation seen in both the stratigraphy of the banks near the outlet and in observations made by long-time residents of the area. Distributary formation and channel avulsion could reduce the consequences of post-restoration channel aggradation and salt marsh accretion by distributing sediment over a wider area.

The two-dimensional model results did not indicate an increase in flooding or shear velocity in flood flows upstream of SR 20. While the model did not include the entire Snow-Salmon valley, these results indicate that conditions upstream of the highways will not be changed relative to existing conditions.

While the probability of an avulsion downstream of SR 20 is high, there are no negative consequences to habitat from the return to natural delta dynamics. The likelihood of avulsion upstream of SR 20 and US 101 is not changed from existing conditions, so the risk level from restoration actions in the Project reach is low.

5.6 Construction Activities

There are several components to the construction of the proposed restoration Project that have the potential of posing hazards to existing habitat. These hazards would be short-term in nature and only be present during the construction of the Project.

Construction will occur during the low-flow season (August-September). Construction will occur according to the daily tides and will be scheduled to maximize work hours during daylight low tides. In order to prevent an increase in turbidity in Snow Creek, the area in the immediate vicinity of the work will be isolated prior to construction. The removal of creosoted bridges will require diversion of Snow Creek, Salmon Creek and the well drainage ditch. The area to be dewatered will be isolated with a cofferdam prior to dewatering and all dewatering water will be pumped away from the creek to adjacent uplands for infiltration, minimizing the potential for turbid release into the creeks.

The dewatering process will result in several hazards, including fish stranding, redd dewatering and turbid water release into the main channel. Any short-term hazards to existing habitat from in-stream construction can be mitigated through timing, fish surveys, site isolation, and relocation of fish. The work window of construction is established to limit impacts on particular species by timing work during periods when their presence is least likely. Prior to any water diversion, a redd survey should take place in the part of the channel to be diverted. Prior to

excavation, the area should be isolated from the surrounding water and any remaining fish will be excluded from the isolated area by trained personnel.

Primary earthmoving activities included in the design are excavation of the salt marsh fill and re-contouring of the ground surface. Grading of staging and stockpile areas is anticipated to be minimal. Any areas that are excavated or filled during construction will lose existing vegetated cover and remain exposed until re-vegetated. Temporary erosion control measures will be put into place where needed while permanent vegetation becomes established.

The potential for redd dewatering, fish stranding or turbid water release during dewatering is low. The construction activities will comply with the National Pollutant Discharge Elimination System (NPDES) permit issued by the Washington State Department of Ecology and would constitute a low level of risk to fish and other aquatic species.

5.7 Public Safety and Recreation

Snow Creek is not considered a navigable waterway by the United States Army Corps of Engineers. While part of the Project site is publicly owned by WDFW, it is not heavily used for recreation. The construction of the Project will not introduce any additional hazard beyond what already exists in all dynamic estuarine systems. Like any outdoor recreational activity, the Snow Creek estuary should only be used by those with appropriate experience and expertise. Experienced users should be capable of identifying obstacles and hazards. The possible future construction of a portion of the Olympic Discovery trail near to SR 20 will not occur as part of the Project and was not considered under this 60 percent design risk assessment. When we combine the low probability of interactions between public users and the proposed Project and the low potential to impact recreational users of the creek relative to existing conditions, the resulting level of risk is low.

5.8 Conclusions

The overall risk associated with the elements of the Snow Creek Estuary Restoration Project is equivalent to that expected in naturally functioning estuarine systems. Restoring ecological, geomorphic and hydraulic processes will result in some unavoidable risks when compared to the existing conditions. The nature of the goals of restoration— increasing dynamic characteristics and encouraging hydraulic and geomorphic habitat-forming processes—will promote changes in delta morphology. Water surface elevations, flow depth and velocity, and shear stress can change with installation of the Project. However the changes are either beneficial to the Project and have low associated risk, or the risk is not changed when compared to the existing conditions.

Chapter 6 Conclusions and Recommendations

The Snow-Salmon estuary is a highly dynamic system that is still responding to major alterations to the channel alignment of Snow Creek over the past century. Full restoration of ecological and geomorphic structures, processes and functions would require the following long-term actions: the relocation of Snow Creek into Salmon Creek upstream of the delta at or near the historical confluence; the removal of fill, dikes, utilities and infrastructure in the delta; the re-establishment of tidal sloughs and distributary channels in the delta; the reconnection of floodplain wetlands to the creek; and removal, raising or substantial widening of the US 101 bridge over Salmon Creek (and the SR 20 bridge over Snow Creek if relocation does not occur). These actions would serve to restore habitat connectivity, fluvial–tidal exchange, sediment transport, and food web production through increases to salt marsh area, tidal channel networks, and tidal prism. Enhancement of the highway bridges is beyond the scope of this Project, however, and the status of land ownership and stakeholder concerns upstream of the delta preclude the relocation of Snow Creek back into Salmon Creek at this time. Any actions undertaken for this Project have to maximize ecological benefits within the existing constraints.

Partial restoration of the Snow Creek estuary can enhance ecological function and meet Project goals. Excavation of fill in the salt marsh and creation of tidal channels will maximize habitat for salmon populations that are in decline and are highly dependent on estuaries for viability. Cardno ENTRIX recommends the removal of dredge spoils and fill from the Snow Creek delta and banks within the Project area to an elevation of approximately 7 feet (NAVD88) in a manner that allows for low flows and minor floods (i.e., less than a 2-year event) to pass through the reach to Discovery Bay. This includes the railroad grade and high ground at and near the banks of the creek. The removal of fill and excavation of tidal channels in the marsh plain would increase hydraulic connectivity, maximize tidal prism, and increase the amount of estuarine habitat available to salmonids during key phases of their life histories. LWD habitat installation in the creek would create and maintain in-stream complexity and provide in-channel holding sites for juvenile salmonids and refugia from high flows, high temperatures and predators. Removal of French drains from the slopes above the salt marsh and the creosote bridges in the railroad grade is also recommended.

The excavation elevation of the marsh surface will allow for the natural colonization of salt marsh vegetation from the existing salt marsh sources on site. Upland areas where excavation materials are stored should be permanently vegetated with Pacific Northwest native trees and shrubs to enhance marine riparian function and prevent the spread of non-native invasive vegetation. The septic system on the east floodplain between the railroad grade and SR 20 would need to be removed before work can be completed in this area. As the upland septic relocation site is still under consideration, work in this area can be deferred to a second Project phase if needed. If the relocation of Snow Creek back into Salmon Creek can occur in the future, the restoration actions undertaken for this Project will be in place, already improving biogeomorphic function of the estuary while awaiting further restoration actions.

Chapter 7 References

Aitken, J.K. 1998. The Importance of Estuarine Habitats to Anadromous Salmonids of the Pacific Northwest: A Literature Review. U.S. Fish and Wildlife Service. Lacey, Washingon.

Ames, J. G. Graves, and C. Weller. 2000. Summer Chum Salmon Conservation Initiative: An Implementation Plan to Recover Summer Chum in the Hood Canal and Strait of Juan de Fuca Region. Washington Department of Fish and Wildlife and Point-No-Point Treaty Tribes, Olympia, WA

American Society of Civil Engineers (ASCE) and Water Environment Federation (WEF). 1992. Design and Construction of Urban Stormwater Management Systems, ASCE, Manuals and Reports of Engineering Practice, No. 77, New York, NY and Water Environment Federation, Manual of Practice No. FD-20, Alexandria, VA.

Barnard, B. 2007. US 101 at Salmon Creek Estuary Restoration and Snow Creek Reconnection Hydraulic Report. State of Washington Department of Fish and Wildlife.

Beamer, E. A. McBride, C. Greene, R. Henderson, G. Hood, K. Wolf, K. Larsen, C. Rice, and K. Fresh. 2005. Delta and Nearshore Restoration For The Recovery Of Wild Skagit River Chinook Salmon: Linking Estuary Restoration To Wild Chinook Salmon Populations. Prepared as a supplement to the Skagit Chinook Recovery Plan. 97 pp.

Brewer, S., J. Watson, D. Christensen, and R. Brocksmith. 2007. Hood Canal and Eastern Strait of Juan de Fuca Summer Chum Salmon Recovery Plan. Hood Canal Coordinating Council. 338 pp.

Cooper, Randy. 2011. Washington Department of Fish and Wildlife. Personal communication with Eliza Ghitis and George Fowler, Cardno ENTRIX, August 22.

Correa, G. 2002. Salmon and Steelhead Habitat Limiting Factors, Water Resources Inventory Area 17. Washington State Conservation Commission. 316 p.

Hood, W.G. 2010. Delta distributary dynamics in the Skagit River Delta (Washington, USA): Extending, testing, and applying avulsion theory in a tidal system. *Geomorphology* 123 (2010) 154–164

Johnson, O.W., W.S. Grant, R.G. Kope, K. Neely, F.W. Waknitz, and R.S. Waples. 1997. Status review of chum salmon from Washington, Oregon, and California. U.S. Dept. Commerce, NOAA Technical Memorandum. NMFS-NWFSC-32. 280 p.

Knowles, S. M. and S. Sumioka. 2001. The national flood-frequency program - methods for estimating flood magnitude and frequency in Washington, 2001, U.S. Geological Survey USGS Fact Sheet 016-01.

Makaske, B., 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth-Science Reviews 53, 149–196.

Moa, Walter. 2011. Personal communication with Chad Krofta, Cardno ENTRIX, September 2.

Montgomery, M. and G. Hartmann. 2011. Cultural Resources Assessment for the Snow Creek Estuary Restoration Project, Jefferson County, Washington. Cultural Resource Consultants, Inc. Technical Memo 1102F-1b. Prepared for North Olympic Salmon Coalition.

National Oceanic and Atmospheric Administration (NOAA). 2011. ESA Salmon Listings. Available at http://www.nwr.noaa.gov/ESA-Salmon-Listings/.

National Atmospheric and Oceanic Administration Coastal Change Analysis Program (NOAA C-CAP). 2011. Land Cover Atlas. http://www.csc.noaa.gov/ccapatlas

Novakowski, K.I., R. Torres, L.R. Gardner, and G. Voulgaris. 2004. Geomorphic analysis of tidal creek networks, *Water Resources Research*, 40 (5): Article W05401.

PRISM Climate Group. 2011. Climate Data Explorer. Oregon State University. Available at http://prismmap.nacse.org/nn/

Schuster, J.E. 2005. Geologic Map of Washington State. Washington Department of Natural Resources, Division of Geology and Earth Resources. Geology Map GM-53.

Simenstad, C.A. 2000. Estuarine landscape impacts on Hood Canal and Strait of Juan de Fuca summer chum salmon and recommended actions. Appendix Report 3.5, pp. A3.111-A3.132 in J. Ames, G. Graves, and C. Weller (*eds.*), Summer Chum Salmon Conservation Initiative: An Implementation Plan to Recover Summer Chum in the Hood Canal and Strait of Juan de Fuca Region. Washington Department of Fish and Wildlife and Point-No-Point Treaty Tribes, Olympia, WA

Slingerland, R., Smith, N.D., 1998. Necessary conditions for a meandering-river avulsion. Geology 26, 435–438.

Steffler, P. and Blackburn, J. 2001. River2D: Two-dimensional depth averaged model of river hydrodynamics and fish habitat, University of Alberta, Edmonton, Alberta, Canada.

Thorson, R.M. 1980. Ice-sheet Glaciation of the Puget Lowland, Washington, during the Vashon Stade (late Pleistocene). *Quaternary Research.* 13:303-321.

Todd, S., N. Fitzpatrick, A. Carter-Mortimer, and C. Weller. 2006. Historical Changes to Estuaries, Spits, and Associated Tidal Wetland Habitats in the Hood Canal and Strait of Juan de Fuca Regions of Washington State. Point No Point Treaty Council, Kingston, Washington.

United States Historical Climatology Network (USHCN). 2011. 456678, Port Townsend, WA. http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn_map_interface.html

United States Geological Survey (USGS). 1981. Guidelines for Determining Flood Flow Frequency. Bulletin 17B of the Hydrology Subcommittee of the Advisory Committee on Water Information. 194 pp.

United States Geological Survey (USGS). 1989. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. USGS Water- Supply Paper 2339.

United States Geological Survey (USGS). 2011. Washington Stream Stats. http://streamstatsags.cr.usgs.gov/wa_ss/

Washington Department of Ecology (WDOE). 2011. Snow Creek @ WDFW. https://fortress.wa.gov/ecy/wrx/wrx/flows/station.asp?sta=17E060

Appendix A

Snow Creek Tidal Hydrology Technical Memorandum

Cardno ENTRIX
200 1st Ave West
Seattle, WA, 98119
206-239-0276 | Fax 206-269-0098
www.cardnoentrix.com

Date: February 21, 2012

To: Kevin Long (NOSC)

cc: Rebecca Benjamin (NOSC)

From: Tim Abbe, CardnoENTRIX, Chad Krofta, Cardno ENTRIX, George Fowler, Cardno ENTRIX

Re: **Snow Creek Tidal Hydrology**

This memorandum summarizes the results of a tidal study performed by Cardno ENTRIX for the Snow Creek Estuary Restoration Project (Project). The recommendations and estimates provided are based on the data available to Cardno ENTRIX at the time of this memorandum. Therefore, these results should only be used in conjunction with a good understanding of the assumptions and limitations guiding this analysis.

Snow Creek Tidal Hydrology

The Project is located adjacent to the tidally influenced Discovery Bay, an inlet of the Strait of Juan de Fuca. Water surfaces within the Project area are either directly influenced by an influx of sea water or indirectly influenced by the fluctuating downstream water surface. Accurate estimates of site specific tidal elevations are essential for predicting the location of salt marsh habitat and assessing inundation extents because salt marsh vegetation communities are commonly established above frequently inundated areas that can be correlated to statistical measures of the local tide elevation statistics (also referred to as tidal "datums") such as mean high water (MHW) or mean higher high water (MHHW) (Orr et al. 2003). At the time of this memo Cardno ENTRIX was not aware of any site specific tidal studies or tide tables that provide site specific tidal elevation statistics for this area. Therefore, two approaches were considered to develop local tidal statistics for the Project area.

The first method utilizes existing National Oceanic and Atmospheric Administration (NOAA) tidal gages at Port Angeles, Port Townsend and Gardiner Bay as surrogates for the Snow Creek site. This method is similar to the methodology employed by the Washington Department of Fish and Wildlife (WDFW) in their hydraulic report entitled "US 101 at Salmon Creek – Estuary Restoration and Snow Creek Reconnection Hydraulic Report" (Barnard 2007). This report made estimates of tidal datum elevations locally at the Snow and Salmon Creek estuary based on a tide gage at Port Townsend, WA. For reasons described in the following sections, it was determined that existing tide gages do not provide sufficient data for this project and should not be used as a surrogate. Therefore, neither the WDFW estimates nor other existing surrogate data was used to

develop the tidal statistics for this project. Instead, a more detailed site specific approach was employed. The second approach utilizes data obtained from four water level monitoring devices, installed to track the tidally influenced water surface elevation at the Snow Creek site to develop localized tidal statistics using published NOAA methodology. These methods and their results are discussed in the following sections.

1.1 Evaluation of Existing NOAA Gages

There are three NOAA tidal gages near the Snow Creek project area. Two of the gages are control stations and the third is a subordinate station. Table 1 shows the type of station and the straight line distance to the project site.

Table 1: NOAA Surrogate Tidal Gages

Station Name	NOAA Station Number	Station Type	Latitude	Longitude	Distance To Site (mi)
Port Townsend, WA	9444900	Control	48°06'58.23" N	122°45'05.43" W	10.6
Gardiner Bay, Discovery Bay, WA	9444705	Subordinate	48°03'23.37" N	122°54'35.32" W	4.2
Port Angeles, WA	9444090	Control	48°0729.57"' N	123°26'19.52" W	27.0

Control stations are locations where there is a measuring device that records real time water surface elevations relative to the elevation of the recording device. The Port Townsend and Port Angeles tidal gages are control gages and have been recording data since 1952 and 1975 respectively. These devices have also been physically surveyed and referenced to the North American Vertical Datum of 1988 (NAVD 88). NAVD 88 is a vertical control datum of orthometric height that allows comparison of ground surface elevations for sites across the United States.

The Gardiner tidal station is a subordinate tidal station. Tidal predictions at the subordinate Gardiner station are reported relative to a site specific mean lower low water (MLLW) tidal datum. Additionally, subordinate tidal stations are locations where tidal data has been collected to develop a relationship between the subordinate location and a control station. A longer tidal series at a subordinate station allows a higher level of accuracy of the tidal predictions for that site. Generalized subordinate station tidal elevation accuracies for the west coast of the United States relative to the length of the tide series record are listed in the table below (NOAA 2003).

Table 2: Generalized Subordinate Station Tidal Elevation Accuracy for the West Coast of the United States (NOAA 2003)

Subordinate Station Tidal Series Length (months)	Vertical Tidal Accuracy (West Coast) (ft)
1	0.13
3	0.11
6	0.08
12	0.06

Tidal elevations were compared between Gardiner Bay and Port Townsend in order to determine if either of the two sites could be used as a surrogate for the Snow Creek Project area. These stations were selected for comparison because they are the closest gages to the Project site. In fact, the Gardiner Bay station is located within Discovery Bay, 3.2 miles from the outlet to the Strait of Juan de Fuca while the Snow Creek Project area is located deeper within Discovery Bay and 7.5 miles from the Strait. The following sections describe the methods and results of this comparison analysis.

1.1.2 Methods

Since tidal datums/statistics (MLLW, MHHW, etc.) are arithmetic means of the local tide characteristics at a particular location, they are site specific and are not "level" or equal. In other words, MLLW at one location is not level in space with MLLW at another location and the two datums cannot be directly compared (NOAA 2011a). Geodetic datums such as NAVD 88 are "level" which allows a comparison between elevations across the United States. The relationship between a site specific MLLW tidal datum and a “level” orthometric datum such as NAVD 88 is not immediately known unless the station was also physically surveyed relative to the NAVD88 datum. The relationship between the tidal and geodetic datums at the Port Townsend control station is known because the recording device was physically surveyed relative to the NAVD 88 datum. The relationship between orthometric and tidal datums at Port Townsend is provided in Figure 1 below (NOAA 2011b).

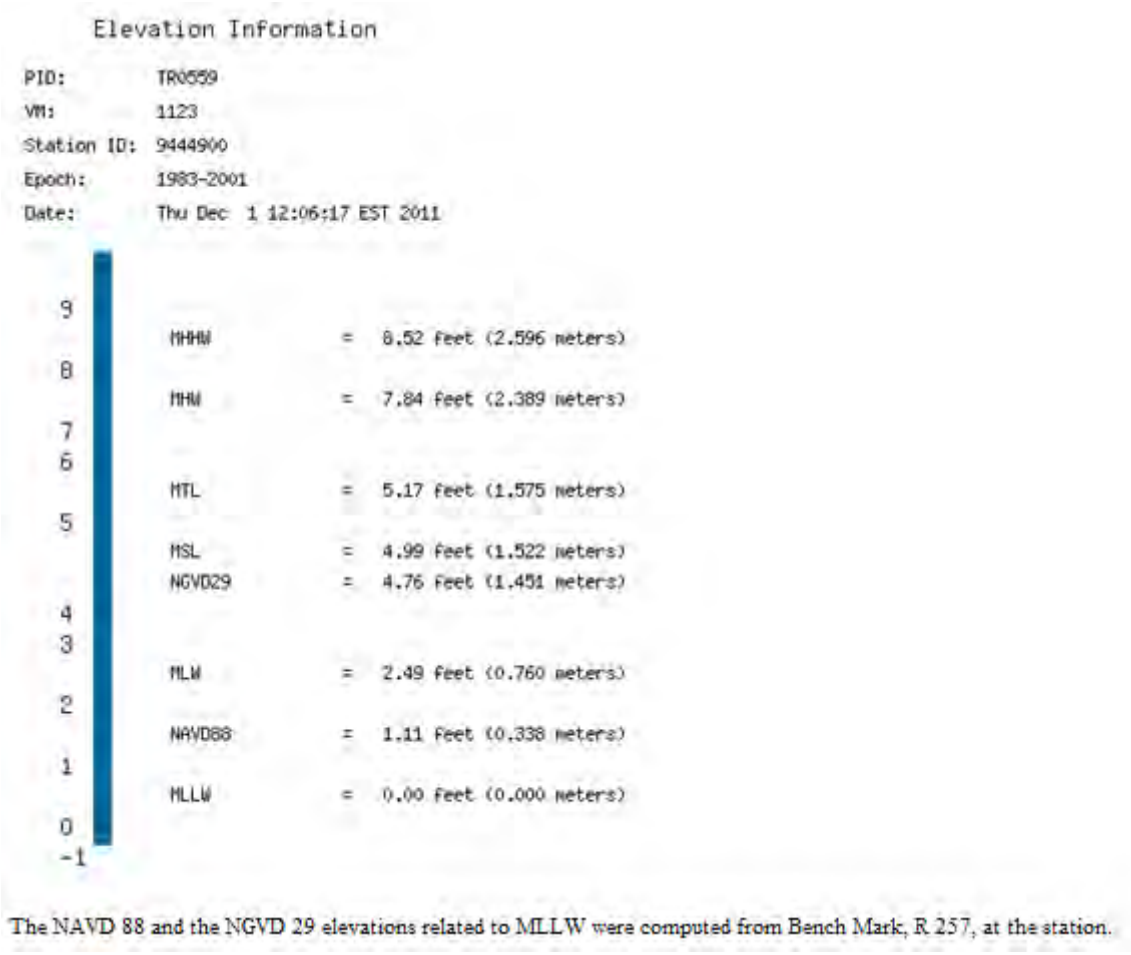


Figure 1: Relationship Between Tidal and Orthometric Datums at Port Townsend (NOAA 2011b)

Because measured tidal elevations at the subordinate Gardiner station are only reported relative to a local MLLW datum, NOAA's VDatum software program was used to estimate the relationship between MLLW at Gardiner and the NAVD88 datum.

VDatum is designed to vertically transform geospatial data among a variety of tidal, othometric and ellipsoidal vertical datums (NOAA 2011b). VDatum uses known differences between tidal and orthometric vertical datums at NOAA control tidal stations and interpolates between the control points to predict differences between tidal and orthometric datums elsewhere. This conversion program should be used with caution, however, because this methodology interpolates data over long distances and between control stations with locally varying tidal behavior.

1.1.3 Results and Conclusions

NOAA has not published tidal statistics such as mean higher high water (MHHW), mean high water (MHW), mean tide level (MTL), mean sea level (MSL), or mean low water (MLW) for the Gardiner site. Therefore published tidal measurements for the month of September 2011 at the Gardiner and Port Townsend gages were compared. The tidal elevations (NAVD 88) reported

by NOAA at Port Townsend and the VDatum converted NOAA tidal elevations for Gardiner are presented in Figure 2 below.

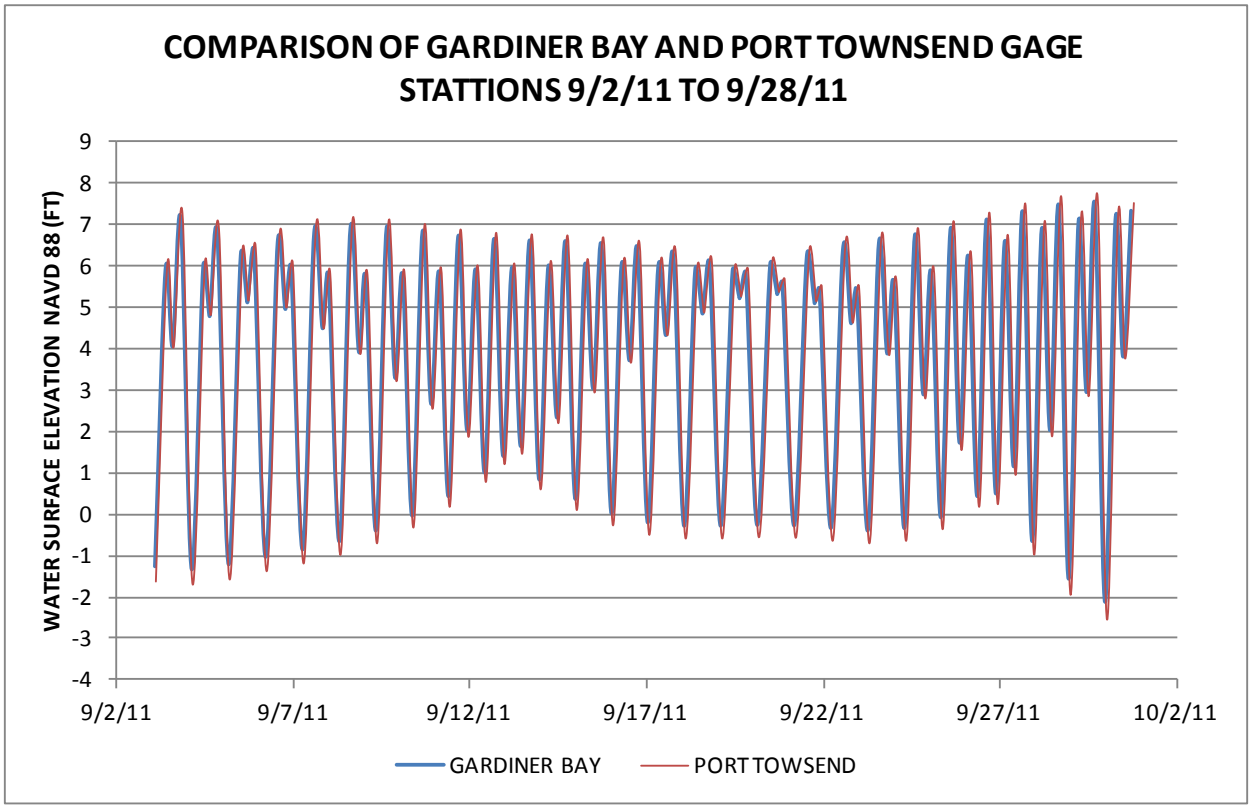


Figure 2: Tidal Elevations Measured by NOAA at Gardiner and Port Townsend during September 2011

The peak tidal elevations (highs and lows) at these two sites during the September 2011 tidal cycle were compared statistically (Table 3).

Table 3: Statistics Describing the Difference in Tidal Elevations at Two NOAA Gage Sites during September 2011

Tide	Maximum (ft)	Minimum (ft)	Median (ft)	Mea (ft)
High	0.22	-0.01	0.14	0.13
Low	0.08	-0.50	-0.17	-0.17
(-) Number= Port Townsend WSE is lower				

Analysis of Figure 2 and Table 3 reveals that high tides at Port Townsend are generally higher than at Gardiner while the low tides are generally lower than at Gardiner. The muted tidal range at Gardiner Bay is likely due to its location 3.2 miles inside Discovery Bay and away from the Strait of Juan de Fuca. Port Townsend is located along the Strait. Because the Snow Creek Project site is located 7.5 miles inside Discovery Bay, even farther away from the Strait than Gardiner, it is likely that the tidal behavior is significantly different than both NOAA sites. Therefore a site specific subordinate tidal study should be conducted.

1.2 Subordinate Tidal Gage Study at Snow Creek

Because an acceptable surrogate tidal gage was not available for the project area as described above, Cardno ENTRIX performed a study of temporary subordinate tidal gages installed within the Snow Creek Estuary in order to establish site specific tidal statistics relative to NAVD 88. The following sections describe the methods and results of this analysis.

1.2.1 Methods

On September 3, 2011, Cardno ENTRIX, installed 4 pressure transducer tide gauges ("pressure transducers" and "gauge" will be used interchangeably for the rest of this memo) and 1 barometric pressure gauge at the Snow Creek project site. The 4 tide gauges were then physically surveyed using a total station set up relative to Washington State Department of Transportation (WSDOT) monument 6511to determine their elevation on the NAVD 88 datum. On October 3 another barometric gauge was installed because the first barometric gauge had become damaged and lost when the project site was cleared of brush. Each tide gauge consisted of a Solinst Levellogger Junior data-logging pressure gauge secured within a perforated PVC pipe stilling well installed at the ground surface. The barometric gauges, Solinist Barologgers, were installed on dry land above tidal and river flow influence. Figure 3 displays a photograph of a typical tide gauge installation.



Figure 3: Typical Tide Gage Installation

The gauges recorded several different parameters at set time intervals over the period September 3, 2011 to November 15, 2011. Table 4 describes the gauges, their locations, and function. The locations of these tide gauges are shown in Figure 4.

Table 4: Tidal Monitoring Gauge Installations at Snow Creek

Gage #	Pressure Transducer Name	Measurement 1	Location	Time Interval	Sampling Duration
1	Bay Pole	Level, Temperature	In Discovery Bay	6 min	9/3/11-11/15/11
2	Artesian Well Ditch	Level, Temperature, Conductivity	Downstream of Pond, at Railroad Bridge	6 min	9/3/11-11/15/11
3	Snow Creek Lower	Level, Temperature	200' Dowstream of Railroad Bridge	6 min	9/3/11-11/15/11
4	SR 20	Level, Temperature	75' Upstream of SR 20 Bridge	6 min	9/3/11-11/15/11
5	Barologger Gold	Level, Temperature	On JLT Property	6 min	9/3/11-?
6	Barologger Edge	Level, Temperature	On JLT Property	15 min	10/3/11-11/15/11

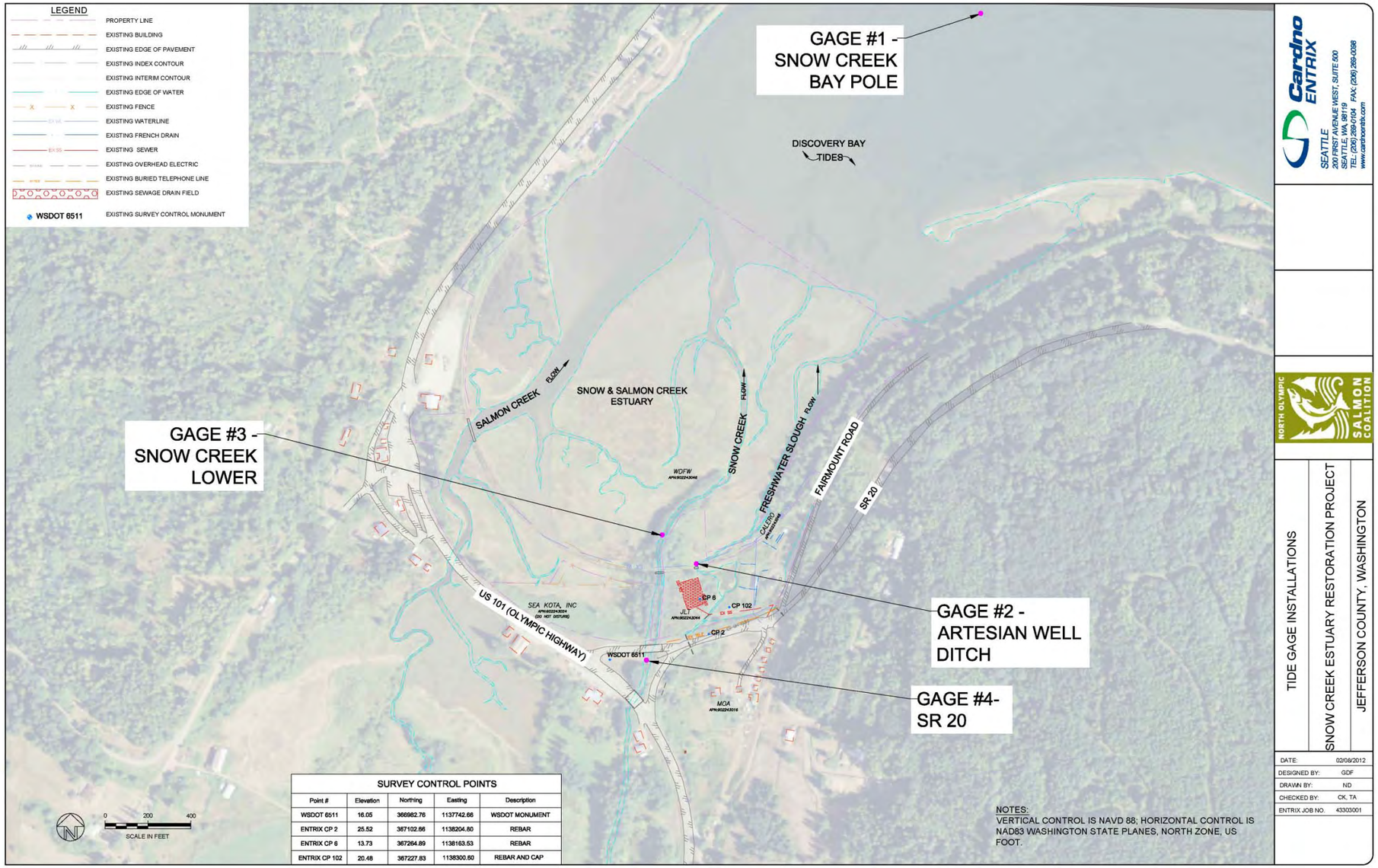


Figure 4: Location of Tidal Gages in the Snow Creek Project Area

Measured depth/level (which can be converted to a water surface elevation on the NAVD 88 datum by adding it to the known gage elevation) is a function of the density of the fluid (air or freshwater or seawater) and the height of the fluid above the pressure transducer membrane. Barometric pressure data is also necessary in order to determine the air pressure influence on the water level gages. This pressure must be removed from the measured depth/level in order to obtain an accurate water depth/level. Equation 1 shows how measured depth and fluid density are related.

Equation 1: Relationship between Measured Depth and Measured Parameters

$$Measured\ depth\ (ft) = \ pressure\ \left(\frac{lbs}{ft^2}\right) \div fluid\ density\ \left(\frac{lbs}{ft^3}\right)$$

Pressure transducers 1-5 recorded water level and temperature every 6 minutes from installation on September 3, 2011 until November 15, 2011. Transducer #2 in the artesian well ditch also measured conductivity because it was assumed this area is inundated with both sea and freshwater. Conductivity can be used as a surrogate measure of salinity and thus, density. Pressure transducer #5 (Barologger Gold) measured barometric pressure and was lost when the site was cleared of brush. Pressure transducer #6 was installed on October 3, 2011 and recorded barometric pressure data every 15 minutes until November 15, 2011.

Measured depth/level data from gauges 1-4 was collected and converted to water surface elevations on the NAVD 88 datum by utilizing the relationship described in Equation 1 above.

To determine tidal statistics and tidal predictions at subordinate tide gage locations, NOAA has published methods that relate tidal harmonics at an area of interest with tidal harmonics at an established permanent control NOAA tidal gage (NOAA 2003). To complete this approach, a subordinate tidal station is compared to the nearest NOAA control station – in this case, Port Townsend, WA.

As will be described in more detail below, sufficient low tide information was not recorded by the temporary subordinate tide gages at the Snow Creek site. Therefore, in instances when a full range of tidal values are not available for the subordinate site and the tidal record is less than 40 days, NOAA provides a direct method for computing individual high tide statistics at the subordinate site known as a "tide by tide comparison" (TBYT). The equations for computation of MHW and MHHW using the TBYT procedure are contained in Equations 2 and 3 below.

Equation 2: Computation of MHW for a Subordinate Tide Station using TBYT (NOAA, 2003)

$$MHW_{CORRECTED\ FOR\ A} = MHW_{\ ACCEPTED\ FOR\ B} + \left(\frac{1}{N}\right) \int_{I=1}^{N} (HW_A(I) - HW_B(I))$$

Equation 3: Computation of MHHW for a Subordinate Tide Station using TBYT (NOAA, 2003)

$$MHHW_{CORRECTED\ FOR\ A} = MHHW_{\ ACCEPTED\ FOR\ B} + (\frac{1}{N}) \int_{I=1}^{N} (HHW_A(I) - HHW_B(I))$$

Where:

$$MHW_{CORRECTED\ FOR\ A} = Calculated\ MHW\ For\ Subordinate\ Station$$
$$MHHW_{CORRECTED\ FOR\ A} = Calculated\ MHHW\ For\ Subordinate\ Station$$
$$MHW_{\ ACCEPTED\ FOR\ B} = Known\ MHW\ Datum\ For\ Control\ Station$$
$$MHHW_{\ ACCEPTED\ FOR\ B} = Known\ MHHW\ Datum\ For\ Control\ Station$$
$$HW_A = Recorded\ MHW\ At\ Subordinate\ Station\ During\ Period\ of\ Record$$
$$HW_B = Recorded\ MHW\ At\ Control\ Station\ During\ Period\ of\ Record$$
$$HHW_A = Recorded\ MHHW\ At\ Subordinate\ Station\ During\ Period\ of\ Record$$
$$HHW_B = Recorded\ MHHW\ At\ Control\ Station\ During\ Period\ of\ Record$$
$$N = Number\ of\ Indiviudal\ Tides\ During\ Period\ of\ Record$$

NOAA provides data for the $MHW_{ACCEPTED\ FOR\ B}$, $MHHW_{ACCEPTED\ FOR\ B}$, MHW_B and $MHHW_B$ variables in the above equations for the control station. Data for the MHW_A and $MHHW_A$ variables in the above equations must be extrapolated from the subordinate station record. To establish an accurate relationship, at least one month of tidal data needs to be collected at the subordinate station. The generalized vertical error associated with tidal records of varying length is displayed above in Table 2 (NOAA 2003).

The estimated tidal vertical accuracies listed in Table 2 (Generalized Accuracies of Tidal Datums) can be translated into a horizontal accuracy for the location of a tidal boundary when the tidal datum line is surveyed to the land (NOAA 2003). The error associated with locating the horizontal extents of the tidal boundary is described in Equation 4, and the NOAA published horizontal errors in estimating tidal boundary extents as a function of land slope are displayed in Table 5 which displays the expected horizontal error if using the vertical error associated with one month of data collection, 0.13'.

Equation 4: Horizontal Accuracy of Tidal Boundary Extents When Estimated from Subordinate Tidal Measurement Data (NOAA, 2003)

$$\Delta x \sim \Delta y \frac{x}{y} = \Delta y cot(\propto)$$
$$\Delta x = horizontal\ error$$
$$\Delta y = vertical\ error$$
$$\frac{x}{y} = reciprocal\ of\ slope$$
$$\propto = degree\ of\ slope$$

Table 5: Horizontal Error in Estimating Tidal Boundary Extents When Estimated from Subordinate Tidal Measurement Data as a Function of Land Slope (NOAA, 2003)

% of slope	Degree of slope	Horizontal Error
%	degree	ft
0.1	0.05	149.0
0.2	0.1	74.5
0.5	0.3	24.8
1	0.6	12.4
2	1	7.4
10	6	1.2
50	30	0.2

The slope of the land within the Project area from the edge of the mud flats to the northern edge of the rail road grade (expected area where the higher tidal datums would end) is generally between 0.2% to 0.3% as estimated from the 2002 Puget Sound LIDAR Consortium (PSLC) topographic data. Therefore, for a vertical tidal accuracy of 0.13' (1 month of subordinate data) the estimated horizontal error for locating a tidal boundary along the existing topography is between 75 and 59 feet using Table 5. An understanding of this potential error is important for designing restored estuarine features.

1.2.2 Results and Conclusions

Gauge #1 – Bay Pole

Gauge #1 (Bay Pole) was located on a power pole within the saline Discovery Bay approximately 2,250 feet north of the project area. This gage was installed within the Bay in order to capture the tidal behavior in the vicinity of the project area without influence from any river or freshwater sources. Figure 5 depicts the measured tidal behavior at the Bay Pole site within Discovery Bay. Forty tidal days were recorded during the time period.

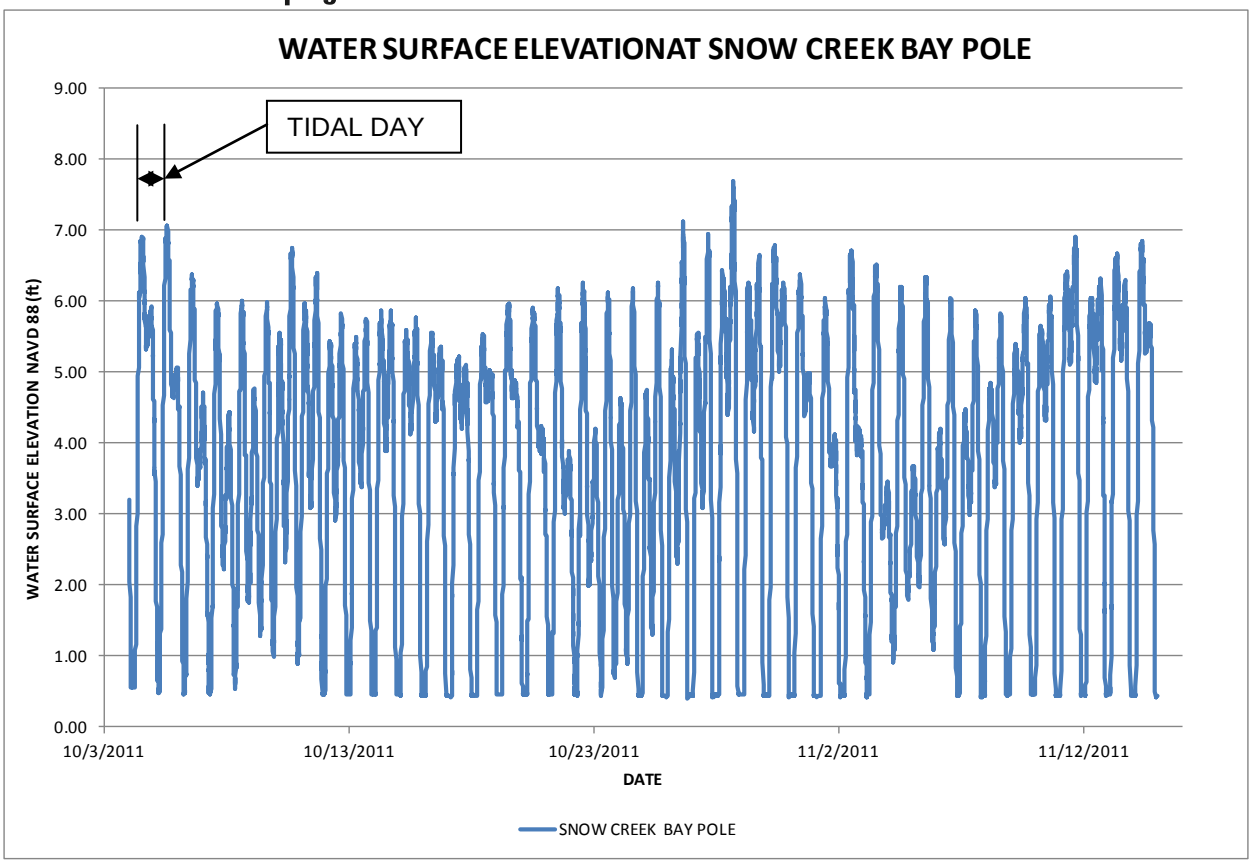


Figure 5: Measured Water Surface Elevation at the Bay Pole Site (Gauge #1)

Visual analysis of Figure 5 reveals that the project site experiences a diurnal tidal cycle typical of the west coast of the United States where two high and two low tides occur each tidal day. The heights are designated as higher high water, lower high water, higher low water and lower low water (NOAA 2003). Table 6 provides statistics of measured tidal water surface elevations for the period of record at the Bay Pole site.

Table 6: Statistics of Measured Water Surface Elevations at the Bay Pole Site (Gauge #1)

TIDAL ELEVATION (NAVD 88 FT)				
Tide	Maximum	Minimum	Median	Mean
High high	7.68	5.34	6.26	6.31
Low high	6.44	3.44	5.18	5.16
High low	5.32	0.70	3.78	3.50
Low low	1.89	0.43	0.46	0.57

The highest tide occurred with the new moon on October 26, 2011 and the lowest tide was not measureable due to the ground surface at the Bay Pole site being higher than the elevation of the lowest low tide. In Figure 5 it is evident that the pressure transducer did not record below the

elevation of 0.43' NAVD 88 because this was the elevation of the pressure transducer membrane and the ground surface. When the water surface elevation dropped below the membrane, the transducer effectively recorded ambient air pressure. During the period of record, 40 lower low tides were recorded, 33 of these tides were below the pressure transducer membrane. Without the data for the lower low tides, the tidal statistics, MLLW, MLW and MSL cannot be calculated. In most restoration projects, however, desired salt marsh vegetation communities are established above frequently inundated areas, i.e. MWH or MHHW tides. (Fetherston et al. 2001) Therefore, the MLLW, MLW and MSL statistics are not considered crucial to this project and have not been estimated.

Gauge #2 – Artesian Well Ditch

Gauge #2 (Artesian Well Ditch) was located within the artesian well drain channel just below the railroad grade footbridge. This gage measured conductivity (salinity) and was installed within the ditch in order to capture the seawater and freshwater tidal flux behavior in the vicinity of the project area. Figure 6 shows the relationship between Snow Creek Bay Pole (Gauge #1) and the artesian well ditch (Gauge #2) during the recorded period.

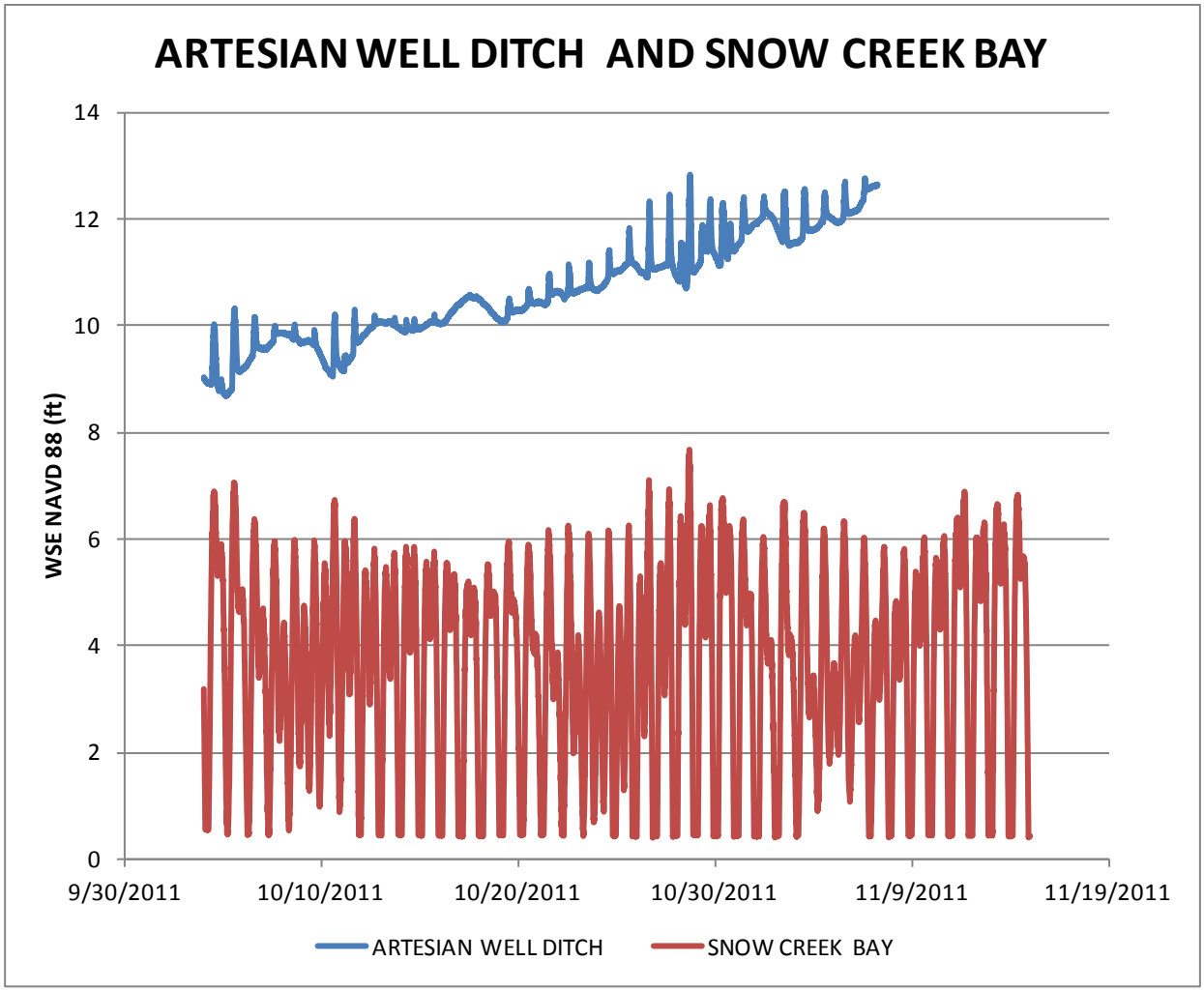


Figure 6: Measured Water Surface Elevation at the Artesian Well Ditch (Gauge #2)

The gage in the ditch shows a unique upward trend in water surface elevation which is not seen in any of the other gages. Cardno ENTRIX spoke with Solinst, the manufacturer of the pressure transducers, and they believe the pressure transducer failed and was not recording pressure accurately.

The peaks in water surface elevation at this gage do align with the tidal peaks measured at Gauge #1, which may indicate that this area is tidally influenced. Since the gauge may have failed and the actual water surface elevation at this time is unknown no further conclusions about the tidal activity can be drawn from this gauge.

Gauge #3 – Snow Creek Lower

Gauge #3 (Snow Creek Lower) was located within the Snow Creek channel approximately 175' downstream of the railroad grade footbridge. This gage did not measure conductivity (salinity) and was installed within the channel in order to capture the tidal impacts within the active creek

channel at the project area. Figure 7 shows the relationship between Snow Creek Bay Pole (Gauge #1) and the Snow Creek Lower (Gauge #3) during the record period. For comparison, 15 minute discharge data was obtained from Washington Department of Ecology (WDOE) (station ID 17E060) and plotted along with the measured pressure transducer data. Because this gage did not measure conductivity (salinity), however, tidal elevations displayed below are for comparison purposes only. Without salinity measurements and when both fresh and salt water are present, density corrections cannot be made and the pressure transducer data cannot be accurately converted to an elevation. Forty tidal days were recorded during the time period.

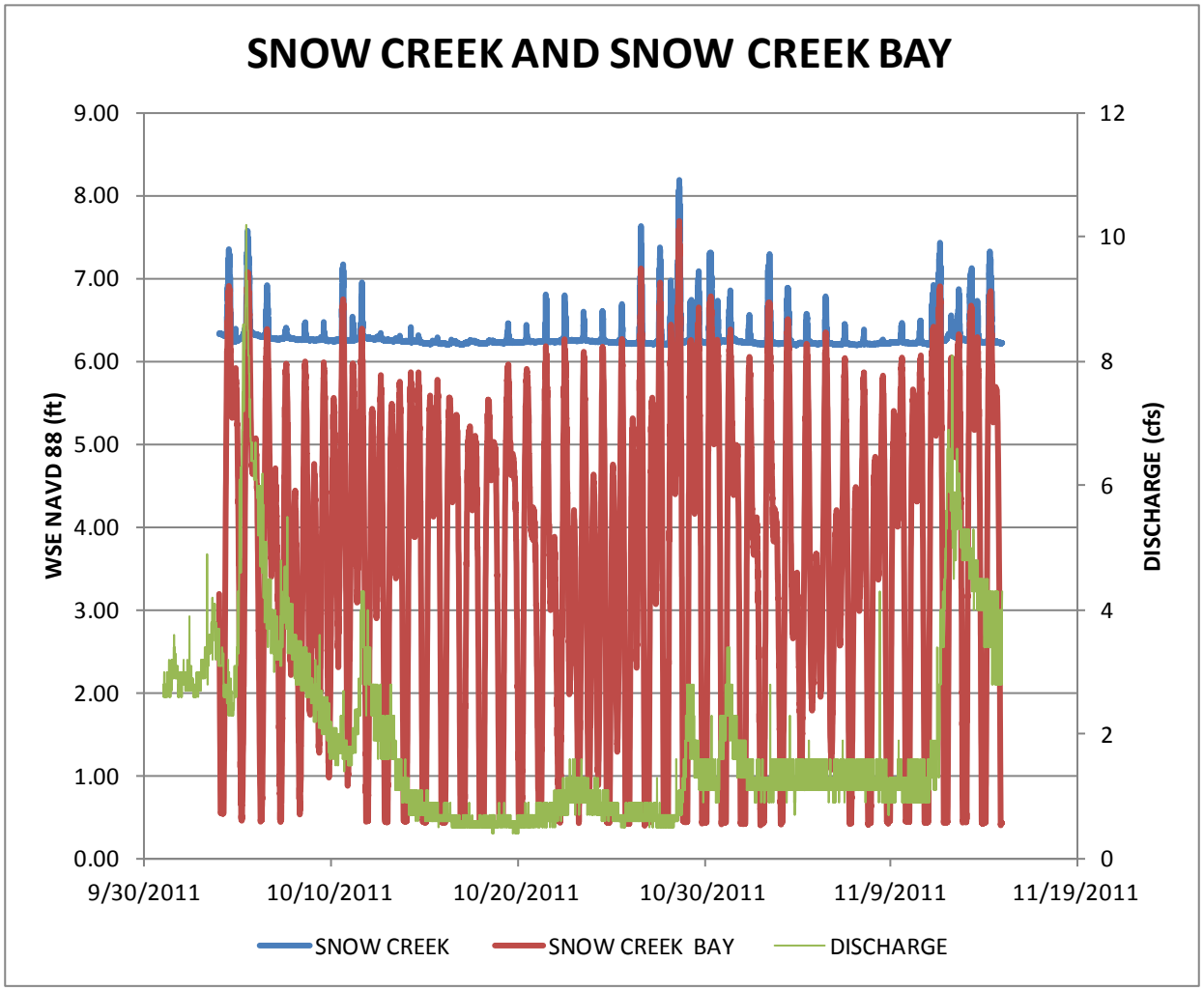


Figure 7: Measured Water Surface Elevation at Snow Creek Lower (Gauge #3) Compared to Data at Snow Creek Bay Pole (Gauge #1) and Discharge Data Reported by WDOE Station 17E060

Visual inspection of Figure 7 reveals a tidally influenced Snow Creek at this location. Peak measurements correspond well with peak tidal measurements made at Bay Pole (Gauge #1) but do not appear to correspond with spikes in the measured discharge. This observation would indicate that the spikes in the water surface elevation at the Snow Creek gage are due to tidal influence and not changes in the freshwater discharge. Because no salinity measurements were

taken at this location no further conclusions about the tidal activity can be drawn from this gauge and the absolute value of the measured tidal elevations displayed above for Gauge #3 should be disregarded.

Gauge #4 – Snow Creek Upper

Gauge #4 (Snow Creek Upper) was located within the Snow Creek channel approximately 35' upstream of the State Route (SR) 20 bridge. This gage did not measure conductivity (salinity) and was installed within the channel in order to capture the tidal impacts within the active creek channel at the project area. Figure 8 shows the relationship between Snow Creek Bay Pole (Gauge #1) and the Snow Creek Upper (Gauge #4) during the record period. For comparison, 15 minute discharge data was obtained from Washington Department of Ecology (WDOE) (station ID 17E060) and plotted along with the measured pressure transducer data. Because this gage did not measure conductivity (salinity), however, tidal elevations displayed below are for comparison purposes only. Without salinity measurements and when both fresh and salt water are present, density corrections cannot be made and the pressure transducer data cannot be accurately converted to an elevation. Forty tidal days were recorded during the time period.

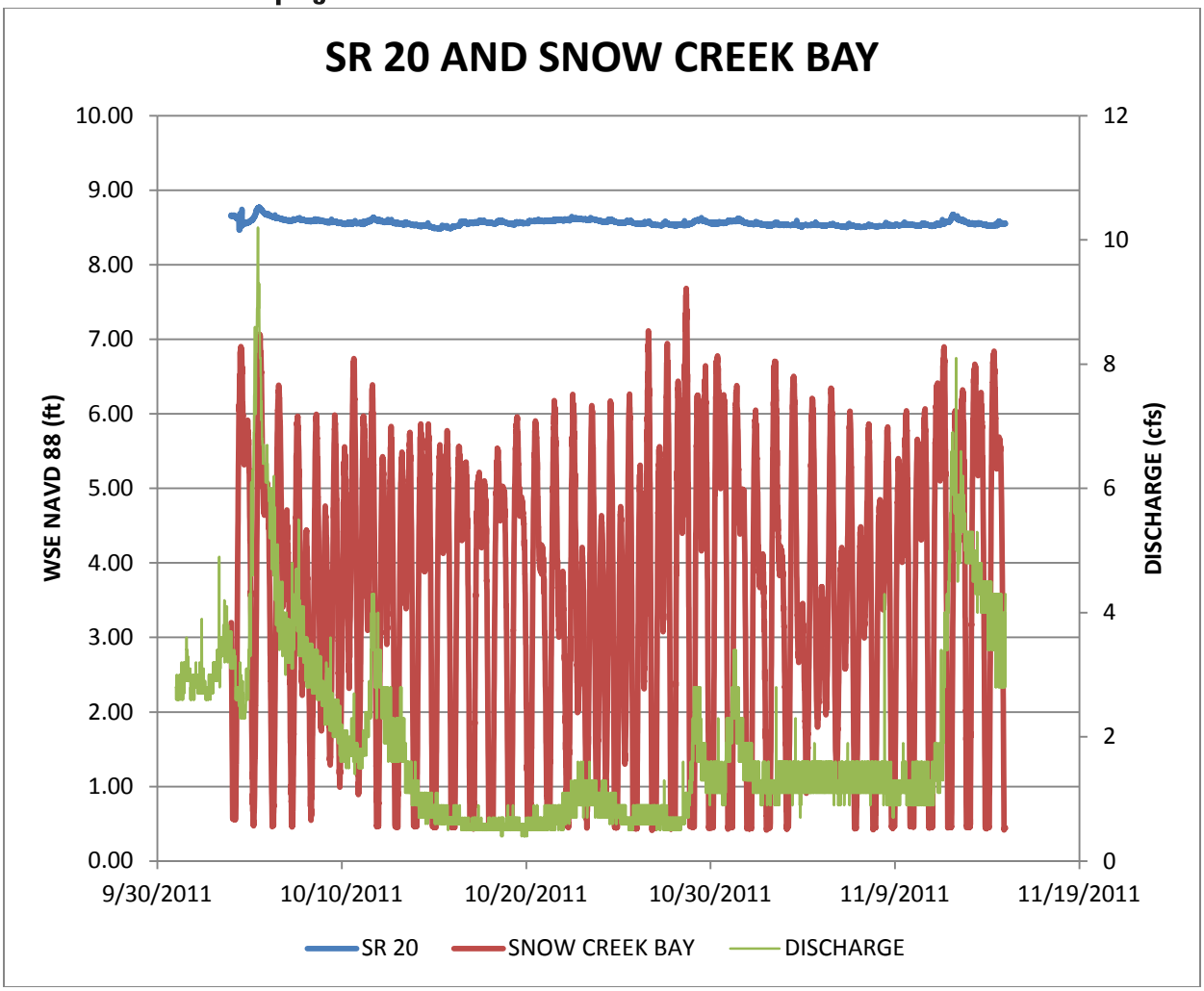


Figure 8: Measured Water Surface Elevation at Snow Creek Upper (Gauge #4) Compared to Data at Snow Creek Bay Pole (Gauge #1) and Discharge Data Reported by WDOE Station 17E060

Visual inspection of Figure 8 reveals that the tidal influence may not extend upstream of SR 20. On the highest recorded tide at Gauge #1 (October 28, 2011), the water surface in the creek at this location did not increase above its average elevation. This observation would indicate that Snow Creek is not tidally influenced at this location.

Tidal Datum Calculations

The NOAA tide by tide comparison calculations described above were utilized to estimate tidal statistics at the Snow Creek Project site based on the Port Townsend, WA NOAA control station and the Snow Creek Bay Pole (Gauge #1) subordinate station. Gauge #1 was selected as the subordinate station because it was the only temporary tidal gauge installed at Snow Creek that was not influenced by freshwater flows and therefore, recorded only the incoming and outgoing

tidal water surface elevations. Figure 9 compares Snow Creek Bay Pole's measured water surface elevation to the NOAA measured water surface elevations at Port Townsend over the 40 day recording period. Table 7 displays Port Townsend's tidal statistics during the same time period.

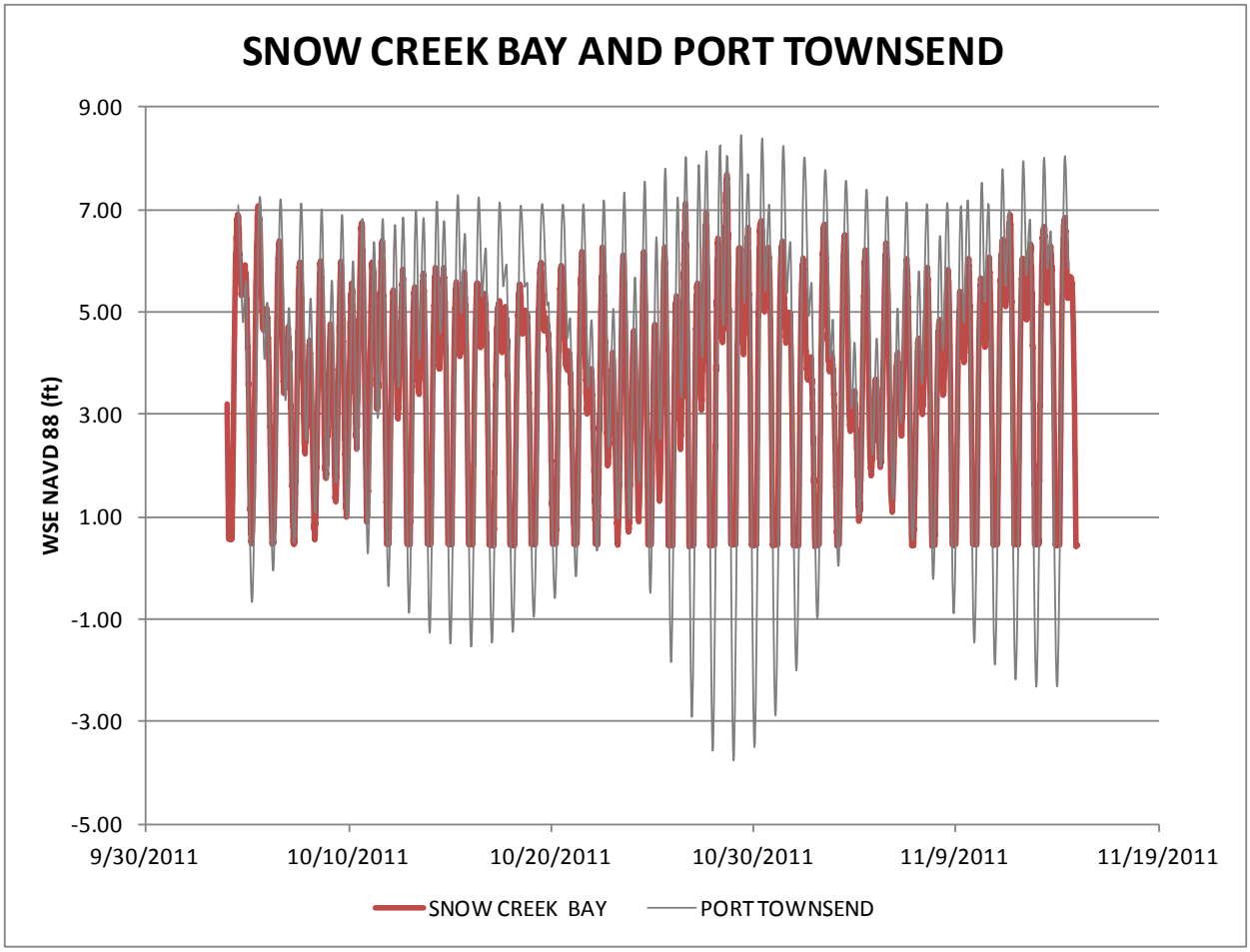


Figure 9: Comparison of Measured Water Surface Elevation at Snow Creek Bay Pole (Gauge #1) and NOAA's Port Townsend, WA Control Gauge.

Table 7: Statistics of NOAA Measured Water Surface Elevations at Port Townsend, WA

ELEVATION (NAVD 88FT)				
TIDE	MAX	MIN	MEDIAN	MEAN
HIGH HIGH	8.14	6.77	7.16	7.33
LOW HIGH	7.79	4.08	6.16	6.00

Calculations to determine the MHHW and MHW at the Snow Creek project site followed the direct method using the tide by tide comparison (TBYT). Inputs and outputs for these

calculations can be seen in Appendix 1. The estimated MHHW and MHW tidal statistics at the Snow Creek project site are 6.38' and 5.76' (NAVD 88) respectively. These statistics and the maximum tide recorded in the monitoring period are seen in Table 8. The maximum tide recorded during this period should not be confused with the maximum tide expected at this area.

Table 8: Tidal Elevations at the Snow Creek Project Site and Port Townsend

Location NAVD 88 (ft)		
Tidal Elevation	Snow Creek Bay	Port Townsend
MHW	5.76	6.73
MHHW	6.38	7.41
Max Recorded	7.38	8.14

Examination of Figure 9 and Tables 7 and 8, reveal that the high tides at the project site were lower than those at Port Townsend for the period of record. No comparison of low tide can be made due to the subordinate gauge's physical position above the low tide. Furthermore, the reported MHHW at Port Townsend is 1.03 feet higher than the computed MHHW at Snow Creek while the reported MHW is 0.97 feet higher than at Snow Creek. Given the potential horizontal error in mapping horizontal tidal extents based on estimated vertical error in tidal statistics (See Methods Section above), it is clear that using Port Townsend as a surrogate for the project site is not appropriate for this project. Figure 10 shows the extents of the estimated MHHW and MHW tidal datums at the Snow Creek site along with the maximum recorded tide (7.68') during the monitoring period. Figure 10 is a comparison of the three tidal elevations to the existing ground topography. Existing ground topography was obtained from combining total station survey data collected in September 2011 by Cardno ENTRIX with 2002 PSLC LiDAR topographic data.

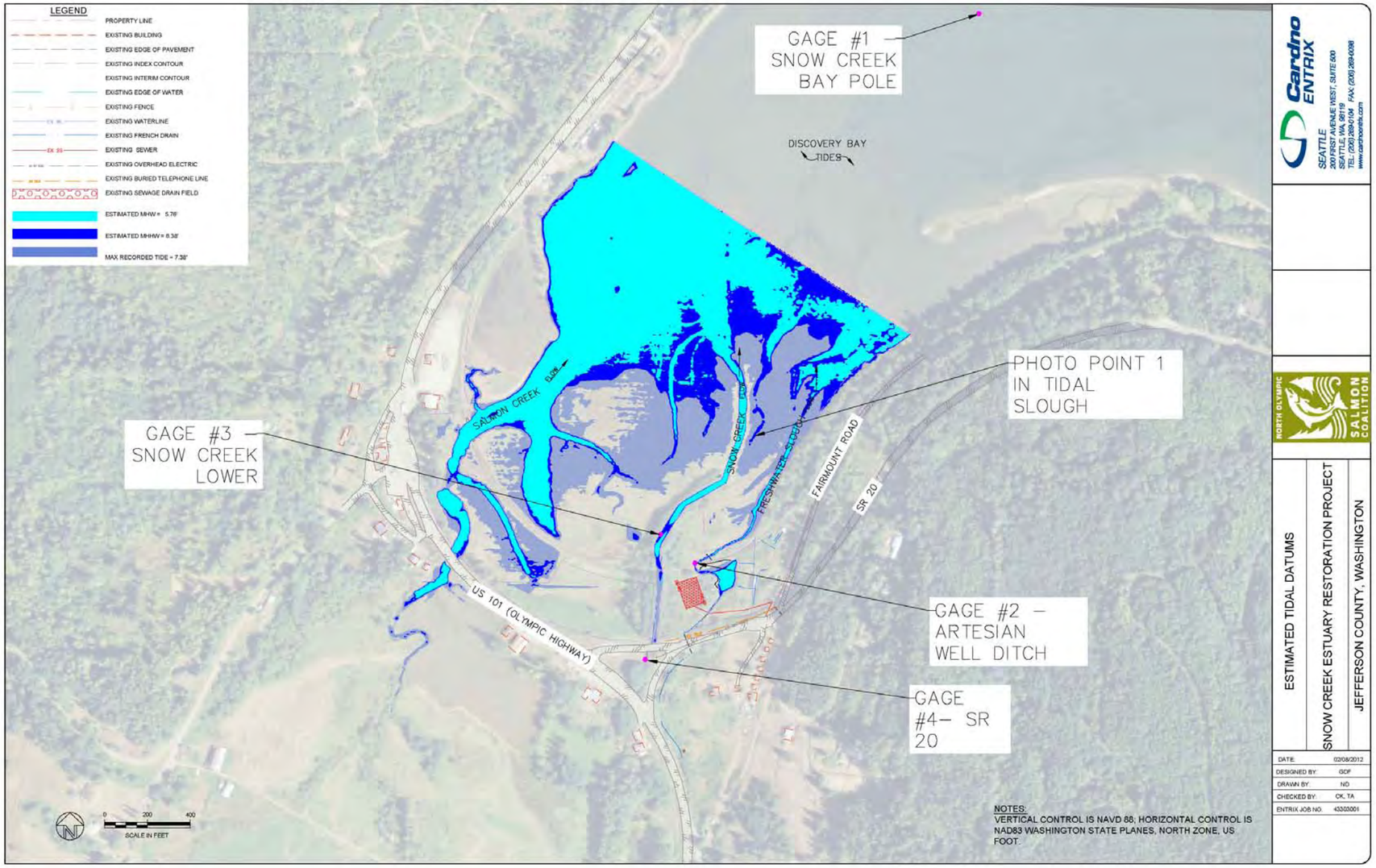


Figure 10: Estimated Existing Tidal Inundation Extents at the Snow Creek Estuary

Calibration of Estimated Tidal Inundation Extents

In order to verify the estimated tidal inundation extents depicted in Figure 10 above, Cardno ENTRIX compared the mapped extents to photographic evidence and mapped vegetation boundaries collected by Cardno ENTRIX during field visits in September 2011.

Figure 11 shows the approximate delineation of mud flats and upland riparian areas delineated in the field. Generally, mudflats can be found in frequently inundated areas and are too wet to support estuarine species and thus are most likely located below the mean higher high tide boundary. Upland areas contain plant species that cannot be frequently inundated and thus are most likely located above the mean higher high tide boundary. Visual examination of Figure 11 reveals a relatively strong correlation between the estimated MHHW boundary and the approximate mud flat boundary. Additionally, a strong correlation exists between the mapped estimated highest recorded tide boundary and the approximate edge of upland vegetation.

Figure 12 is a photo taken on September 29, 2011 at 6:00 p.m.. Its location can be seen on Figure 11 (Photo Point 1). The water surface elevation recorded by Gauge #1was 7.09' (NAVD 88) at the time the photo was taken. In the background of the photo is the tidal slough (labeled tidal slough in Figure 11) completely full of water and running over its banks into the marsh. The elevation of the top of bank of the tidal slough is roughly 6.5-6.7' (NAVD 88) as estimated from the combined Cardno ENTRIX/2002 PSLC LIDAR topography. The elevation of the inundated area in the photo is between 6.7 and 7.2' feet according to the PSLC topography which agrees well with the elevation of the inundated area in Figure 11. The estimated water surface elevation at MHHW is 6.38' which would be contained entirely within the tidal slough as seen in Figure 12. This photo evidence supports the mapped extents of tidal inundation depicted in Figures 9 and 10.

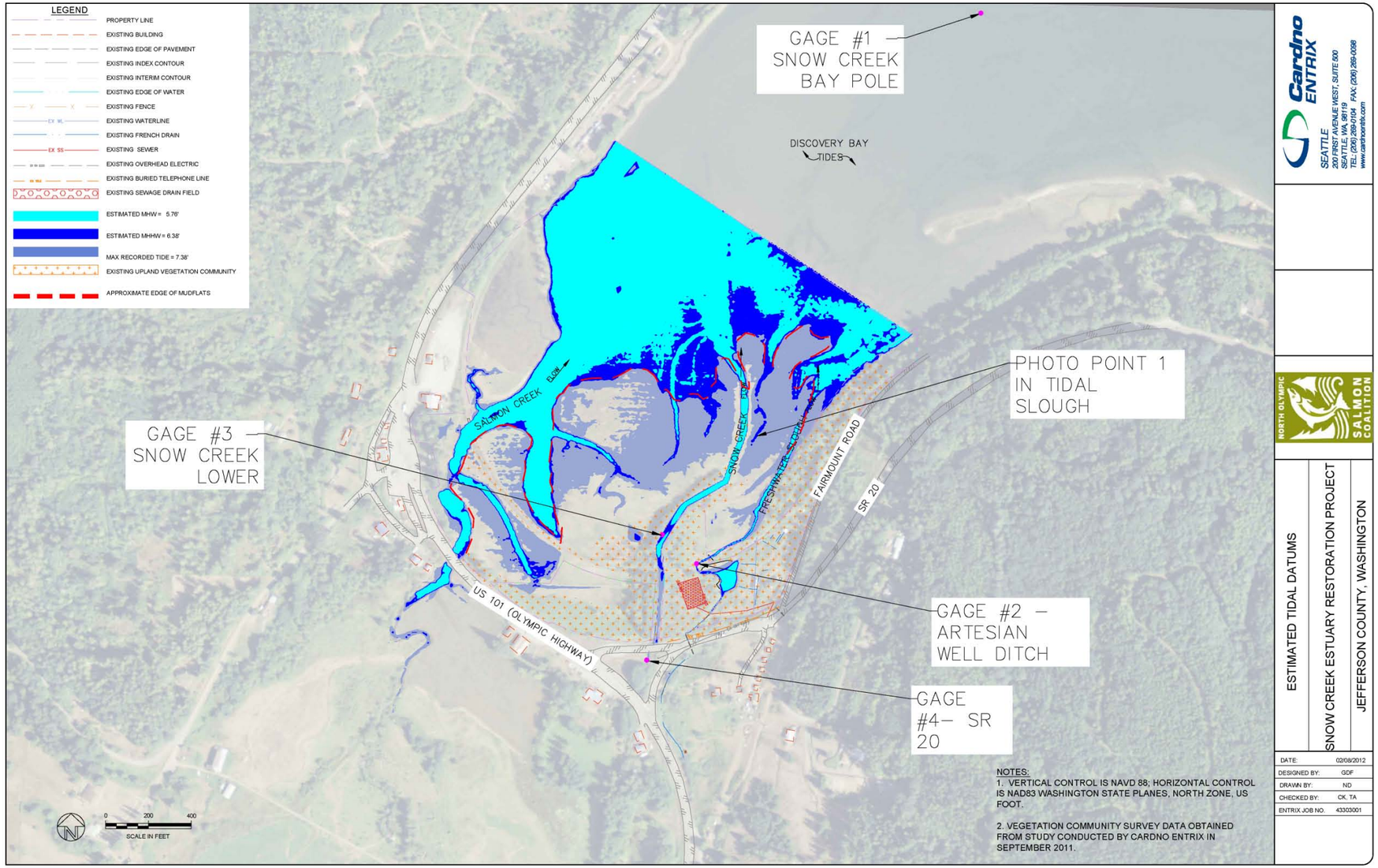


Figure 11: Inundation Areas with Upland Vegetation Community.

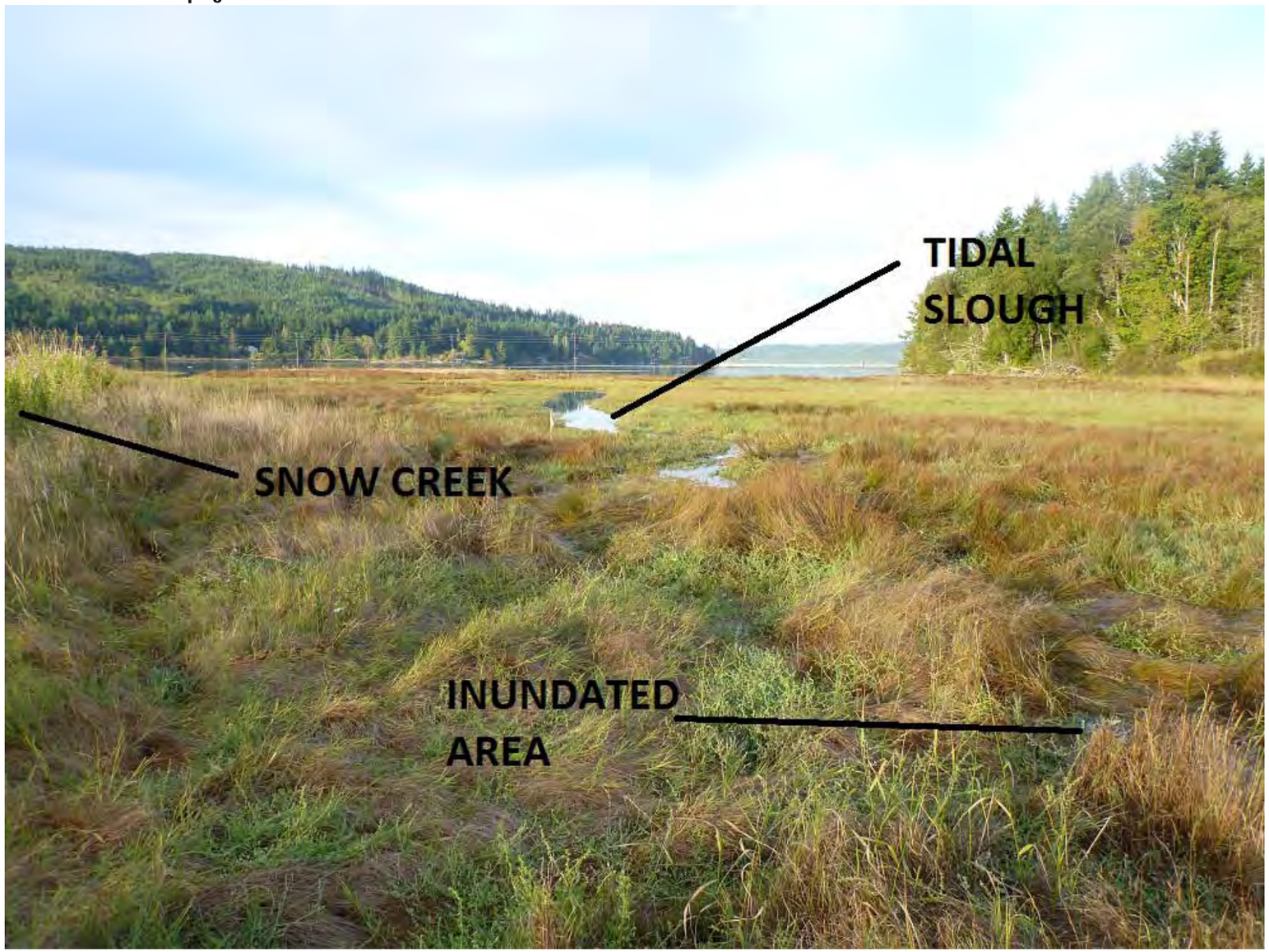


Figure 12: Photo of Snow Creek Estuary Tidal Slough on September 29, 2011 at 6:00 p.m. (Photo Point 1

Cardno ENTRIX

Shaping the Future

References

Barnard, B. 2007. US 101 at Salmon Ck. Estuary Restoration and Snow Creek Reconnection Hydraulic Report. State of Washington Department of Fish and Wildlife.

Fetherston, K.L., T.B. Abbe, and L. Ellis. 2001. Reference Site Study and Conceptual Design Alternatives for Restoration of the Miller Creek Estuary in King County. Prepared for Puget Sound Restoration Fund and King County.

National Oceanic and Atmospheric Administration (NOAA). 2003. Computational Techniques For Tidal Datums Handbook. NOAA Special Publication NOS CO_OPS 2.

National Oceanic and Atmospheric Administration (NOAA). 2011a. Personal Communication.

National Oceanic and Atmospheric Administration (NOAA). 2011b. Estimation of Vertical Uncertainties in VDatum.

Orr, M., Crooks, S, and P.B. Williams. 2003. Will Restored Tidal Marshes Be Sustainable? San Francisco Estuary and Watershed Science Volume 1, Issue 1

Cardno ENTRIX

Shaping the Future

Appendix 1: Tide by Tide Analysis Input Data

PORT TOWNSEND				SNOW CREEK BAY					DELTA
	NAVD88				NAVD 88				
DATE/TIME	WSE (ft)	TIDE	TIDAL DATUMS	Date	WSE (ft)	TIDE	TIDAL DATUMS		BAY-PT
10/4/11 12:35	7.08	H	HH	10/4/11 12:26	6.90	H	HH		-0.18
10/5/11 13:33	7.13	H	HH	10/5/11 12:38	7.07	H	HH		-0.06
10/6/11 14:19	7.15	H	HH	10/6/11 13:38	6.38	H	HH		-0.77
10/7/11 14:56	7.1	H	HH	10/7/11 14:14	5.97	H	HH		-1.13
10/8/11 15:24	7	H	HH	10/8/11 14:02	5.96	H	HH		-1.04
10/9/11 15:44	6.89	H	HH	10/9/11 14:32	5.98	H	HH		-0.91
10/10/11 15:59	6.8	H	HH	10/10/11 15:32	6.74	H	HH		-0.06
10/11/11 16:14	6.77	H	HH	10/11/11 15:50	6.34	H	HH		-0.43
10/13/11 6:39	6.85	H	HH	10/12/11 16:02	5.83	H	HH		-1.02
10/14/11 7:21	7	H	HH	10/14/11 6:38	5.86	H	HH		-1.14
10/15/11 8:05	7.06	H	HH	10/14/11 16:32	5.86	H	HH		-1.20
10/16/11 8:53	7.05	H	HH	10/15/11 16:56	5.77	H	HH		-1.28
10/17/11 9:47	6.98	H	HH	10/16/11 16:56	5.34	H	HH		-1.64
10/18/11 10:46	6.92	H	HH	10/18/11 11:20	5.49	H	HH		-1.43
10/19/11 11:45	6.91	H	HH	10/19/11 12:14	5.96	H	HH		-0.95
10/20/11 12:33	6.95	H	HH	10/20/11 11:50	5.91	H	HH		-1.04
10/21/11 13:11	7.03	H	HH	10/21/11 12:20	6.18	H	HH		-0.85

10/22/11 13:42	7.16	H	HH	10/22/11 12:26	6.26	H	HH		-0.90
10/23/11 14:11	7.33	H	HH	10/23/11 13:14	6.11	H	HH		-1.22
10/24/11 14:40	7.53	H	HH	10/24/11 13:26	6.17	H	HH		-1.36
10/25/11 15:10	7.74	H	HH	10/25/11 14:26	6.27	H	HH		-1.47
10/26/11 15:42	7.89	H	HH	10/26/11 14:56	7.11	H	HH		-0.78
10/27/11 16:17	7.93	H	HH	10/27/11 15:32	6.94	H	HH		-0.99
10/28/11 6:54	8.02	H	HH	10/28/11 16:14	7.68	H	HH		-0.34
10/29/11 7:51	8.14	H	HH	10/29/11 17:14	6.64	H	HH		-1.50
10/30/11 8:48	8.1	H	HH	10/30/11 8:50	6.78	H	HH		-1.32
10/31/11 9:48	7.96	H	HH	10/31/11 9:56	6.38	H	HH		-1.58
11/1/11 10:47	7.79	H	HH	11/1/11 10:32	6.05	H	HH		-1.74
11/2/11 11:43	7.65	H	HH	11/2/11 11:20	6.71	H	HH		-0.94
11/3/11 12:33	7.52	H	HH	11/3/11 11:26	6.49	H	HH		-1.03
11/4/11 13:13	7.38	H	HH	11/4/11 12:38	6.19	H	HH		-1.19
11/5/11 13:45	7.24	H	HH	11/5/11 12:32	6.34	H	HH		-0.90
11/6/11 13:09	7.11	H	HH	11/6/11 13:20	6.04	H	HH		-1.07
11/7/11 13:27	7.03	H	HH	11/7/11 13:44	5.86	H	HH		-1.17
11/8/11 13:45	6.99	H	HH	11/8/11 14:26	5.82	H	HH		-1.17
11/10/11 5:11	7.3	H	HH	11/9/11 14:50	6.04	H	HH		-1.26
11/11/11 5:48	7.57	H	HH	11/11/11 7:26	6.41	H	HH		-1.16
11/12/11 6:24	7.73	H	HH	11/11/11 15:50	6.90	H	HH		-0.83

11/13/11 7:02	7.8	H	HH	11/13/11 7:50	6.67	H	HH		-1.13
11/14/11 7:42	7.81	H	HH	11/14/11 8:56	6.84	H	HH		-0.97
10/4/11 21:58	5.54	H	LH	10/4/11 21:14	5.92	H	LH		0.38
10/5/11 23:27	5.1	H	LH	10/5/11 23:02	5.07	H	LH		-0.03
10/7/11 1:08	5.02	H	LH	10/7/11 0:20	4.71	H	LH		-0.31
10/8/11 2:32	5.25	H	LH	10/8/11 1:44	4.44	H	LH		-0.81
10/9/11 3:36	5.61	H	LH	10/9/11 2:14	4.76	H	LH		-0.85
10/10/11 4:29	5.98	H	LH	10/10/11 3:26	5.56	H	LH		-0.42
10/11/11 5:15	6.33	H	LH	10/11/11 4:02	5.97	H	LH		-0.36
10/12/11 5:58	6.62	H	LH	10/12/11 5:32	5.39	H	LH		-1.23
10/12/11 16:33	6.75	H	LH	10/13/11 6:08	5.49	H	LH		-1.26
10/13/11 16:56	6.69	H	LH	10/13/11 16:08	5.74	H	LH		-0.95
10/14/11 17:22	6.57	H	LH	10/15/11 7:32	5.58	H	LH		-0.99
10/15/11 17:50	6.39	H	LH	10/16/11 8:02	5.56	H	LH		-0.83
10/16/11 18:19	6.16	H	LH	10/17/11 10:44	5.22	H	LH		-0.94
10/17/11 18:47	5.89	H	LH	10/17/11 17:26	5.10	H	LH		-0.79
10/18/11 19:21	5.56	H	LH	10/18/11 17:50	5.02	H	LH		-0.54
10/19/11 20:36	5.18	H	LH	10/19/11 18:38	4.84	H	LH		-0.34
10/20/11 22:12	4.85	H	LH	10/20/11 20:26	4.23	H	LH		-0.62
10/21/11 23:49	4.76	H	LH	10/21/11 23:32	3.89	H	LH		-0.87
10/23/11 1:24	5.05	H	LH	10/23/11 0:38	4.21	H	LH		-0.84

10/24/11 2:47	5.67	H	LH	10/24/11 1:50	4.63	H	LH		-1.04
10/25/11 3:58	6.42	H	LH	10/25/11 2:44	4.76	H	LH		-1.66
10/26/11 5:00	7.13	H	LH	10/26/11 3:32	5.18	H	LH		-1.95
10/27/11 5:58	7.68	H	LH	10/27/11 5:26	5.56	H	LH		-2.12
10/28/11 16:54	7.79	H	LH	10/28/11 5:32	6.44	H	LH		-1.35
10/29/11 17:36	7.47	H	LH	10/29/11 6:32	6.25	H	LH		-1.22
10/30/11 18:23	6.95	H	LH	10/30/11 17:44	6.19	H	LH		-0.76
10/31/11 19:17	6.28	H	LH	10/31/11 18:32	4.98	H	LH		-1.30
11/1/11 20:21	5.52	H	LH	11/1/11 19:26	4.10	H	LH		-1.42
11/2/11 21:41	4.8	H	LH	11/2/11 20:32	4.17	H	LH		-0.63
11/3/11 23:25	4.36	H	LH	11/3/11 22:56	3.44	H	LH		-0.92
11/5/11 1:26	4.48	H	LH	11/5/11 0:50	3.68	H	LH		-0.80
11/6/11 1:54	5.05	H	LH	11/6/11 2:38	4.21	H	LH		-0.84
11/7/11 2:58	5.73	H	LH	11/7/11 3:20	4.48	H	LH		-1.25
11/8/11 3:49	6.37	H	LH	11/8/11 4:26	4.85	H	LH		-1.52
11/9/11 4:32	6.9	H	LH	11/9/11 4:14	5.40	H	LH		-1.50
11/9/11 14:06	6.97	H	LH	11/10/11 5:02	5.66	H	LH		-1.31
11/10/11 14:31	6.94	H	LH	11/10/11 15:08	6.07	H	LH		-0.87
11/11/11 14:58	6.86	H	LH	11/12/11 7:20	6.04	H	LH		-0.82
11/12/11 15:26	6.71	H	LH	11/12/11 16:02	6.32	H	LH		-0.39
11/13/11 15:55	6.51	H	LH	11/13/11 15:56	6.29	H	LH		-0.22

Cardno ENTRIX

Shaping the Future

Tide by Tide Analysis Output Calculations

NAVD88		
$(\frac{1}{N}) \int_{I=1}^{N} (HW_A(I) - HW_B(I))$	-0.97	FT
$(\frac{1}{N}) \int_{I=1}^{N} (HHW_A(I) - HHW_B(I))$	-1.03	FT
$MHW_{ACCEPTEDFOR\ B}$	6.73	FT
$MHHW_{ACCEPTEDFORB}$	7.41	FT
$MHW_{CORRECTEDFORA}$	5.76	FT
$MHHW_{CORRECTEDFORA}$	6.38	FT

Appendix B

Historical Maps and Aerial Photographs



0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX
Shaping the Future



0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX
Shaping the Future



0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

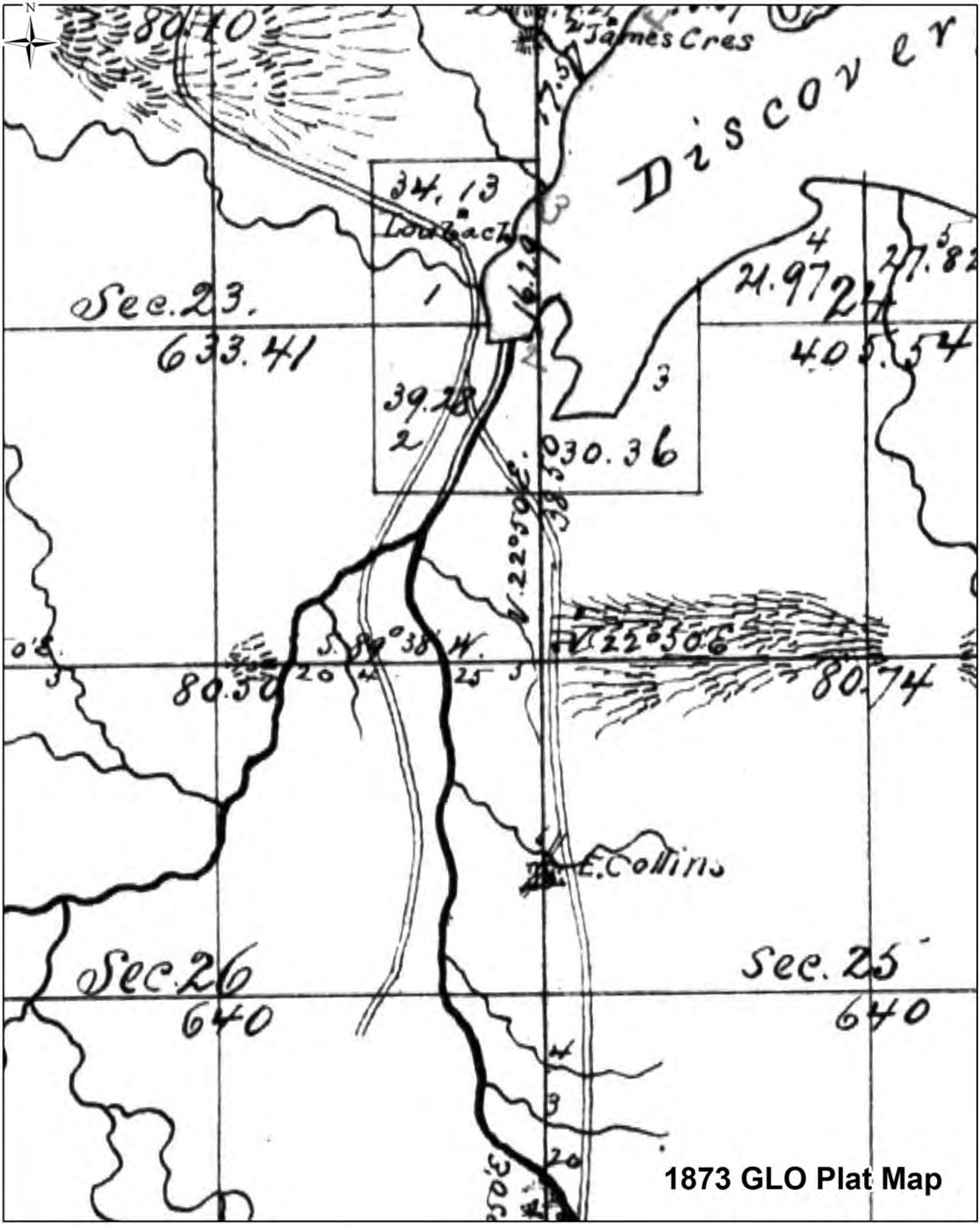
Cardno ENTRIX
Shaping the Future



0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX
Shaping the Future



0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX
Shaping the Future



1870 T-Sheet

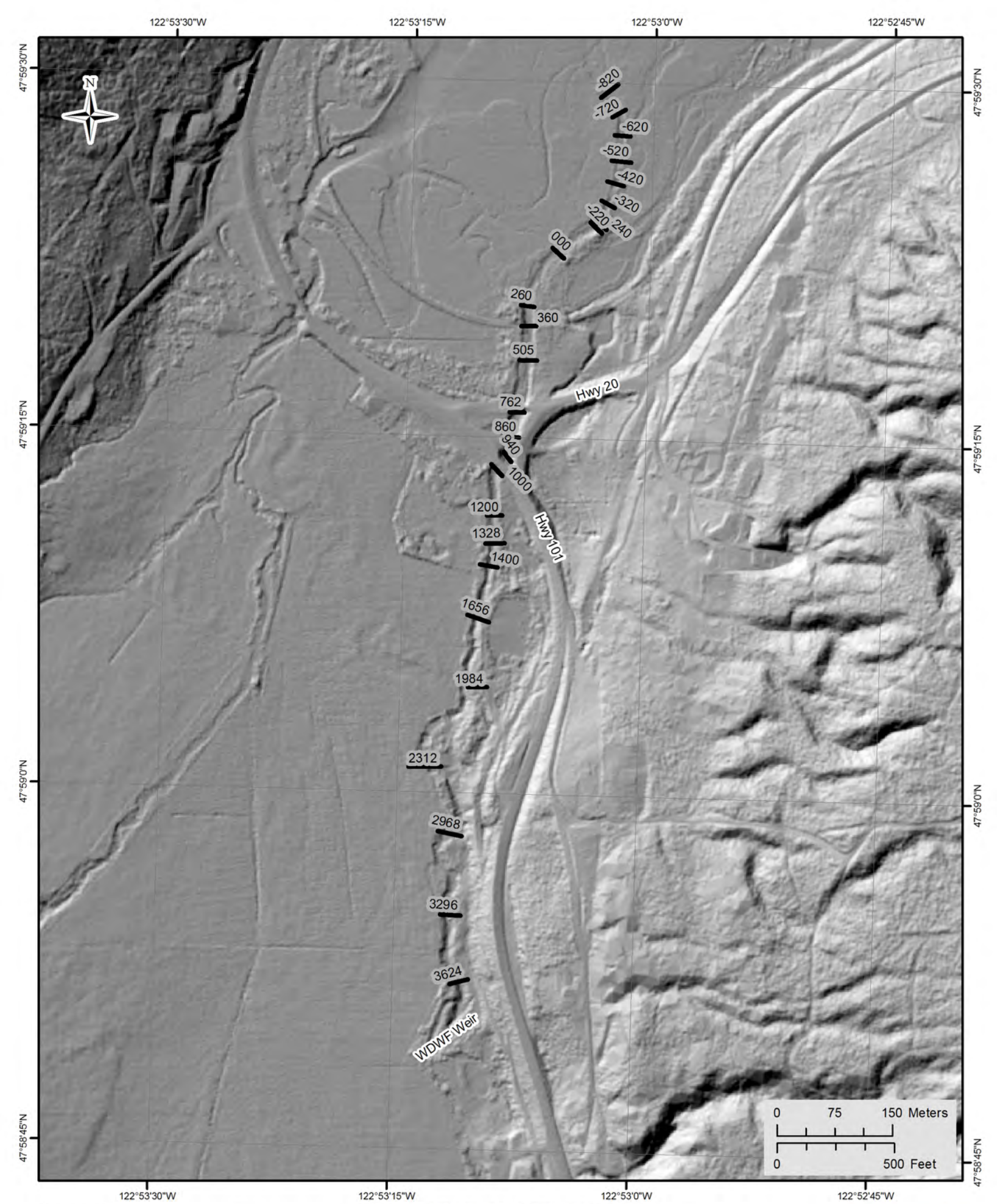
0 500 Feet

Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX

Appendix C

Channel Survey Cross Sections

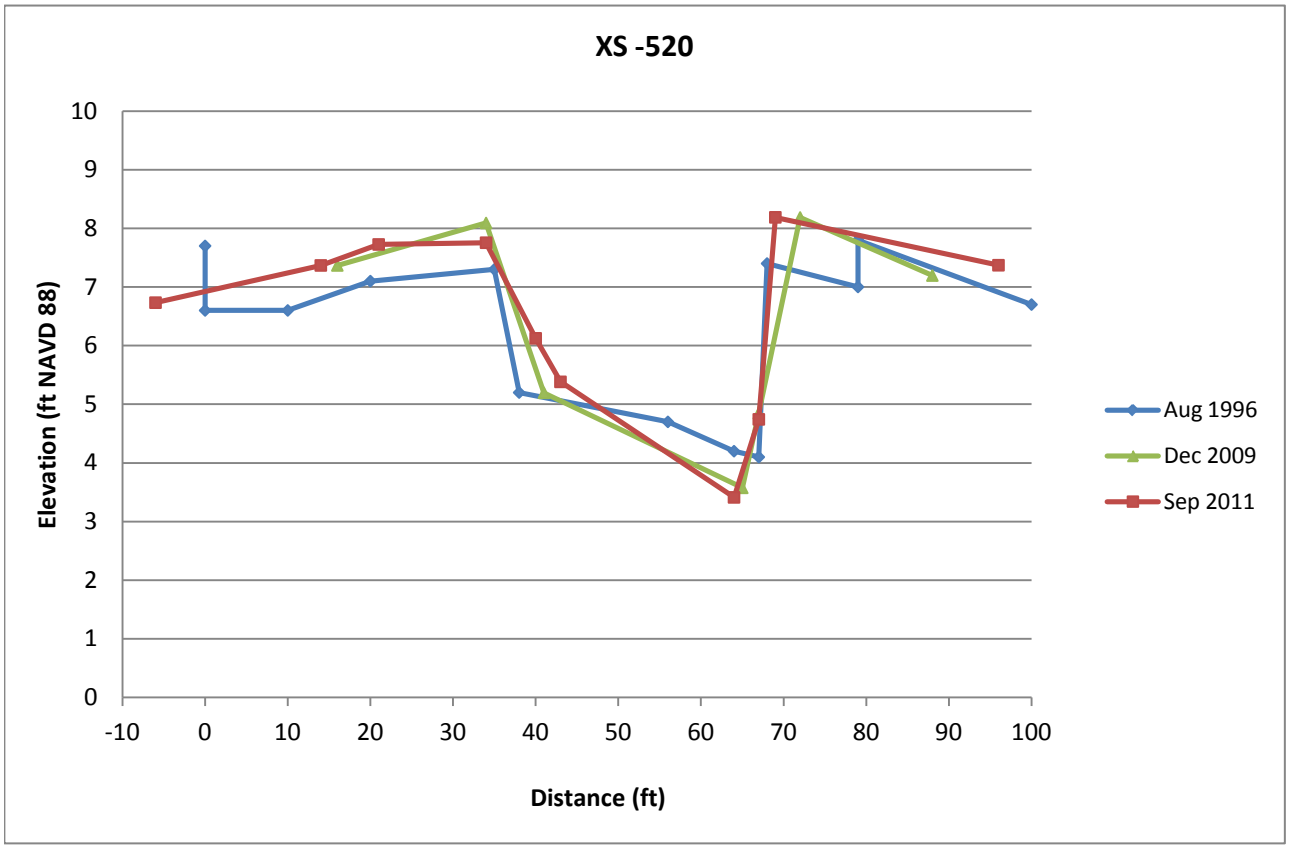


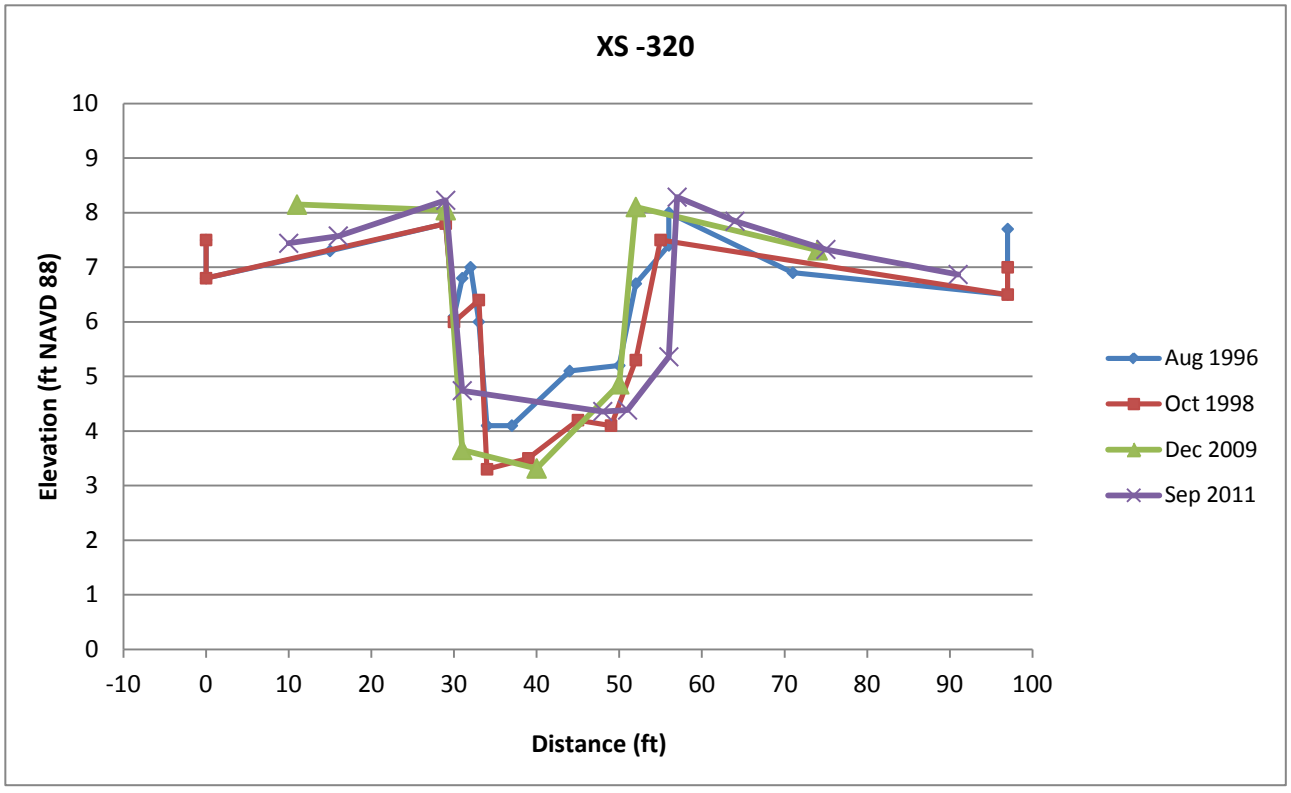
Background:
2002 LiDAR PSLC

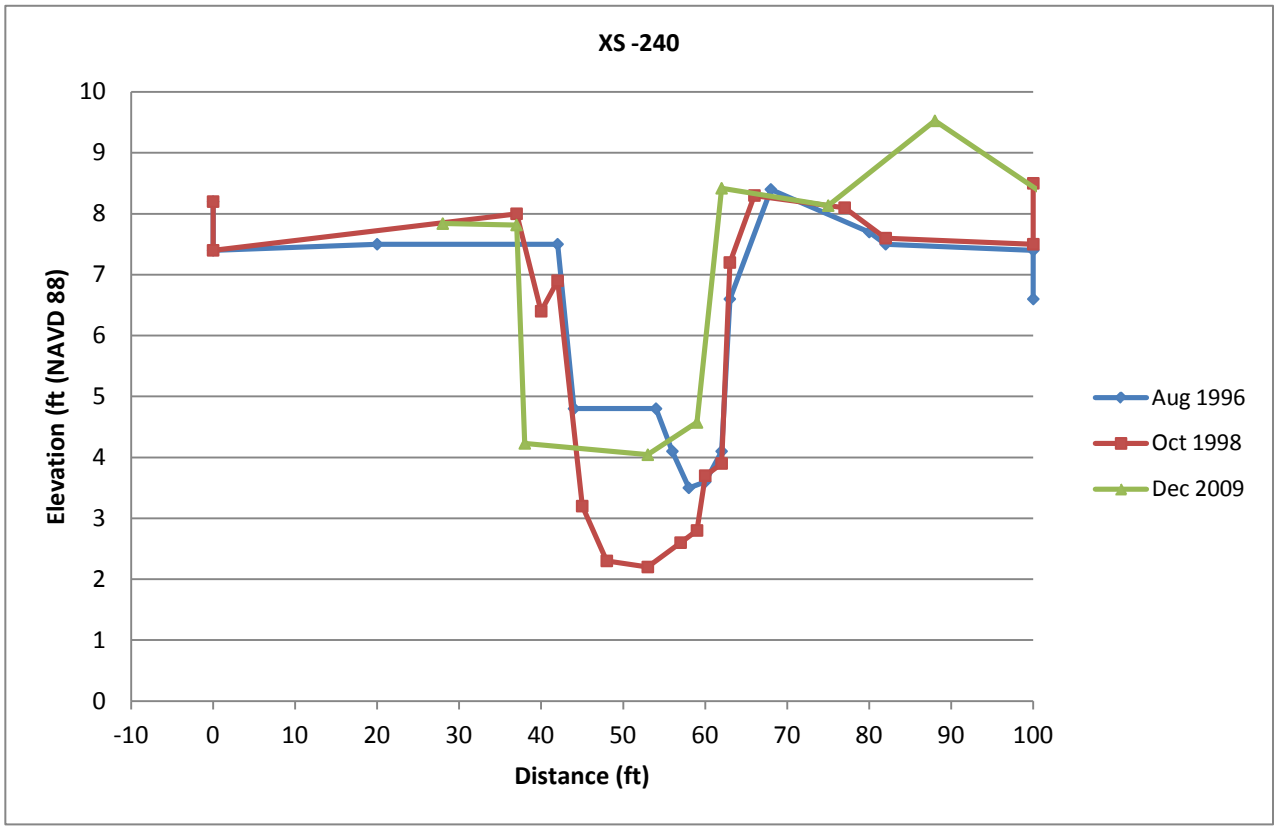
Coordinate System:
NAD 1983 HARN WA State Plane N

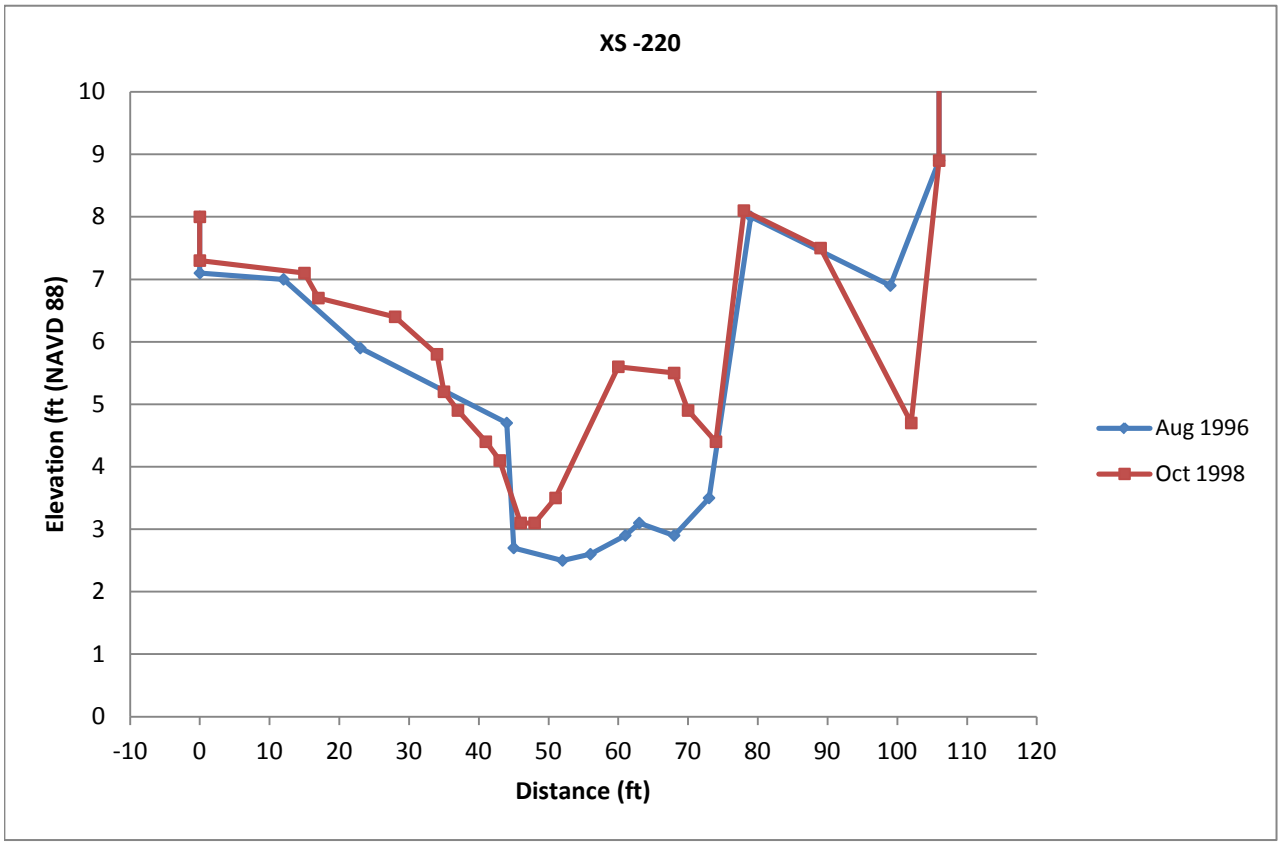
Channel Cross Section Locations
Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

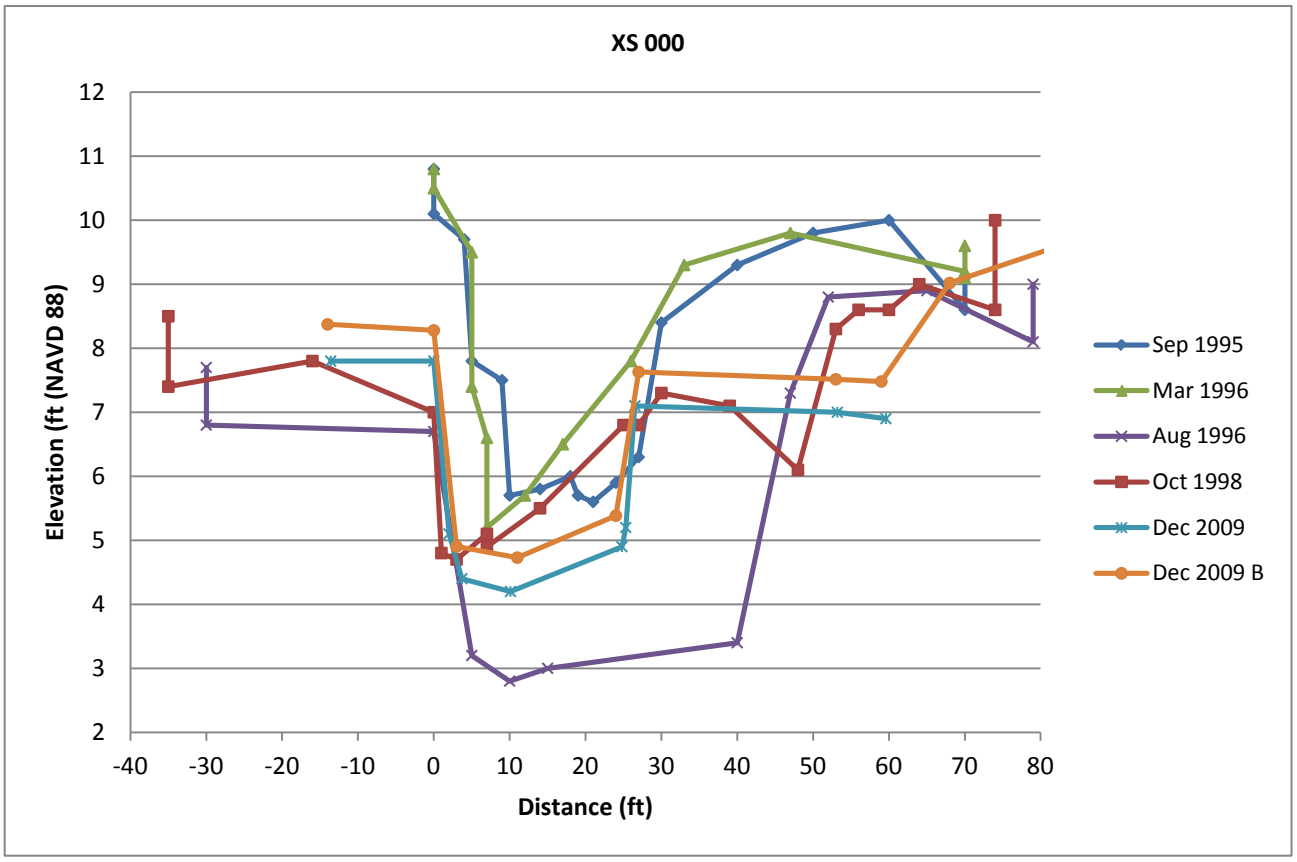
Cardno ENTRIX
Shaping the Future

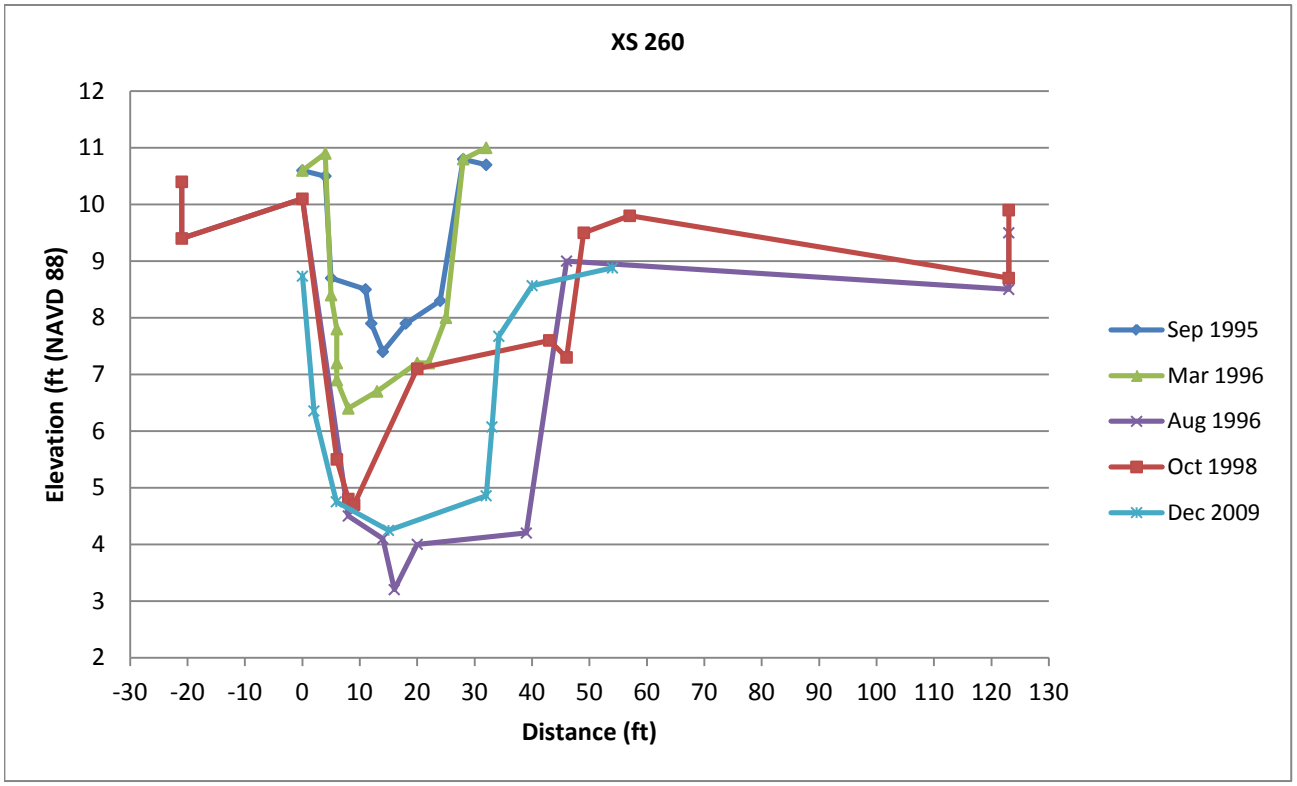

XS -520
Elevation (ft NAVD 88)
Distance (ft)
Aug 1996
Dec 2009
Sep 2011

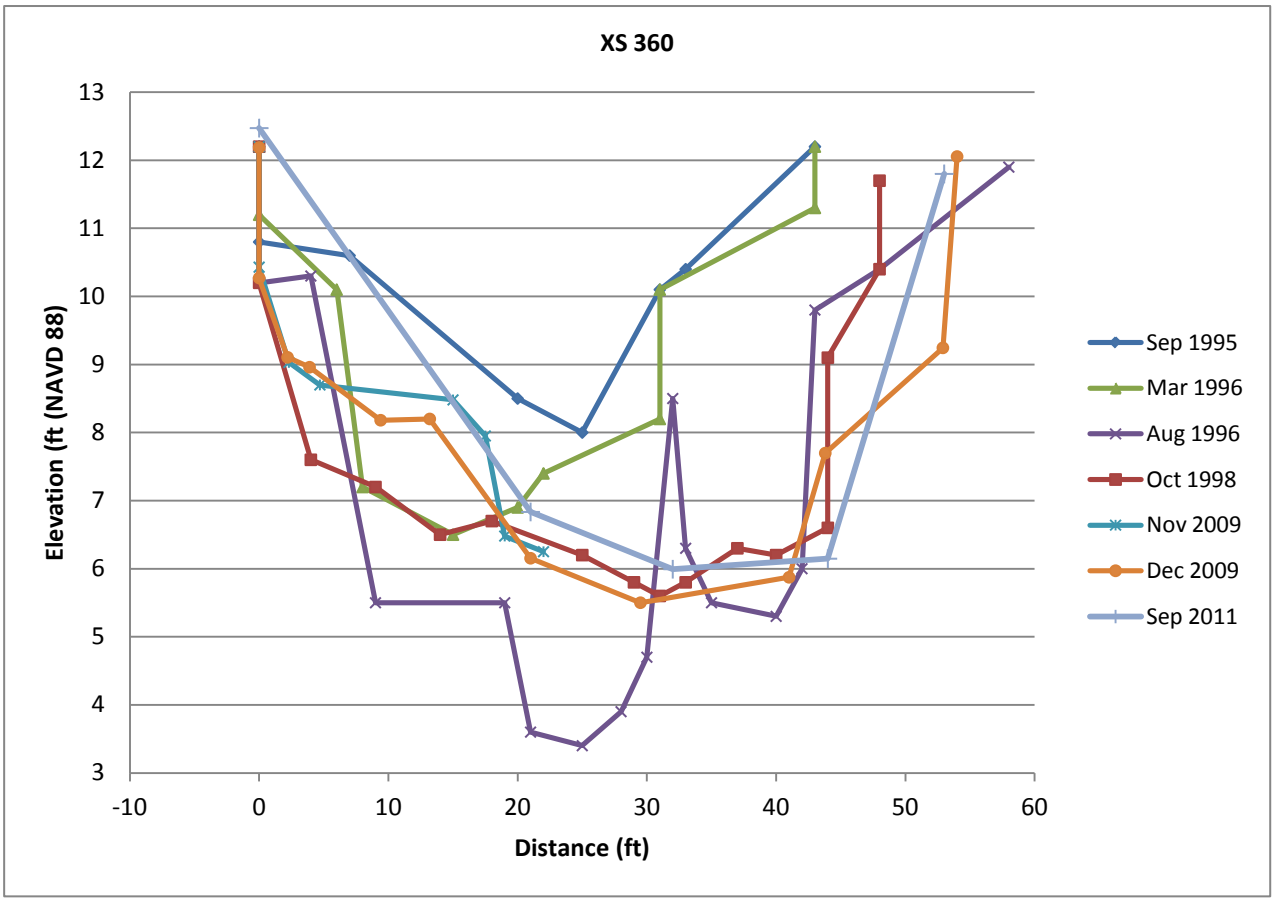

XS -320
Elevation (ft NAVD 88)
Distance (ft)
Aug 1996
Oct 1998
Dec 2009
Sep 2011

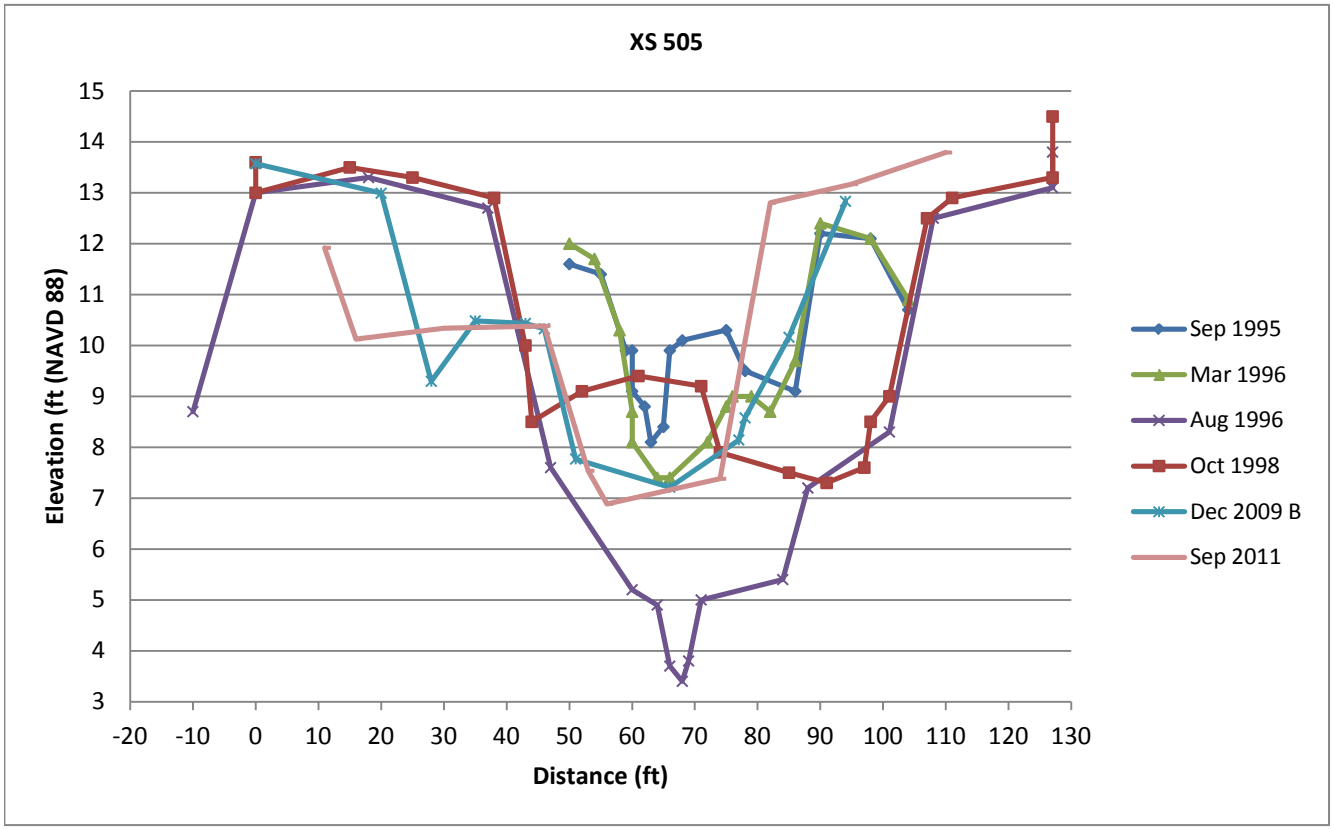

XS -240
Elevation (ft (NAVD 88)
10
9
8
7
6
5
4
3
2
1
0
-10
0
10
20
30
40
50
60
70
80
90
100
Distance (ft)
Aug 1996
Oct 1998
Dec 2009

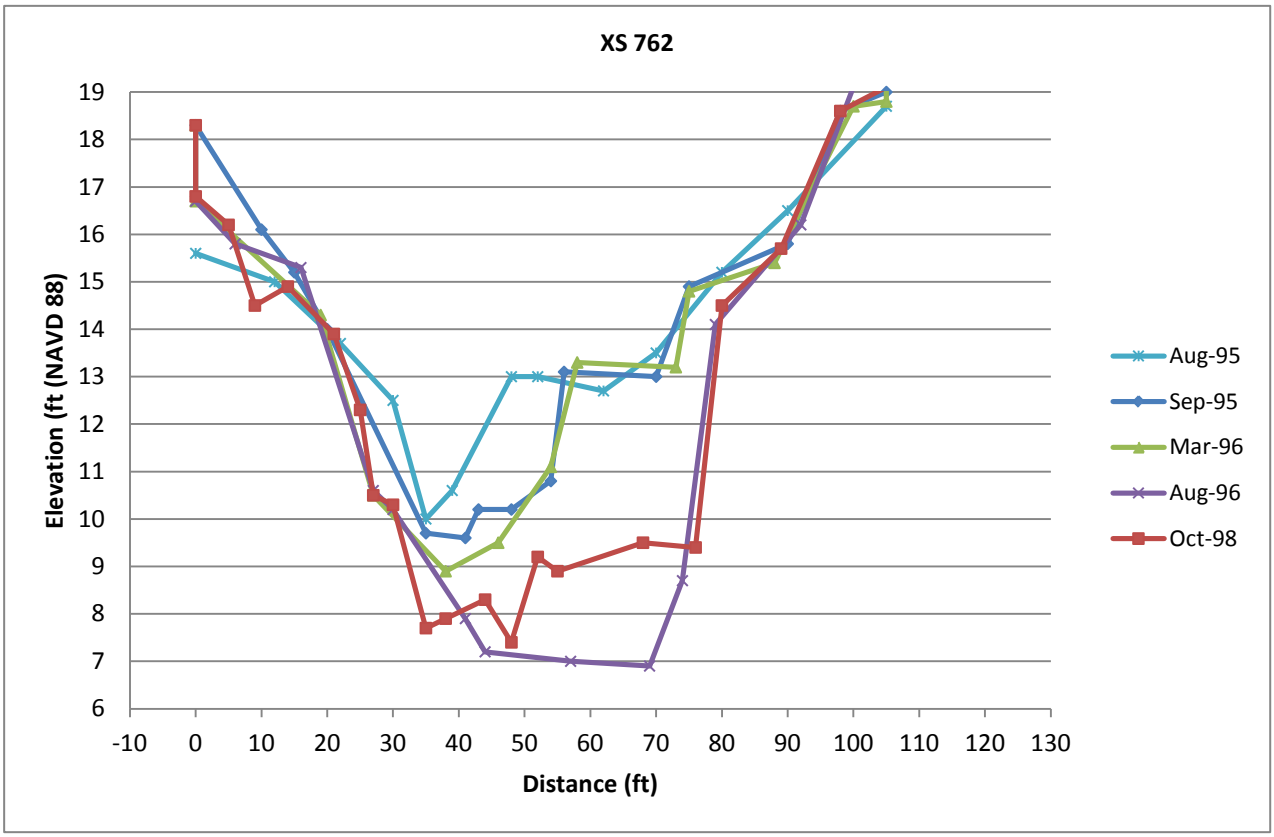

XS -220
Elevation (ft (NAVD 88)
10
9
8
7
6
5
4
3
2
1
0
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
Distance (ft)
Aug 1996
Oct 1998

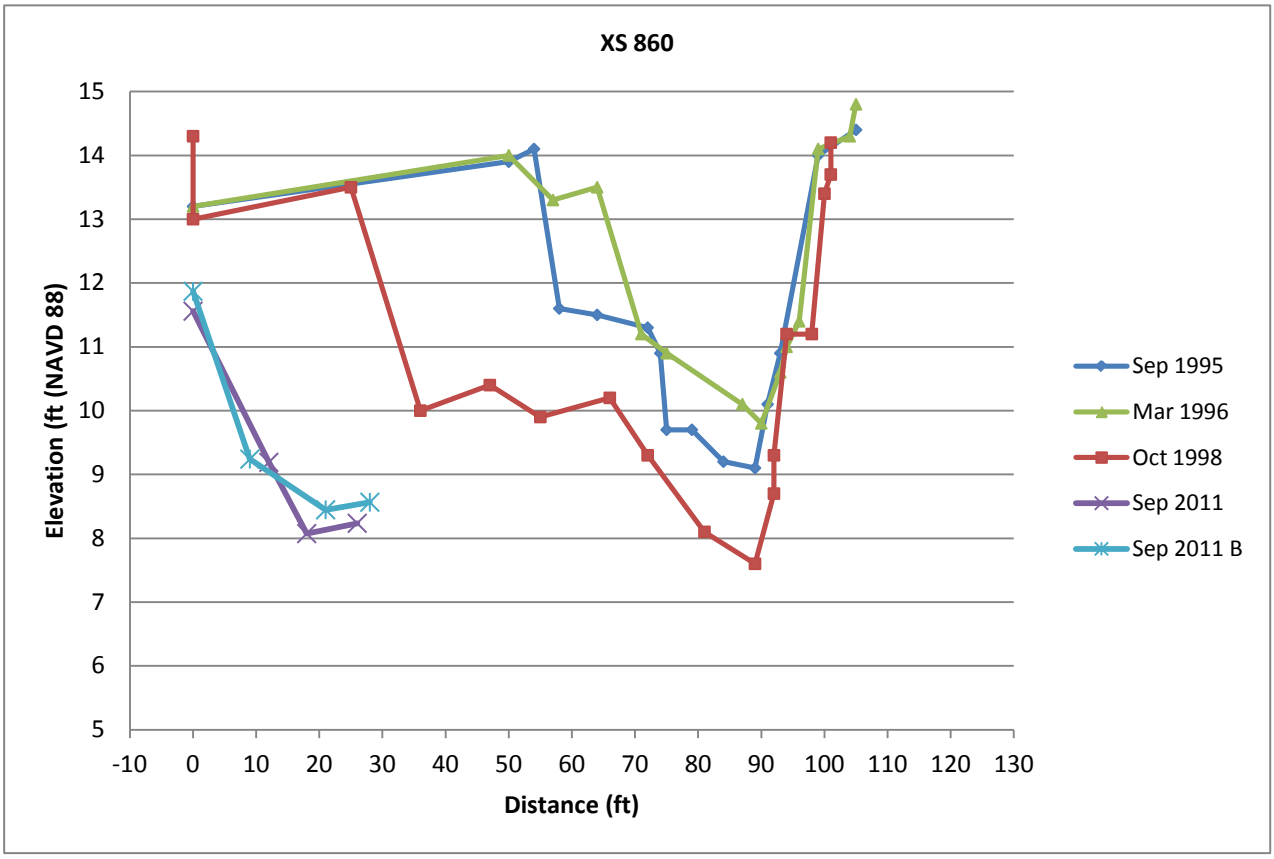

XS 000
Elevation (ft (NAVD 88)
12
11
10
9
8
7
6
5
4
3
2
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
Distance (ft)
Sep 1995
Mar 1996
Aug 1996
Oct 1998
Dec 2009
Dec 2009 B

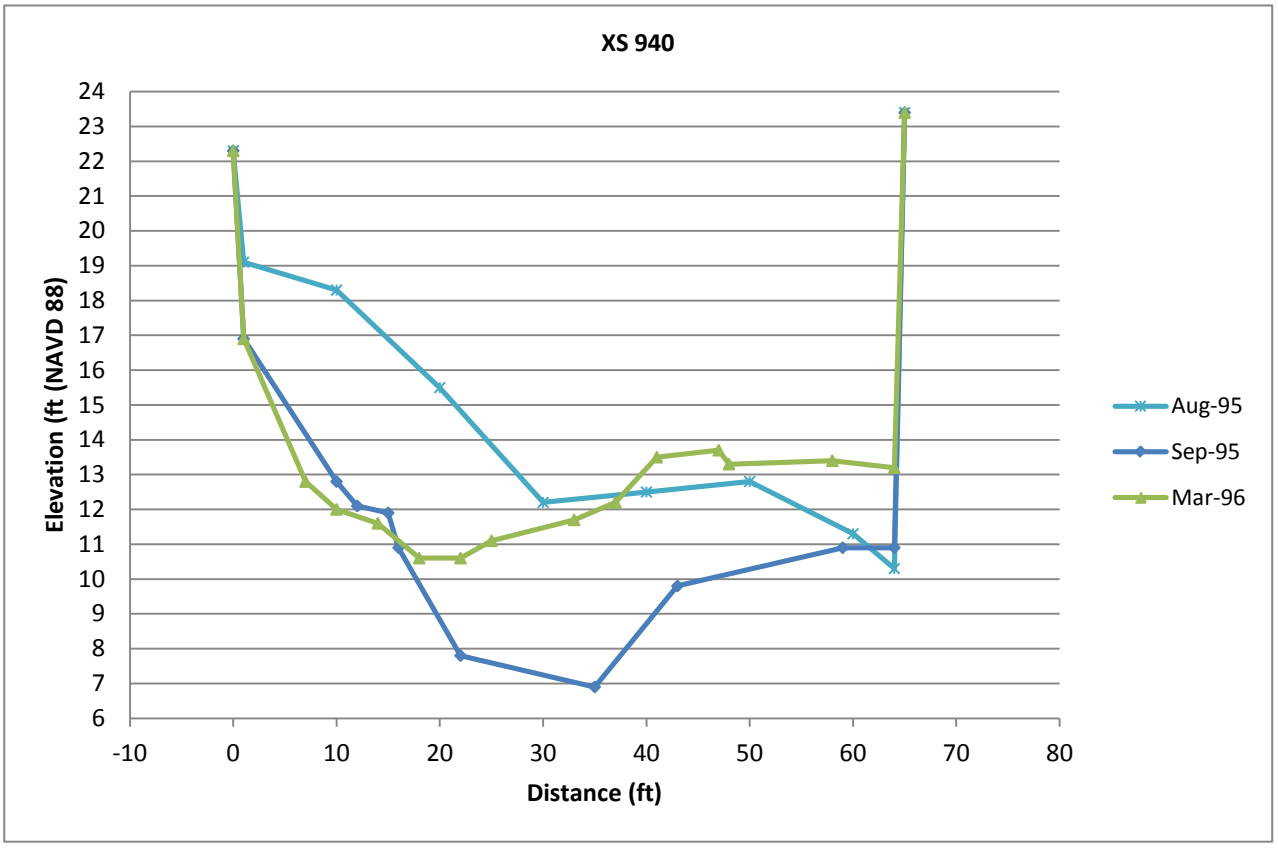

XS 260
Elevation (ft (NAVD 88)
12
11
10
9
8
7
6
5
4
3
2
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Distance (ft)
Sep 1995
Mar 1996
Aug 1996
Oct 1998
Dec 2009

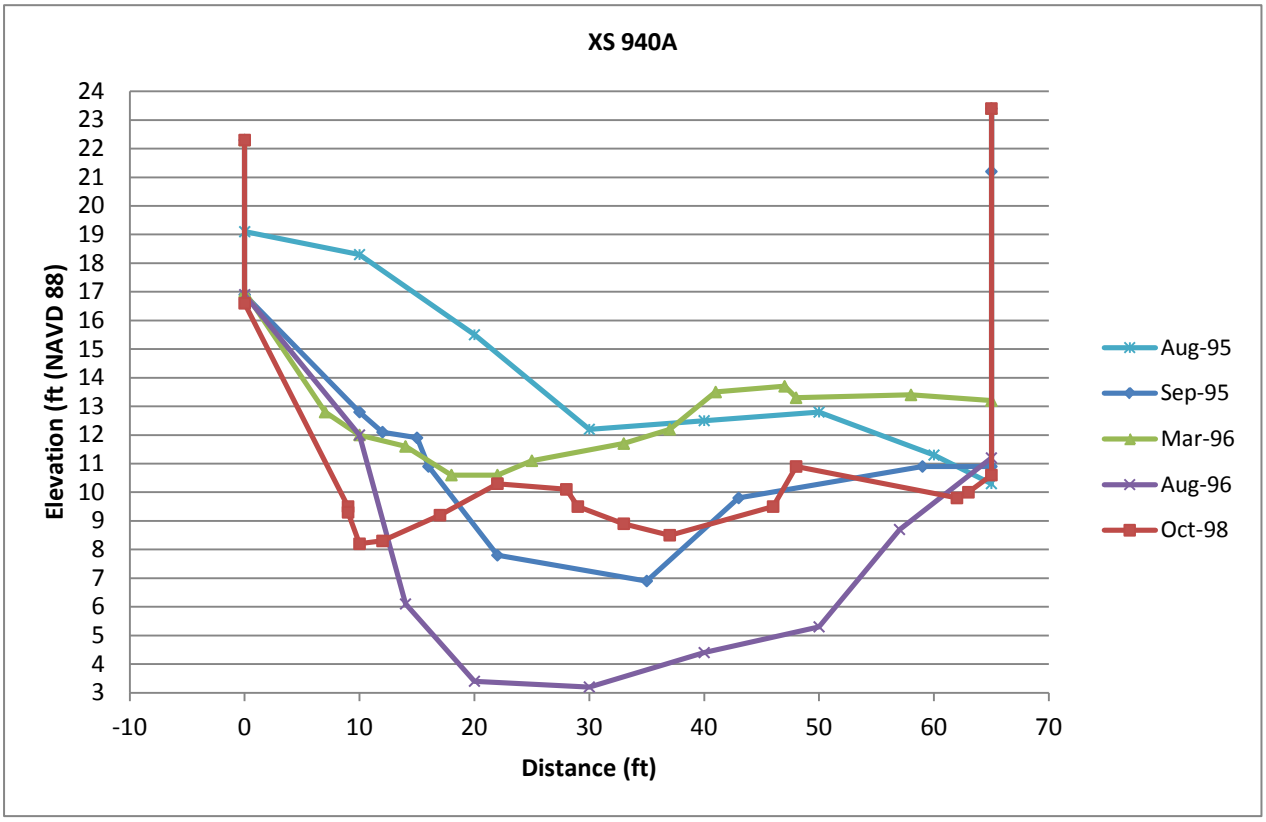

XS 360
Elevation (ft (NAVD 88)
Distance (ft)
13
12
11
10
9
8
7
6
5
4
3
-10
0
10
20
30
40
50
60
Sep 1995
Mar 1996
Aug 1996
Oct 1998
Nov 2009
Dec 2009
Sep 2011

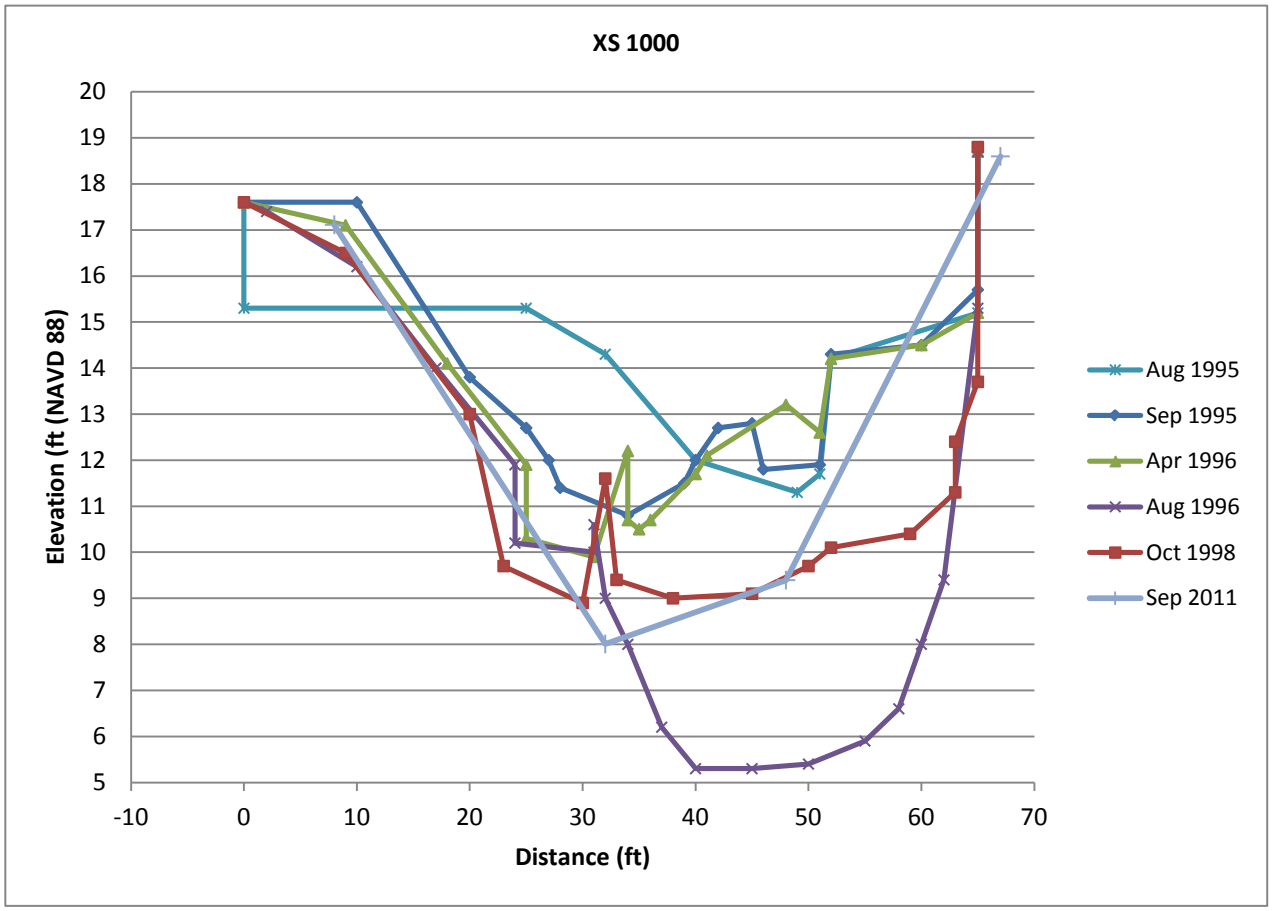

XS 505
Elevation (ft (NAVD 88)
Distance (ft)
15
14
13
12
11
10
9
8
7
6
5
4
3
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Sep 1995
Mar 1996
Aug 1996
Oct 1998
Dec 2009 B
Sep 2011

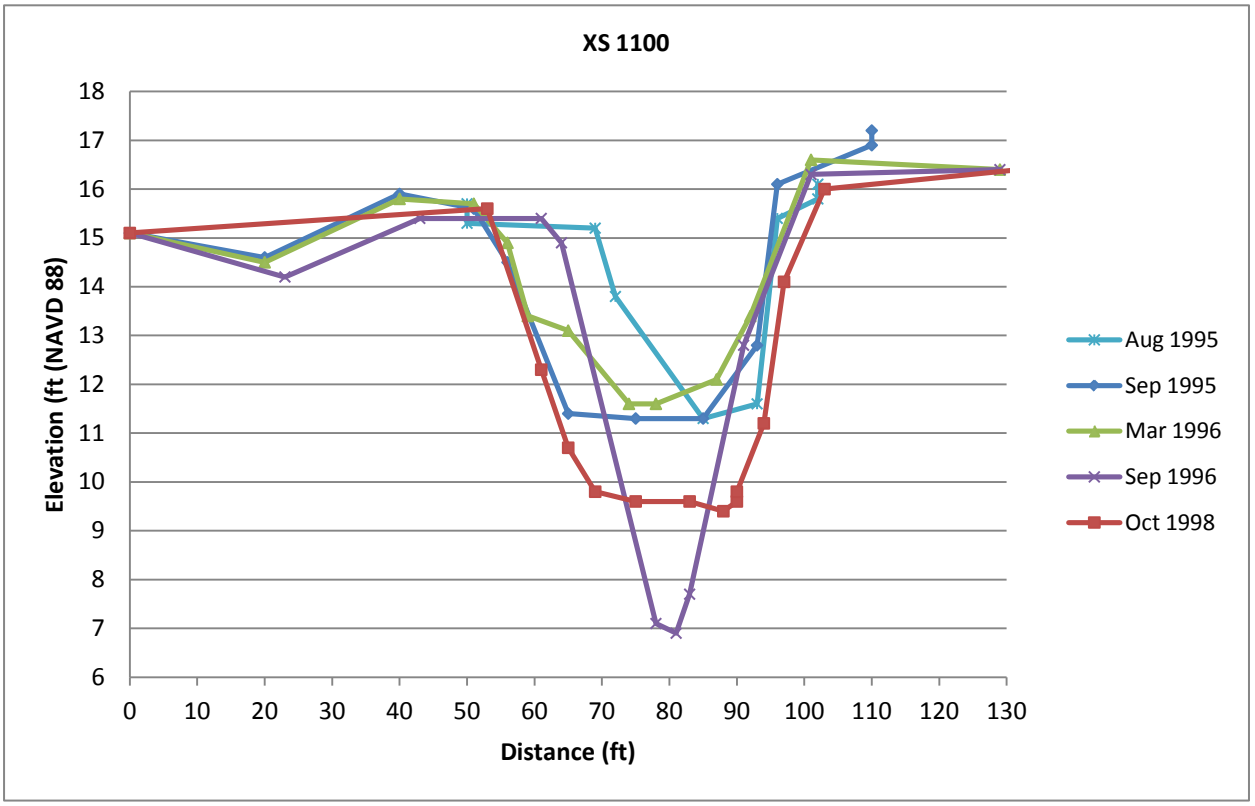

XS 762
Elevation (ft (NAVD 88)
Distance (ft)
Aug-95
Sep-95
Mar-96
Aug-96
Oct-98

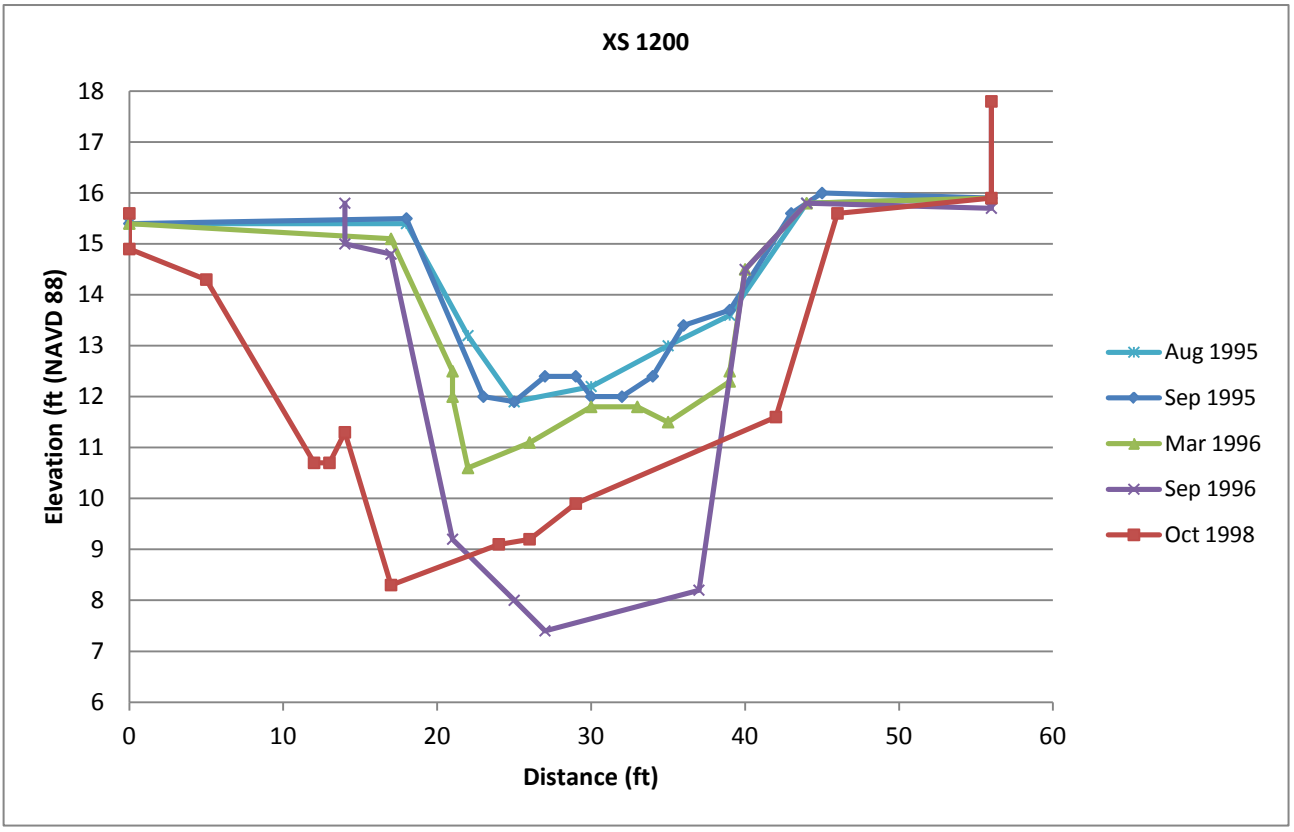

XS 860
Elevation (ft (NAVD 88)
Distance (ft)
Sep 1995
Mar 1996
Oct 1998
Sep 2011
Sep 2011 B

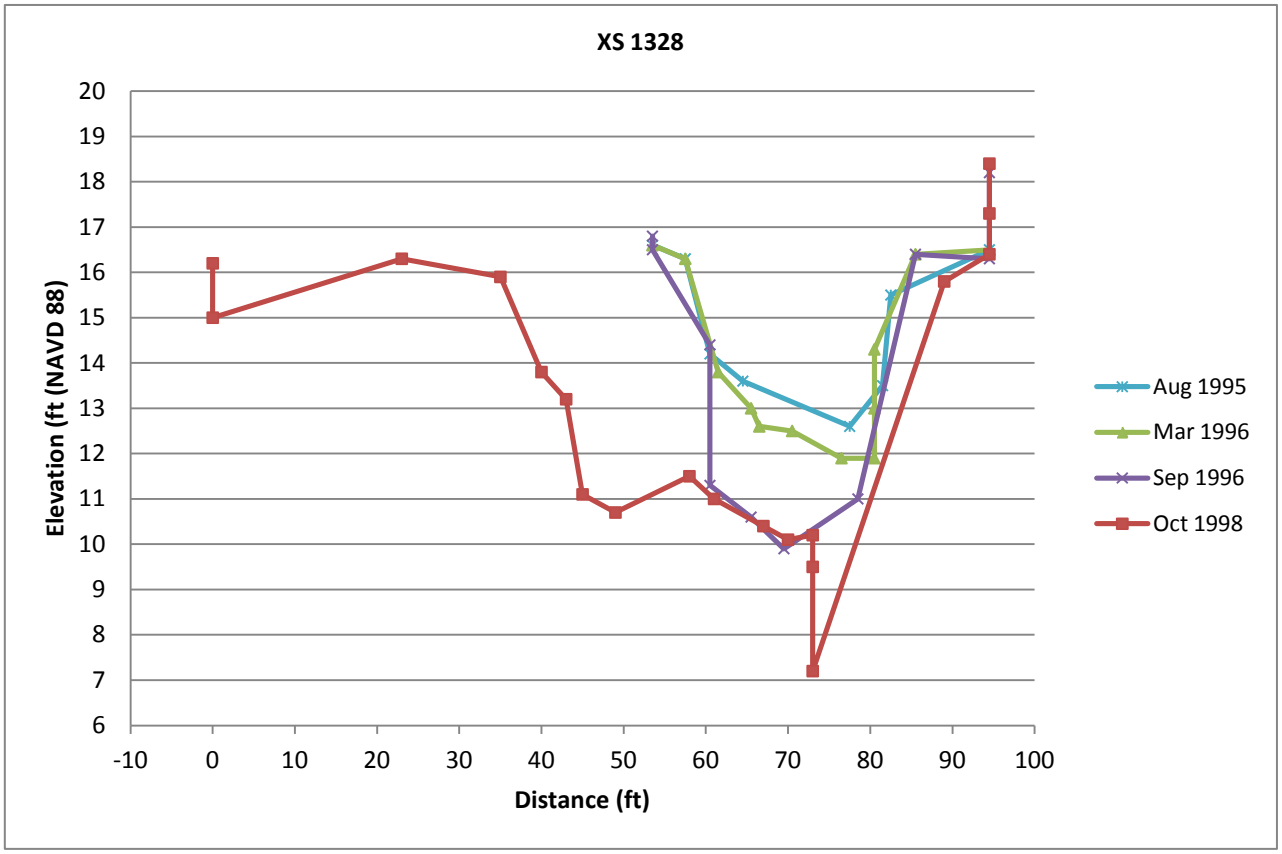

XS 940
Elevation (ft (NAVD 88)
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
-10
0
10
20
30
40
50
60
70
80
Distance (ft)
Aug-95
Sep-95
Mar-96

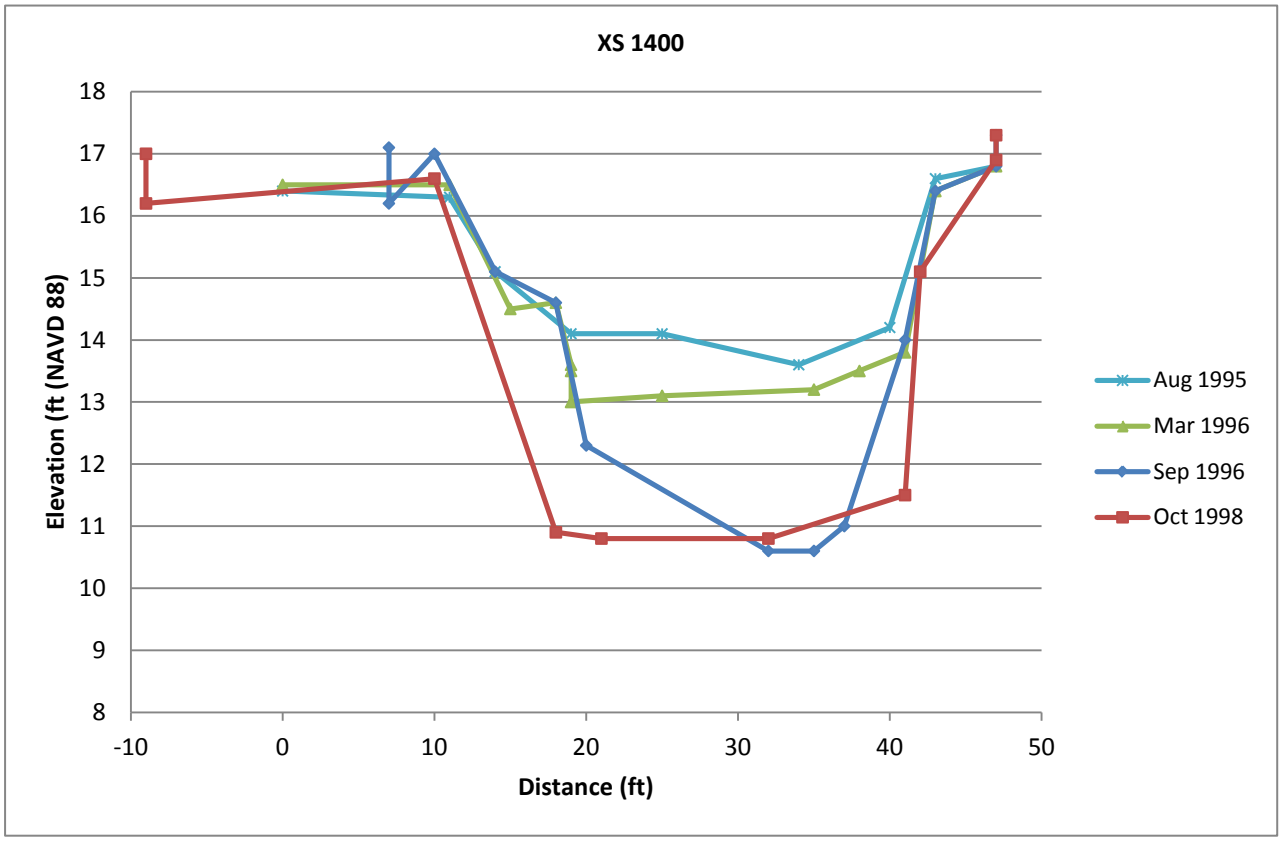

XS 940A
Elevation (ft (NAVD 88)
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
-10
0
10
20
30
40
50
60
70
Distance (ft)
Aug-95
Sep-95
Mar-96
Aug-96
Oct-98

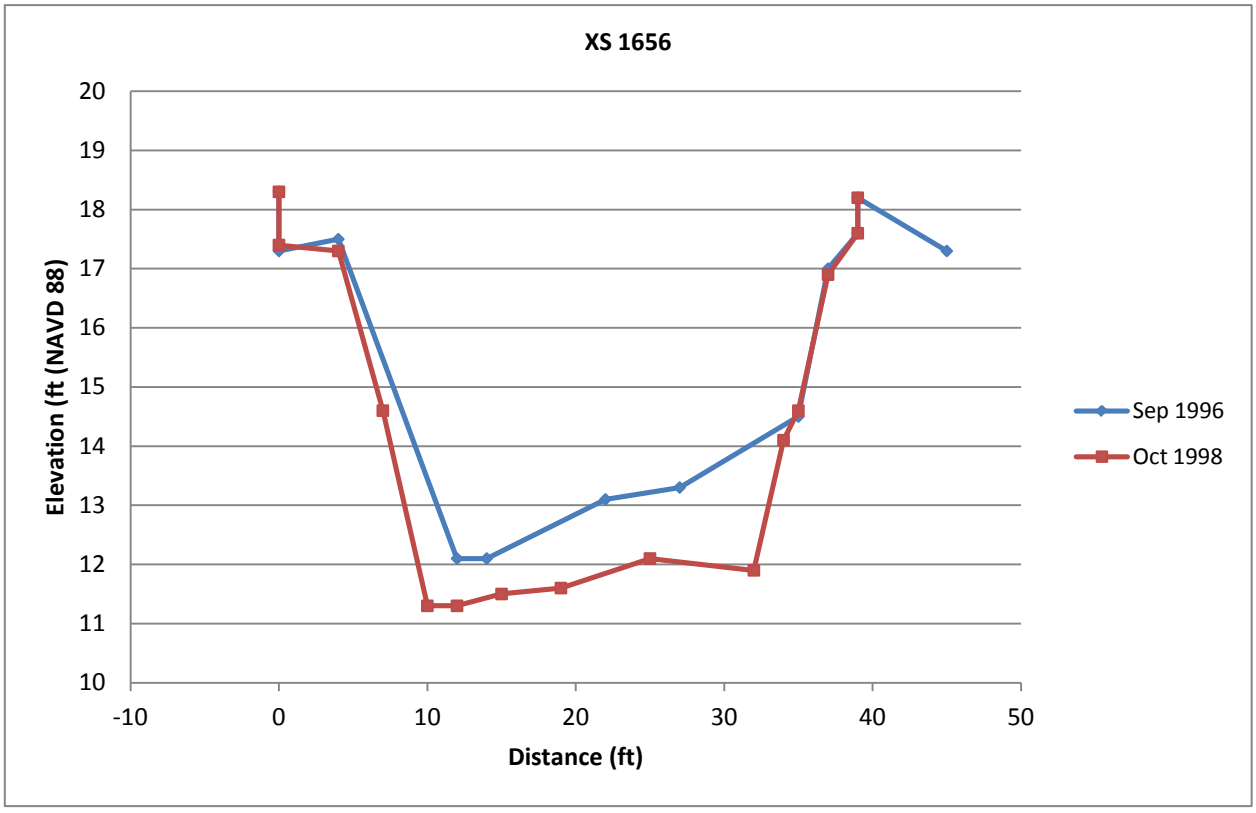

XS 1000
Elevation (ft (NAVD 88)
Distance (ft)
Aug 1995
Sep 1995
Apr 1996
Aug 1996
Oct 1998
Sep 2011

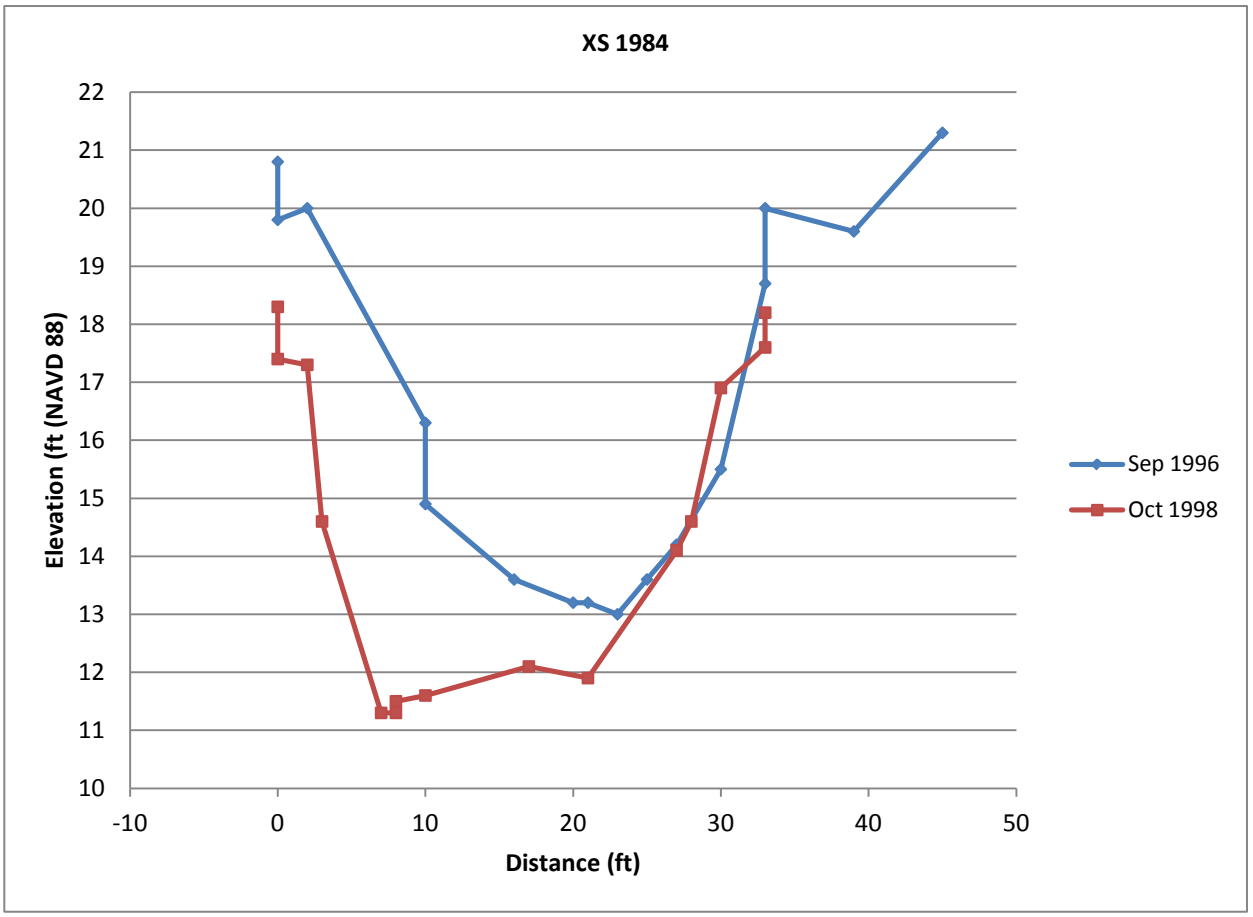

XS 1100
Elevation (ft (NAVD 88)
Distance (ft)
Aug 1995
Sep 1995
Mar 1996
Sep 1996
Oct 1998

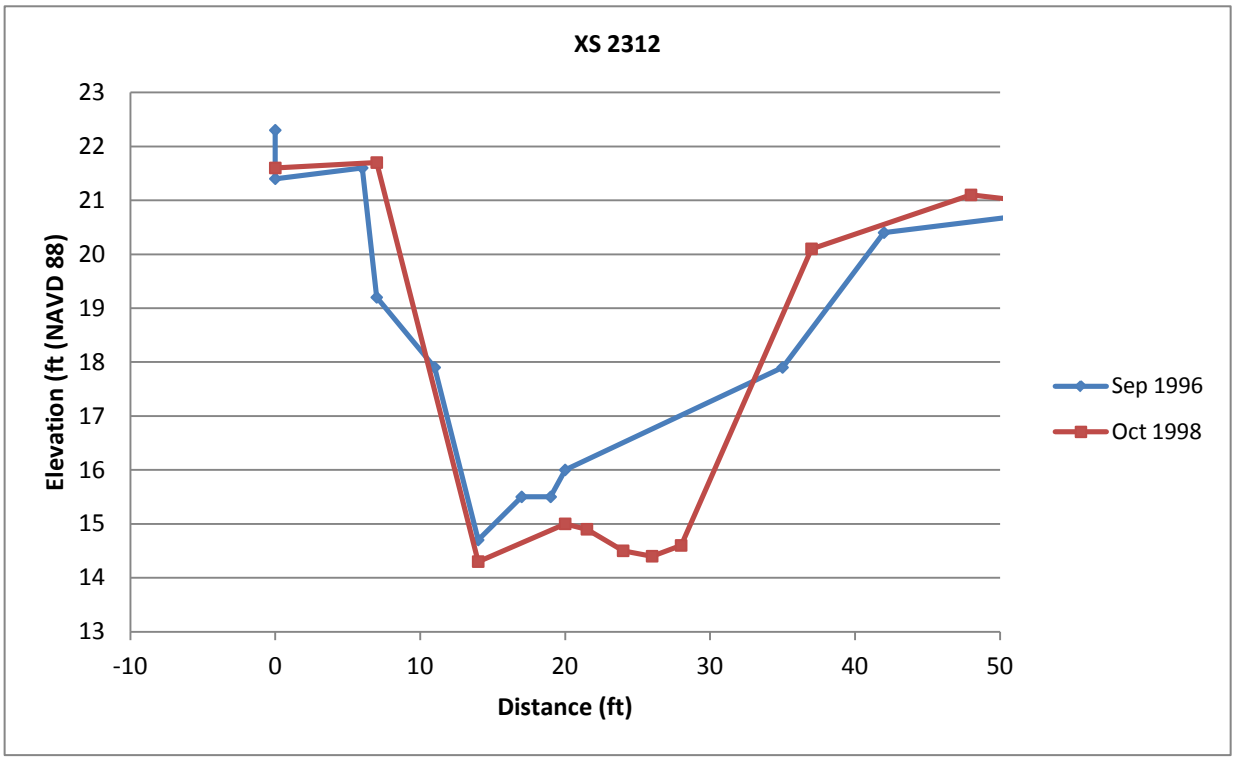

XS 1200
Elevation (ft (NAVD 88)
Distance (ft)
18
17
16
15
14
13
12
11
10
9
8
7
6
0
10
20
30
40
50
60
Aug 1995
Sep 1995
Mar 1996
Sep 1996
Oct 1998


XS 1328
Elevation (ft (NAVD 88)
Distance (ft)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
-10
0
10
20
30
40
50
60
70
80
90
100
Aug 1995
Mar 1996
Sep 1996
Oct 1998

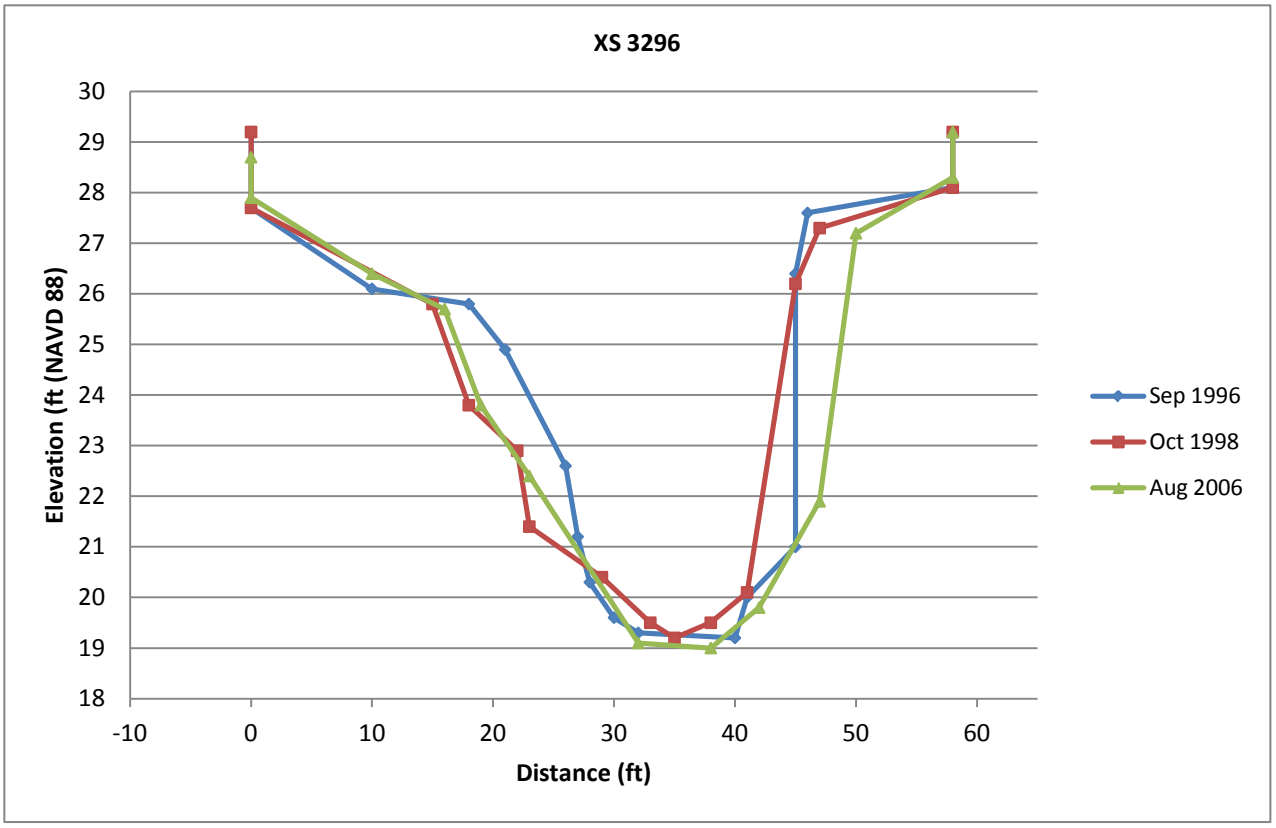

XS 1400
Elevation (ft (NAVD 88)
18
17
16
15
14
13
12
11
10
9
8
-10
0
10
20
30
40
50
Distance (ft)
Aug 1995
Mar 1996
Sep 1996
Oct 1998

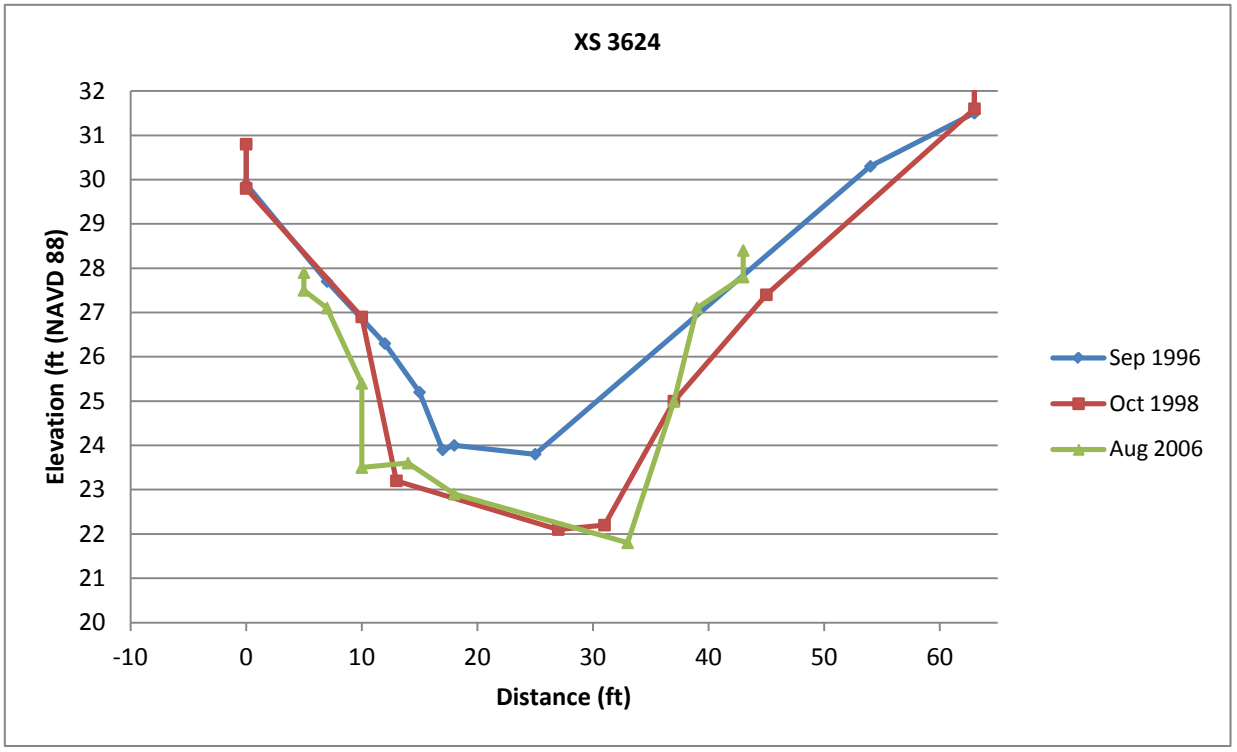

XS 1656
Elevation (ft (NAVD 88)
20
19
18
17
16
15
14
13
12
11
10
-10
0
10
20
30
40
50
Distance (ft)
Sep 1996
Oct 1998


XS 1984
Elevation (ft (NAVD 88)
22
21
20
19
18
17
16
15
14
13
12
11
10
-10
0
10
20
30
40
50
Distance (ft)
Sep 1996
Oct 1998


XS 2312
Elevation (ft (NAVD 88)
23
22
21
20
19
18
17
16
15
14
13
-10
0
10
20
30
40
50
Distance (ft)
Sep 1996
Oct 1998

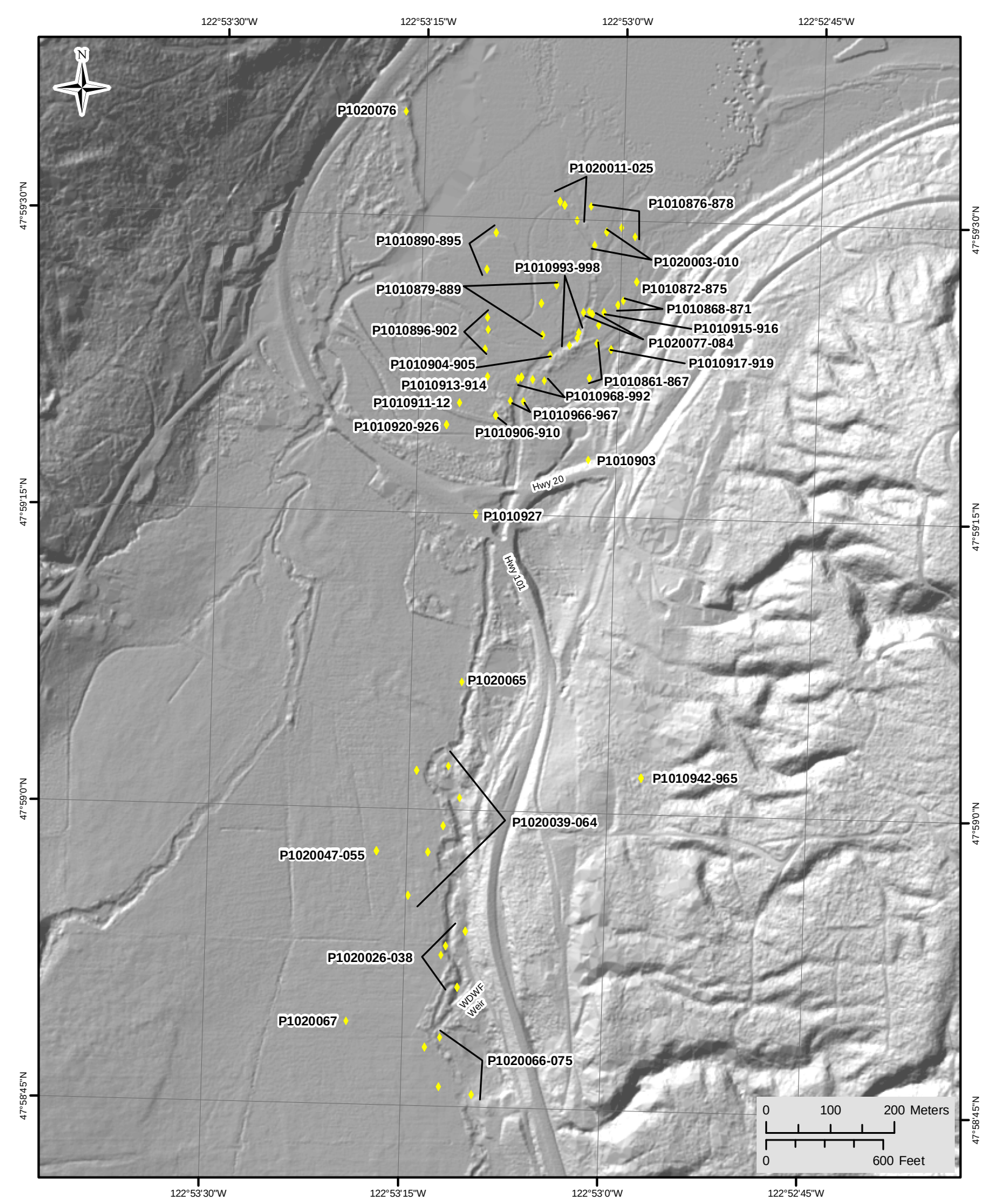

XS 2968
Elevation (ft (NAVD 88)
28
27
26
25
24
23
22
21
20
19
18
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
Distance (ft)
Sep 1996
Oct 1998


XS 3296
Elevation (ft (NAVD 88)
30
29
28
27
26
25
24
23
22
21
20
19
18
-10
0
10
20
30
40
50
60
Distance (ft)
Sep 1996
Oct 1998
Aug 2006


XS 3624
Elevation (ft (NAVD 88)
32
31
30
29
28
27
26
25
24
23
22
21
20
-10
0
10
20
30
40
50
60
Distance (ft)
Sep 1996
Oct 1998
Aug 2006

Appendix D

Site Photographs



Background:
2002 LiDAR PSLC

Coordinate System:
NAD 1983 HARN WA State Plane N

Field Photo Locations
Snow Creek Estuary Restoration Project, Jefferson County, WA
North Olympic Salmon Coalition

Cardno ENTRIX
Shaping the Future


09/28/11 Snow Creek P1010861
N 47° 59.3667' W 122° 53.0362' 315°


09/28/11 Snow Creek P1010863
N 47° 59.3667' W 122° 53.0362' 270°


09/23/11 Snow Creek P1010860
N 47° 11.4103' W 120° 43.0292' 242°


09/28/11 Snow Creek P1010862
N 47° 59.3667' W 122° 53.0362' 45°

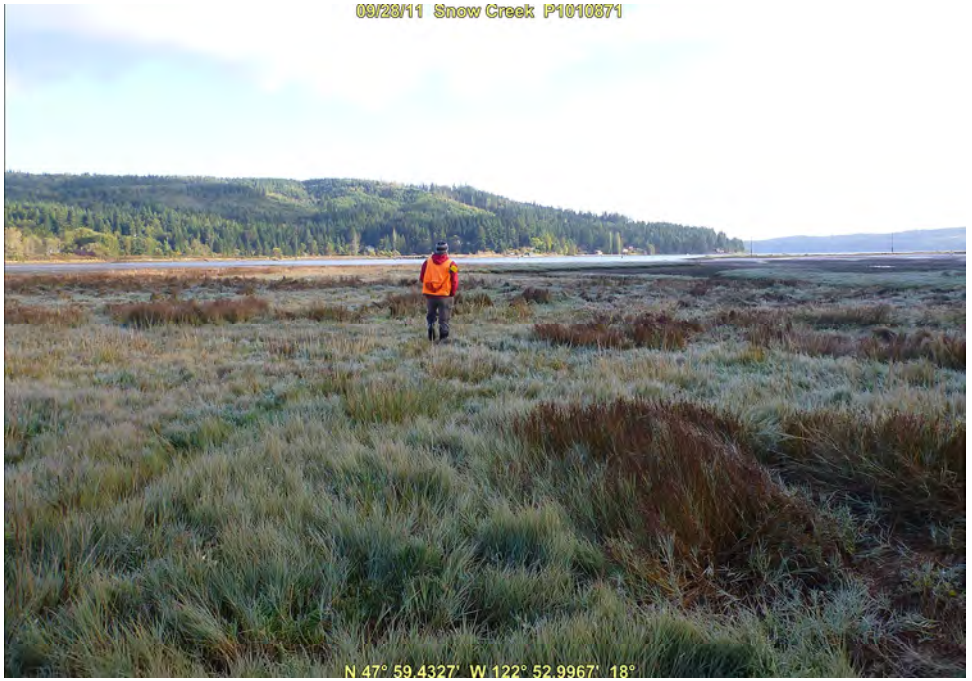

09/28/11 Snow Creek P1010865
N 47° 59.3960' W 122° 53.0283' 198°


09/28/11 Snow Creek P1010867
N 47° 59.3960' W 122° 53.0283' 108°

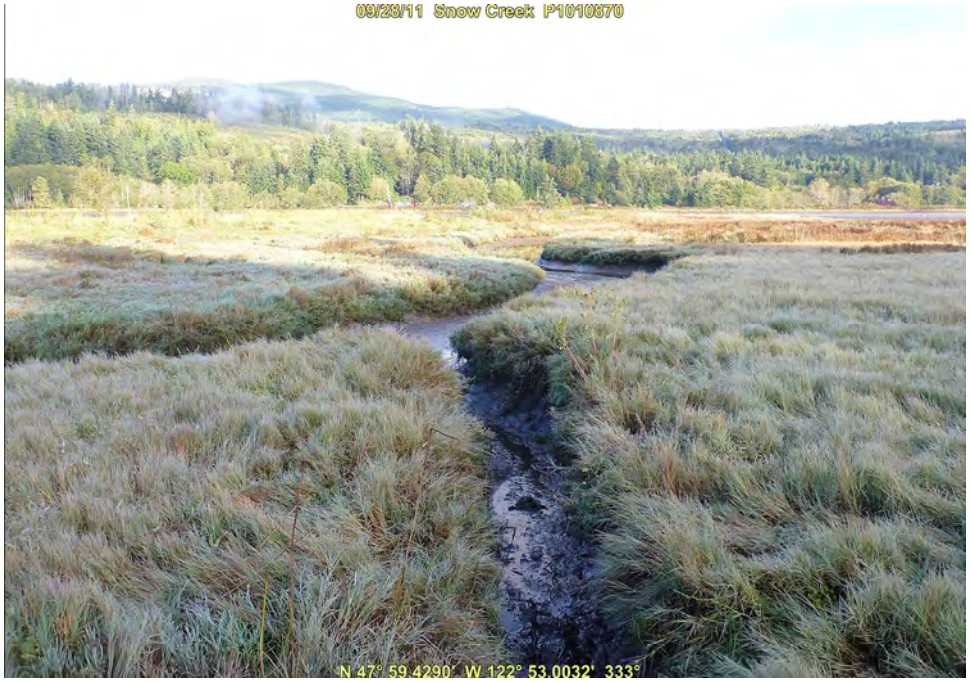

09/28/11 Snow Creek P1010864
N 47° 59.3960' W 122° 53.0283' 63°


09/28/11 Snow Creek P1010866
N 47° 59.3960' W 122° 53.0283' 243°


09/28/11 Snow Creek P1010869
N 47° 59.4290' W 122° 53.0032' 0°


09/28/11 Snow Creek P1010871
N 47° 59.4327' W 122° 52.9967' 18°


09/28/11 Snow Creek P1010868
N 47° 59.4290' W 122° 53.0032' 225°


09/28/11 Snow Creek P1010870
N 47° 59.4290' W 122° 53.0032' 333°


09/28/11 Snow Creek P1010873
N 47° 59.4488' W 122° 52.9802' 180°


09/28/11 Snow Creek P1010875
N 47° 59.4488' W 122° 52.9802' 18°


09/28/11 Snow Creek P1010872
N 47° 59.4488' W 122° 52.9802' 225°


09/28/11 Snow Creek P1010874
N 47° 59.4488' W 122° 52.9802' 225°


09/28/11 Snow Creek P1010878
N 47° 59.5120' W 122° 53.0400' 288°


09/28/11 Snow Creek P1010880
N 47° 59.4447' W 122° 53.0810' 108°


09/28/11 Snow Creek P1010876
N 47° 59.4943' W 122° 53.0013' 63°


09/28/11 Snow Creek P1010879
N 47° 59.4447' W 122° 53.0810' 18°


09/28/11 Snow Creek P1010882


09/28/11 Snow Creek P1010884


09/28/11 Snow Creek P1010883


09/28/11 Snow Creek P1010883


09/28/11 Snow Creek P1010886
N 47° 59.4288' W 122° 53.0993' 333°


09/28/11 Snow Creek P1010888
N 47° 59.4025' W 122° 53.0963' 315°


09/28/11 Snow Creek P1010885
N 47° 59.4288' W 122° 53.0993' 18°


09/28/11 Snow Creek P1010887
N 47° 59.4025' W 122° 53.0963' 225°


09/28/11 Snow Creek P1010890
N 47° 59.4877' W 122° 53.1582' 225°


09/28/11 Snow Creek P1010892
N 47° 59.4877' W 122° 53.1582' 90°


09/28/11 Snow Creek P1010889
N 47° 59.4025' W 122° 53.0963' 63°


09/28/11 Snow Creek P1010891
N 47° 59.4877' W 122° 53.1582' 270°


09/28/11 Snow Creek P1010894
N 47° 59.4562' W 122° 53.1685' 90°


09/28/11 Snow Creek P1010896
N 47° 59.4160' W 122° 53.1665' 315°


09/28/11 Snow Creek P1010893
N 47° 59.4562' W 122° 53.1685' 270°


09/28/11 Snow Creek P1010895
N 47° 59.4562' W 122° 53.1685' 288°


09/28/11 Snow Creek P1010898
N 47° 59.4055' W 122° 53.1648' 315°


09/28/11 Snow Creek P1010900
N 47° 59.3890' W 122° 53.1680' 225°


09/28/11 Snow Creek P1010897
N 47° 59.4160' W 122° 53.1665' 108°


09/28/11 Snow Creek P1010899
N 47° 59.4055' W 122° 53.1648' 333°


09/28/11 Snow Creek P1010902
N 47° 59.3890' W 122° 53.1680' 333°


09/28/11 Snow Creek P1010904
N 47° 59.3852' W 122° 53.0862' 198°


09/28/11 Snow Creek P1010901
N 47° 59.3890' W 122° 53.1680' 0°


09/28/11 Snow Creek P1010903
N 47° 59.2977' W 122° 53.0348' 315°


09/28/11 Snow Creek P1010906
N 47° 59.3333' W 122° 53.1527' 90°


09/28/11 Snow Creek P1010909
N 47° 59.3333' W 122° 53.1527' 18°


09/28/11 Snow Creek P1010905
N 47° 59.3852' W 122° 53.0862' 153°


09/28/11 Snow Creek P1010908
N 47° 59.3333' W 122° 53.1527' 63°


09/28/11 Snow Creek P1010911
N 47° 59.3433' W 122° 53.1987' 0°


09/28/11 Snow Creek P1010913
N 47° 59.3660' W 122° 53.1642' 225°


09/28/11 Snow Creek P1010910
N 47° 59.3333' W 122° 53.1527' 63°


09/28/11 Snow Creek P1010912
N 47° 59.3433' W 122° 53.1987' 63°


09/28/11 Snow Creek P1010915
N 47° 59.4225' W 122° 53.0200' 0°


09/28/11 Snow Creek P1010917
N 47° 59.3913' W 122° 53.0103' 45°


09/28/11 Snow Creek P1010914
N 47° 59.3660' W 122° 53.1642' 18°


09/28/11 Snow Creek P1010916
N 47° 59.4225' W 122° 53.0200' 108°

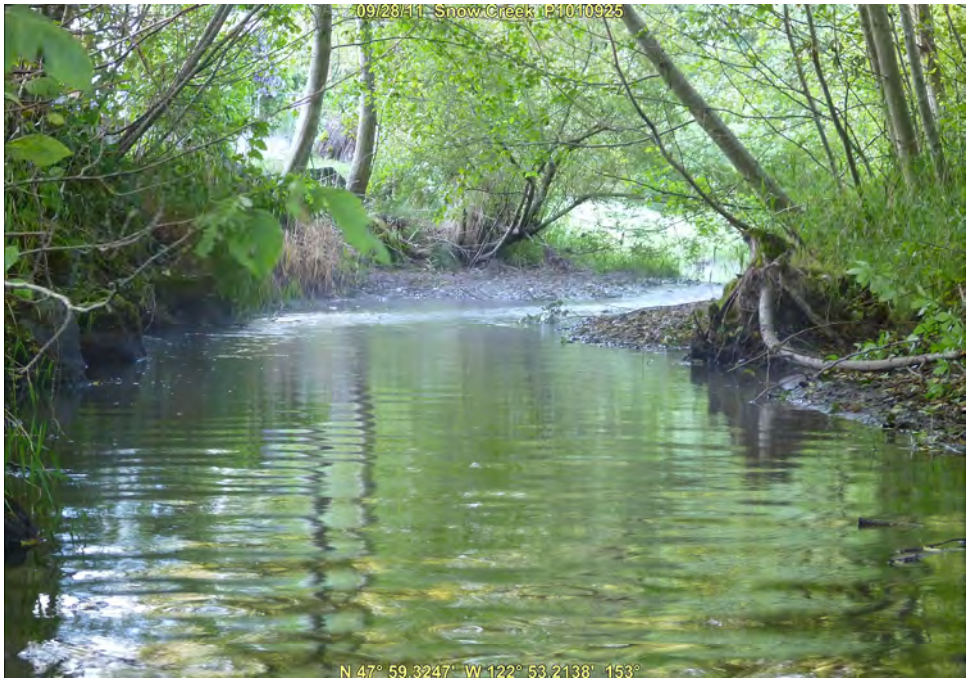

09/28/11 Snow Creek P1010919
N 47° 59.3913' W 122° 53.0103' 288°


09/28/11 Snow Creek P1010921
N 47° 59.3247' W 122° 53.2138' 153°


09/28/11 Snow Creek P1010918
N 47° 59.3913' W 122° 53.0103' 45°


09/28/11 Snow Creek P1010920
N 47° 59.3247' W 122° 53.2138' 198°


09/28/11 Snow Creek P1010923
N 47° 59.3247' W 122° 53.2138' 198°


09/28/11 Snow Creek P1010925
N 47° 59.3247' W 122° 53.2138' 153°


09/28/11 Snow Creek P1010922
N 47° 59.3247' W 122° 53.2138' 243°


09/28/11 Snow Creek P1010924
N 47° 59.3247' W 122° 53.2138' 153°


09/29/11 Snow Creek P1010927
N 47° 59.2500' W 122° 53.1743' 315°


09/29/11 Snow Creek P1010929
N 47° 59.2500' W 122° 53.1743' 225°


09/28/11 Snow Creek P1010926
N 47° 59.3247' W 122° 53.2138' 108°


09/29/11 Snow Creek P1010928
N 47° 59.2500' W 122° 53.1743' 315°


09/29/11 Snow Creek P1010931
N 47° 59.2500' W 122° 53.1743' 108°


09/29/11 Snow Creek P1010933
N 47° 59.2500' W 122° 53.1743' 333°


09/29/11 Snow Creek P1010930
N 47° 59.2500' W 122° 53.1743' 63°


09/29/11 Snow Creek P1010932
N 47° 59.2500' W 122° 53.1743' 333°


09/29/11 Snow Creek P1010936
N 47° 59.2500' W 122° 53.1743' 243°


09/29/11 Snow Creek P1010939
N 47° 59.2500' W 122° 53.1743' 288°


09/29/11 Snow Creek P1010935
N 47° 59.2500' W 122° 53.1743' 18°


09/29/11 Snow Creek P1010938
N 47° 59.2500' W 122° 53.1743' 18°


09/29/11 Snow Creek P1010941
N 47° 59.2500' W 122° 53.1743' 18°


09/29/11 Snow Creek P1010943
N 47° 59.0305' W 122° 52.9582' 45°


09/29/11 Snow Creek P1010940
N 47° 59.2500' W 122° 53.1743' 63°


09/29/11 Snow Creek P1010942
N 47° 59.0305' W 122° 52.9582' 225°


09/29/11 Snow Creek P1010945
N 47° 59.0305' W 122° 52.9582' 63°


09/29/11 Snow Creek P1010947
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010944
N 47° 59.0305' W 122° 52.9582' 108°


09/29/11 Snow Creek P1010946
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010949
N 47° 59.0305' W 122° 52.9582' 153°


09/29/11 Snow Creek P1010952
N 47° 59.0305' W 122° 52.9582' 63°


09/29/11 Snow Creek P1010948
N 47° 59.0305' W 122° 52.9582' 63°


09/29/11 Snow Creek P1010951
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010954
N 47° 59.0305' W 122° 52.9582' 333°


09/29/11 Snow Creek P1010956
N 47° 59.0305' W 122° 52.9582' 243°


09/29/11 Snow Creek P1010953
N 47° 59.0305' W 122° 52.9582' 198°


09/29/11 Snow Creek P1010955
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010958
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010960
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010957
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010959
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010962
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010964
N 47° 59.0305' W 122° 52.9582' 288°


09/29/11 Snow Creek P1010961
N 47° 59.0305' W 122° 52.9582' 243°


09/29/11 Snow Creek P1010963
N 47° 59.0305' W 122° 52.9582' 243°


09/29/11 Snow Creek P1010966
N 47° 59.3460' W 122° 53.1345' 243°


09/29/11 Snow Creek P1010968
N 47° 59.3640' W 122° 53.0930' 288°


09/29/11 Snow Creek P1010965
N 47° 59.0305' W 122° 52.9582' 243°


09/29/11 Snow Creek P1010967
N 47° 59.3455' W 122° 53.1185' 243°


09/29/11 Snow Creek P1010970
N 47° 59.3650' W 122° 53.1260' 180°


09/29/11 Snow Creek P1010972
N 47° 59.3650' W 122° 53.1260' 198°


09/29/11 Snow Creek P1010969
N 47° 59.3650' W 122° 53.1260' 315°


09/29/11 Snow Creek P1010974
N 47° 59.3650' W 122° 53.1260' 45°


09/29/11 Snow Creek P1010974
N 47° 59.3650' W 122° 53.1260' 198°


09/29/11 Snow Creek P1010975
N 47° 59.3650' W 122° 53.1260' 243°


09/29/11 Snow Creek P1010973
N 47° 59.3650' W 122° 53.1260' 108°


09/29/11 Snow Creek P1010976
N 47° 59.3650' W 122° 53.1260' 198°


09/29/11 Snow Creek P1010978
N 47° 59.3647' W 122° 53.1073' 18°


09/29/11 Snow Creek P1010980
N 47° 59.3663' W 122° 53.1220' 63°


09/29/11 Snow Creek P1010977
N 47° 59.3647' W 122° 53.1073' 180°


09/29/11 Snow Creek P1010979
N 47° 59.3663' W 122° 53.1220' 270°


09/29/11 Snow Creek P1010982
N 47° 59.3663' W 122° 53.1220' 243°


09/29/11 Snow Creek P1010984
N 47° 59.3663' W 122° 53.1220' 333°


09/29/11 Snow Creek P1010981
N 47° 59.3663' W 122° 53.1220' 243°


09/29/11 Snow Creek P1010983
N 47° 59.3663' W 122° 53.1220' 333°


09/29/11 Snow Creek P1010986
N 47° 59.3663' W 122° 53.1220' 333°


09/29/11 Snow Creek P1010988
N 47° 59.3663' W 122° 53.1220' 198°


09/29/11 Snow Creek P1010985
N 47° 59.3663' W 122° 53.1220' 333°


09/29/11 Snow Creek P1010987
N 47° 59.3663' W 122° 53.1220' 63°


09/29/11 Snow Creek P1010990
N 47° 59.3663' W 122° 53.1220' 63°


09/29/11 Snow Creek P1010992
N 47° 59.3663' W 122° 53.1220' 153°


09/29/11 Snow Creek P1010989
N 47° 59.3663' W 122° 53.1220' 243°


09/29/11 Snow Creek P1010991
N 47° 59.3663' W 122° 53.1220' 153°


09/29/11 Snow Creek P1010994
N 47° 59.4008' W 122° 53.0530' 135°


09/29/11 Snow Creek P1010996
N 47° 59.4050' W 122° 53.0513' 90°


09/29/11 Snow Creek P1010993
N 47° 59.3938' W 122° 53.0625' 135°


09/29/11 Snow Creek P1010995
N 47° 59.4008' W 122° 53.0530' 333°


09/29/11 Snow Creek P1010998
N 47° 59.4050' W 122° 53.0513' 63°


09/29/11 Snow Creek P1020001
N 47° 59.4222' W 122° 53.0458' 333°


09/29/11 Snow Creek P1010997
N 47° 59.4050' W 122° 53.0513' 108°


09/29/11 Snow Creek P1010999
N 47° 59.4222' W 122° 53.0458' 315°


09/29/11 Snow Creek P1020003
N 47° 59.4905' W 122° 53.0193' 180°


09/29/11 Snow Creek P1020005
N 47° 59.4905' W 122° 53.0193' 18°


09/29/11 Snow Creek P1020002
N 47° 59.4225' W 122° 53.0388' 288°


09/29/11 Snow Creek P1020004
N 47° 59.4905' W 122° 53.0193' 315°


09/29/11 Snow Creek P1020007
N 47° 59.4905' W 122° 53.0193' 288°


09/29/11 Snow Creek P1020009
N 47° 59.4792' W 122° 53.0343' 270°


09/29/11 Snow Creek P1020006
N 47° 59.4905' W 122° 53.0193' 333°


09/29/11 Snow Creek P1020008
N 47° 59.4905' W 122° 53.0193' 288°


09/29/11 Snow Creek P1020011
N 47° 59.4997' W 122° 53.0568' 270°


09/29/11 Snow Creek P1020013
N 47° 59.5152' W 122° 53.0793' 225°


09/29/11 Snow Creek P1020010
N 47° 59.4792' W 122° 53.0343' 288°


09/29/11 Snow Creek P1020012
N 47° 59.4997' W 122° 53.0568' 0°


09/29/11 Snow Creek P1020015
N 47° 59.5152' W 122° 53.0793' 0°


09/29/11 Snow Creek P1020017
N 47° 59.5152' W 122° 53.0793' 153°


09/29/11 Snow Creek P1020014
N 47° 59.5152' W 122° 53.0793' 270°


09/29/11 Snow Creek P1020016
N 47° 59.5152' W 122° 53.0793' 45°


09/29/11 Snow Creek P1020019
N 47° 59.5122' W 122° 53.0728' 270°


09/29/11 Snow Creek P1020021
N 47° 59.5122' W 122° 53.0728' 243°


09/29/11 Snow Creek P1020018
N 47° 59.5152' W 122° 53.0793' 18°


09/29/11 Snow Creek P1020020
N 47° 59.5122' W 122° 53.0728' 243°


09/29/11 Snow Creek P1020023
N 47° 59.5122' W 122° 53.0728' 243°


09/29/11 Snow Creek P1020025
N 47° 59.5122' W 122° 53.0728' 153°


09/29/11 Snow Creek P1020022
N 47° 59.5122' W 122° 53.0728' 243°


09/29/11 Snow Creek P1020024
N 47° 59.5122' W 122° 53.0728' 243°


09/29/11 Snow Creek P1020027
N 47° 58.8507' W 122° 53.1820' 45°


09/29/11 Snow Creek P1020029
N 47° 58.8507' W 122° 53.1820' 315°


09/29/11 Snow Creek P1020026
N 47° 58.8772' W 122° 53.2038' 198°


09/29/11 Snow Creek P1020028
N 47° 58.8507' W 122° 53.1820' 0°


09/29/11 Snow Creek P1020031
N 47° 58.8507' W 122° 53.1820' 315°


09/29/11 Snow Creek P1020033
N 47° 58.8853' W 122° 53.1985' 270°


09/29/11 Snow Creek P1020030
N 47° 58.8507' W 122° 53.1820' 0°


09/29/11 Snow Creek P1020032
N 47° 58.8853' W 122° 53.1985' 0°


09/29/11 Snow Creek P1020035
N 47° 58.8978' W 122° 53.1740' 243°


09/29/11 Snow Creek P1020037
N 47° 58.8978' W 122° 53.1740' 333°


09/29/11 Snow Creek P1020034
N 47° 58.8978' W 122° 53.1740' 315°


09/29/11 Snow Creek P1020036
N 47° 58.8978' W 122° 53.1740' 243°


09/29/11 Snow Creek P1020039
N 47° 58.9268' W 122° 53.2472' 90°


09/29/11 Snow Creek P1020041
N 47° 58.9268' W 122° 53.2472' 0°


09/29/11 Snow Creek P1020038
N 47° 58.8978' W 122° 53.1740' 153°


09/29/11 Snow Creek P1020040
N 47° 58.9268' W 122° 53.2472' 180°


09/29/11 Snow Creek P1020043
N 47° 58.9635' W 122° 53.2233' 225°


09/29/11 Snow Creek P1020045
N 47° 58.9635' W 122° 53.2233' 315°


09/29/11 Snow Creek P1020042
N 47° 58.9268' W 122° 53.2472' 135°


09/29/11 Snow Creek P1020044
N 47° 58.9635' W 122° 53.2233' 0°


09/29/11 Snow Creek P1020047
N 47° 58.9635' W 122° 53.2883' 225°


09/29/11 Snow Creek P1020049
N 47° 58.9635' W 122° 53.2883' 135°


09/29/11 Snow Creek P1020046
N 47° 58.9635' W 122° 53.2233' 153°


09/29/11 Snow Creek P1020048
N 47° 58.9635' W 122° 53.2883' 270°


09/29/11 Snow Creek P1020051
N 47° 58.9635' W 122° 53.2883' 0°


09/29/11 Snow Creek P1020053
N 47° 58.9635' W 122° 53.2883' 90°


09/29/11 Snow Creek P1020050
N 47° 58.9635' W 122° 53.2883' 315°


09/29/11 Snow Creek P1020052
N 47° 58.9635' W 122° 53.2883' 90°


09/29/11 Snow Creek P1020055
N 47° 58.9635' W 122° 53.2883' 63°


09/29/11 Snow Creek P1020057
N 47° 58.9863' W 122° 53.2050' 63°


09/29/11 Snow Creek P1020054
N 47° 58.9635' W 122° 53.2883' 0°


09/29/11 Snow Creek P1020056
N 47° 58.9863' W 122° 53.2050' 108°


09/29/11 Snow Creek P1020059
N 47° 59.0105' W 122° 53.1853' 18°


09/29/11 Snow Creek P1020061
N 47° 59.0325' W 122° 53.2400' 45°


09/29/11 Snow Creek P1020058
N 47° 58.9863' W 122° 53.2050' 18°


09/29/11 Snow Creek P1020060
N 47° 59.0368' W 122° 53.2008' 63°


09/29/11 Snow Creek P1020063
N 47° 59.0325' W 122° 53.2400' 180°


09/29/11 Snow Creek P1020065
N 47° 59.1082' W 122° 53.1867' 243°


09/29/11 Snow Creek P1020062
N 47° 59.0325' W 122° 53.2400' 180°


09/29/11 Snow Creek P1020064
N 47° 59.0325' W 122° 53.2400' 18°


09/29/11 Snow Creek P1020067
N 47° 58.8197' W 122° 53.3202' 108°


09/29/11 Snow Creek P1020070
N 47° 58.7992' W 122° 53.2210' 288°


09/29/11 Snow Creek P1020068
N 47° 58.8082' W 122° 53.2027' 243°


09/29/11 Snow Creek P1020069
N 47° 58.7992' W 122° 53.2210' 225°


09/29/11 Snow Creek P1020072
N 47° 58.7662' W 122° 53.2023' 108°


09/29/11 Snow Creek P1020074
N 47° 58.7607' W 122° 53.1605' 315°


09/29/11 Snow Creek P1020071
N 47° 58.7662' W 122° 53.2023' 225°


09/29/11 Snow Creek P1020073
N 47° 58.7607' W 122° 53.1605' 135°


09/29/11 Snow Creek P1020076
N 47° 59.5877' W 122° 53.2750' 180°


09/29/11 Snow Creek P1020078
N 47° 59.4207' W 122° 53.0350' 135°


09/29/11 Snow Creek P1020075
N 47° 58.7607' W 122° 53.1605' 153°


09/29/11 Snow Creek P1020077
N 47° 59.4207' W 122° 53.0350' 180°


09/29/11 Snow Creek P1020080
N 47° 59.4207' W 122° 53.0350' 45°


09/29/11 Snow Creek P1020082
N 47° 59.4207' W 122° 53.0350' 0°


09/29/11 Snow Creek P1020079
N 47° 59.4207' W 122° 53.0350' 90°


09/29/11 Snow Creek P1020081
N 47° 59.4207' W 122° 53.0350' 0°


09/29/11 Snow Creek P1020084
N 47° 59.4117' W 122° 53.0263' 243°


09/29/11 Snow Creek P1020083
N 47° 59.4117' W 122° 53.0263' 315°

Appendix E

Two-Dimensional Hydraulic Model Memorandum

Cardno ENTRIX
200 1st Ave West
Seattle, WA, 98119
206-239-0276 | Fax 206-269-0098
www.cardnoentrix.com

Date: July 10, 2012

To: Kevin Long, North Olympic Salmon Coalition

cc: Rebecca Benjamin, North Olympic Salmon Coalition

From: Eliza Ghitis and Chad Krofta, Cardno ENTRIX

Re: **Snow Creek Restoration Project Preliminary Two-Dimensional Hydraulic Model Shear Velocity Results**

This memorandum summarizes the results of a two-dimensional hydraulic model performed by Cardno ENTRIX for the Snow Creek Estuary Restoration Project (Project). The recommendations and results provided are based on the data available to Cardno ENTRIX at the time of this memorandum. Therefore, these results should only be used in conjunction with a good understanding of the assumptions and limitations guiding this analysis.

Methods

A two-dimensional hydraulic computer model (River2D) was run under existing conditions and under a new alternative 50% design proposed condition. The existing conditions topography utilized the combined 2002 LiDAR/ 2011 Cardno ENTRIX ground survey DEM. The design-proposed conditions incorporated the following additional features (see Figure 1):

1) Dredge spoil/fill soil removal along channel banks downstream of SR 20 (with the exception of the Sea-Kota property on the left bank),

2) Removal of the railroad grade up to the Calero property line, and

3) Removal of dredge spoil/fill soil on the delta surface within the existing estuary to an average of 7 feet elevation (NAVD 88).

The sediment-transporting ability of the flow can be represented by the *shear velocity*, which scales with rates of bedload sediment transport and is defined by Equation 1:

Equation 1: $$V^* = \sqrt{(g\ R\ S_f)}$$

Where V^* = the shear velocity
g = gravitational constant (9.81 m/s^2)
R = hydraulic radius (the cross sectional area of flow divided by the wetted perimeter)
S_f = friction slope

The *critical* shear velocity (V^*_c) is the value of V* for which sediment of a specified size first begins to move.

Shear velocities were modeled throughout the project reach for the estimated 2-year flow (443 cfs) and the estimated 100-year flow (1,909 cfs) with a downstream boundary condition of MHHW (6.38 ft NAVD 88). For each flow, the shear velocity output was classified in ArcGIS using the values found in the U.S. Army Corps of Engineers empirical measurements of critical shear velocity for entrainment of particles of different sizes (Fischenich 2001). These values give a range of critical shear velocities required to initiate motion for each particle size (Table 1). While these shear velocity classes indicate the particle sizes that would be entrained at a given value, sediment transport will also be influenced by flow variability (pulses of higher velocity which may occur), suspended sediments (which can dampen turbulence), and particle interactions. In mixtures of particle sizes, coarser sediment will be entrained with lower shear velocity than predicted in Table 1, while the fine particles will require a higher shear velocity than predicted by Table 1. Because of this variability, the model output should be considered only an estimate of potential sediment transport, assuming minimal clast interactions and a constant sediment supply. The output is most useful in comparing the spatial patterns of predicted sediment mobilization, and the differences (if any) between current and future scenarios.

Table 1: Critical shear velocity for entrainment of particles of different sizes (adapted from Fischenich 2001).

Particle Class	Minimum Particle Diameter (mm)	V^*_c (m/s)
Boulder		
Very large	2032	1.329
Large	1016	0.939
Medium	508	0.671
Small	254	0.469
Cobble		
Large	127	0.329
Small	64	0.229
Gravel		
Very coarse	33	0.158
Coarse	15	0.110
Medium	8	0.073
Fine	4	0.052
Very fine	2	0.037
Sands		
Very coarse	1.02	0.021
Coarse	0.51	0.017
Medium	0.25	0.014
Fine	0.13	0.012
Very fine	0.08	0.011
Silts		
Coarse	0.05	0.009
Medium	0.03	0.008

Results

Shear velocity output from the 2-dimensional model were correlated to potential particle entrainment size according to Table 1. The particle entrainment potential was then plotted on the project base map (Figures 2 to 5) and the results were compared to field data of substrate size collected through Wolman pebble counts at 3 locations in the channel.

The changes seen between existing and proposed conditions at the 2-year flow (443 cfs) at MHHW (6.38 ft NAVD 88) were as follows:

- Upstream of SR 20, shear velocities decrease from values correlated to a range of medium gravel to cobble to a range of silt to fine gravel. This reduction in sediment entrainment capacity appears to be the result of lowered flood elevations throughout this reach due to increased conveyance capacity below SR 20.
- Just downstream of SR 20, the existing channel bed elevation is approximately equal to the proposed marsh surface elevation (~7 feet NAVD88). Therefore, removal of dredge spoils/fill soils from the right bank of Snow Creek within the reach just downstream of SR 20 to an elevation of ~7 feet NAVD88 would eliminate the defined stream channel through this reach. The lack of a defined stream channel causes even low streamflows to "fan out" into the estuary after passing under the SR 20 bridge.
- In the 700 feet downstream of SR 20, shear velocities in the channel under existing conditions correspond to medium to very coarse gravel sizes. The median grain size in the channel as measured in the field downstream of SR 20 ranged from medium gravel to very coarse gravel. Therefore, the modeled existing condition substrate size aligns well with this field measured value. Under proposed conditions, shear velocities here are reduced to values ranging from silt to very fine gravel.
- Downstream of this 700-foot reach, the 2-year flow velocities at MHHW are reduced below the threshold for sediment incipient motion in the channel. Although no modeling of low-tide water levels has been performed to date, it is almost certain that at MLLW the gradient of the water surface is sufficient to allow the 2-year flow to entrain sediment. At the mudflat north of the Snow Creek outlet into Discovery Bay, combined flows with Salmon Creek are sufficient to mobilize particles in the silt to fine gravel range even during high tides.
- On the delta surface, the existing conditions model indicates that most values of shear velocity fall in the range of very coarse sand to very fine gravel. The shear velocities capable of transporting material are concentrated in the existing tidal sloughs and the drainage ditch since flow is concentrated in these areas. While water depth will increase in the vicinity of the removed dredged spoils and excavated marsh under proposed conditions, shear velocities will be reduced below the threshold for sediment transport for the entirety of the vegetated salt marsh. This indicates that at the model conditions of 2-year flow and MHHW, no appreciable sediment deposition will occur, except for fines settling out of suspension.

The changes observed between existing and proposed conditions at the 100-year flow (1,909 cfs) and MHHW (6.38 ft NAVD 88) were as follows:

- The area upstream of SR 20 shows no change to shear velocity and thus no change to sediment transport conditions. These results also show some lowering of the 100-year flood elevation upstream of US 101 (Figures 6 to 7), owing to reduced backwater effects farther downstream from the less constrained channel after berm removal.
- Within the channel downstream of SR 20, the modeled existing conditions indicate entrainment of coarse gravel to cobbles during this event. Reduction of the shear velocities in the channel under proposed conditions suggest that large and rare events may shift sediment deposition towards a finer size range within this reach (i.e., to very coarse sand–coarse gravel).

- The introduction of flows and hence shear velocity on the right-bank floodplain suggests that a range of sediment sizes could accumulate in this area during large floods. On the right bank downstream of the removed railroad grade, the existing potential sediment transport was focused in the vegetated swale at values for silt to very fine gravel, and the areas in and around the Moa well drainage ditch and existing tidal slough at values for coarse sand to medium gravel. Under proposed conditions, the model showed the entire right-bank floodplain as a potential zone for very fine to very coarse gravel entrainment. A flood event of this magnitude is capable of scouring sediments in this range that have accumulated on the marsh surface. Areas of low elevation due to localized scour would then become sites of preferential sediment deposition under more moderate flows.
- Increased shear velocities in the Moa well drainage ditch could coarsen the substrate materials from very fine gravel to medium gravel, while flushing finer sediments through. While dynamic modeling of tidal flushing has not been completed to date, it can be hypothesized that finer sediments deposited during smaller flood events will be flushed from this channel during the regular tidal cycle.
- Overbank flows at 100-yr flood during MHHW will be able to deposit sand and gravel on the left-bank floodplain in the newly excavated areas and more coarse gravel on the marsh north of the excavated areas, with values shifting from the range of sand to fine gravel under existing conditions to the medium to coarse gravel range under proposed conditions.
- The results generally show increased inundation of the estuary throughout the project area with decreased inundation of the Sea-Kota property (Figures 6-7).

Conclusions

The following paragraphs summarize the key changes that may be experienced within the analyzed portion of the system under proposed conditions:

- Snow Creek Channel Upstream of SR 20: Sediment transport capacity within the Snow Creek channel upstream of SR 20 may remain the same or be decreased during small, frequent flow events (i.e. the 2-year event) but is generally maintained during larger flood events (i.e. the 100-year flood). Therefore, this non-tidal section of channel is likely to undergo periods of aggradation and substrate fining during small events followed by scouring and flushing during larger, less frequent flows. No increase in significant flood impacts are therefore anticipated.
- Floodplain Upstream of SR 20: Within the floodplain upstream of SR 20, the model results indicate no change to shear velocity and thus no change to sediment transport conditions. These results also show some lowering of the 100-year flood elevation upstream of US 101, owing to reduced backwater effects from the less constrained channel after berm removal downstream.
- Snow Creek Channel Downstream of SR 20: Removal of dredge spoils and fill from the right bank of Snow Creek to an elevation of ~7 feet (NAVD88) downstream of SR 20 would eliminate the defined stream channel. The lack of a defined stream channel causes even low streamflows to “fan out” into the marsh surface after passing under the SR 20 bridge. This lack of a defined channel reduces sediment transport capacity of both

freshwater and tidal flows, but it also greatly expands the area over which sediment can be deposited. The area presently occupied by the Snow Creek channel downstream of SR 20 will experience aggradation and fining of sediments under 2-year and 100-year flows as sediment entrainment capacity is reduced under both small, frequent flows and large, infrequent flows. Although dynamic tidal modeling has not been completed for the project area, it is expected that creek flows during periods of ebbing tides will flush some of these finer sediments during each tidal cycle. The channel response to bed aggradation may be avulsion and/or the formation of distributary channels on the delta. This would represent the resumption of natural delta channel dynamics that had been limited by artificial constraints, and minimize the consequences of subsequent aggradation by spreading the volume of deposited sediment over a much wider area.

- Floodplain and Delta Downstream of SR 20: Within the floodplain and delta downstream of SR 20, the results generally show increased inundation throughout the project area, but with decreased inundation of the Sea-Kota property. The restored connection between Snow Creek and its floodplain during out-of-bank events will result in an increased potential for fine sand to coarse gravel sediment accumulation on the marsh surface and within tidal slough channels. Although dynamic tidal modeling has not been completed for this tidal section of the project area, it is expected that freshwater flows and ebbing tides will flush some finer sediments from slough channels, including the Moa well drainage ditch, during each tidal cycle. The result may be coarsening of the slough channel bed substrates and possibly some aggradation of the slough channel beds and marsh surface.

Recommendations

The results of this analysis indicate that if sediment supply and watershed hydrology remain constant in the future, flooding and sediment transport conditions are likely to remain unchanged on the private properties upstream and adjacent to the project area under proposed conditions. Generally, model results indicate a reduction in flood extents on these properties due to proposed conditions. Within the delta and project area, the Snow Creek channel and the re-connected tidal plain and slough channels may experience more frequent and deeper levels of inundation. The Snow Creek channel bed substrate is likely to become finer, while the estuary and slough channels may see an influx of coarser sediments. Avulsion of the Snow Creek channel to new paths within its estuary and/or the formation of multiple distributaries is also possible as the channel aggrades. This would represent the resumption of natural delta channel dynamics that had been limited by artificial constraints. Because the additional modeling indicates that natural dynamic process can be restored to the project area without impacting flood or sediment transport conditions on adjoining or upstream private properties, Cardno ENTRIX recommends the following adjustments to the 50% design plans:

- Removal of dredge spoils/fill soils from the Snow Creek delta and banks within the project area to an elevation of approximately 7 feet (NAVD88) in a manner which allows for low flow and small event (less than 2-year event) conveyance through the reach to Discovery Bay.

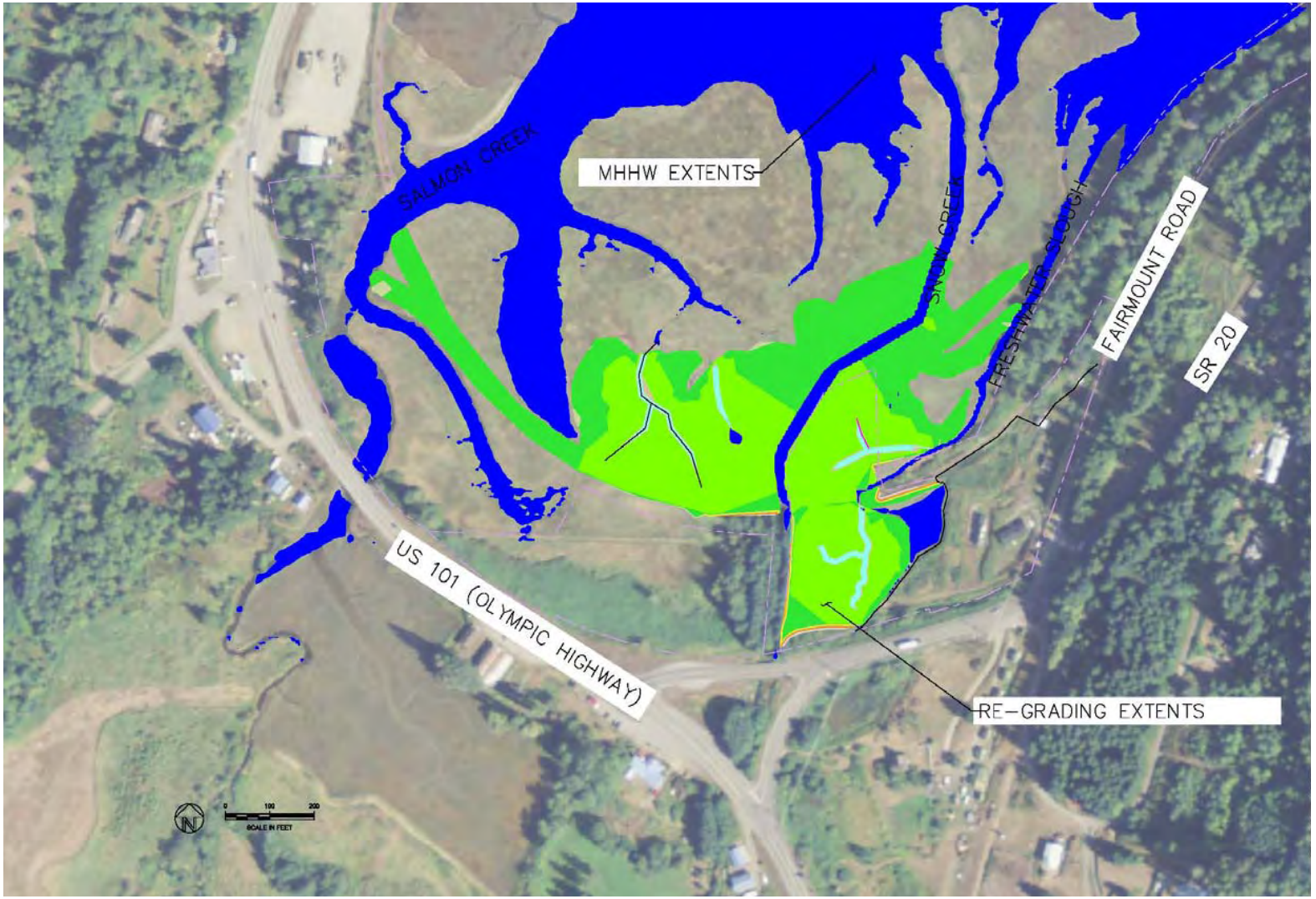


Figure 1: Alternative 50% design proposed grading extents

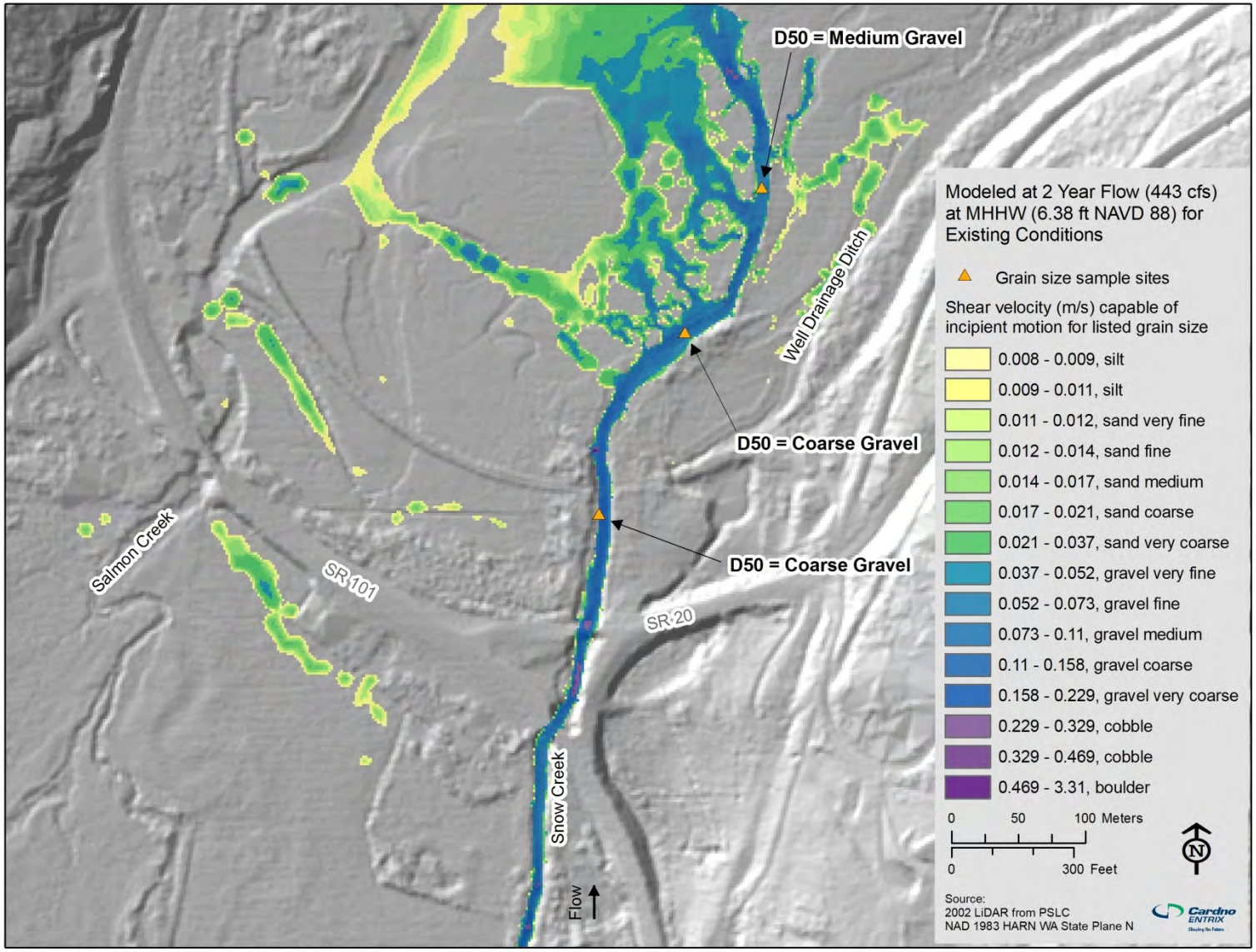


Figure 2: Existing conditions shear velocity model results in the Snow Creek Project Area for 2-year flow (443 cfs) at MHHW (6.38 ft NAVD 88).

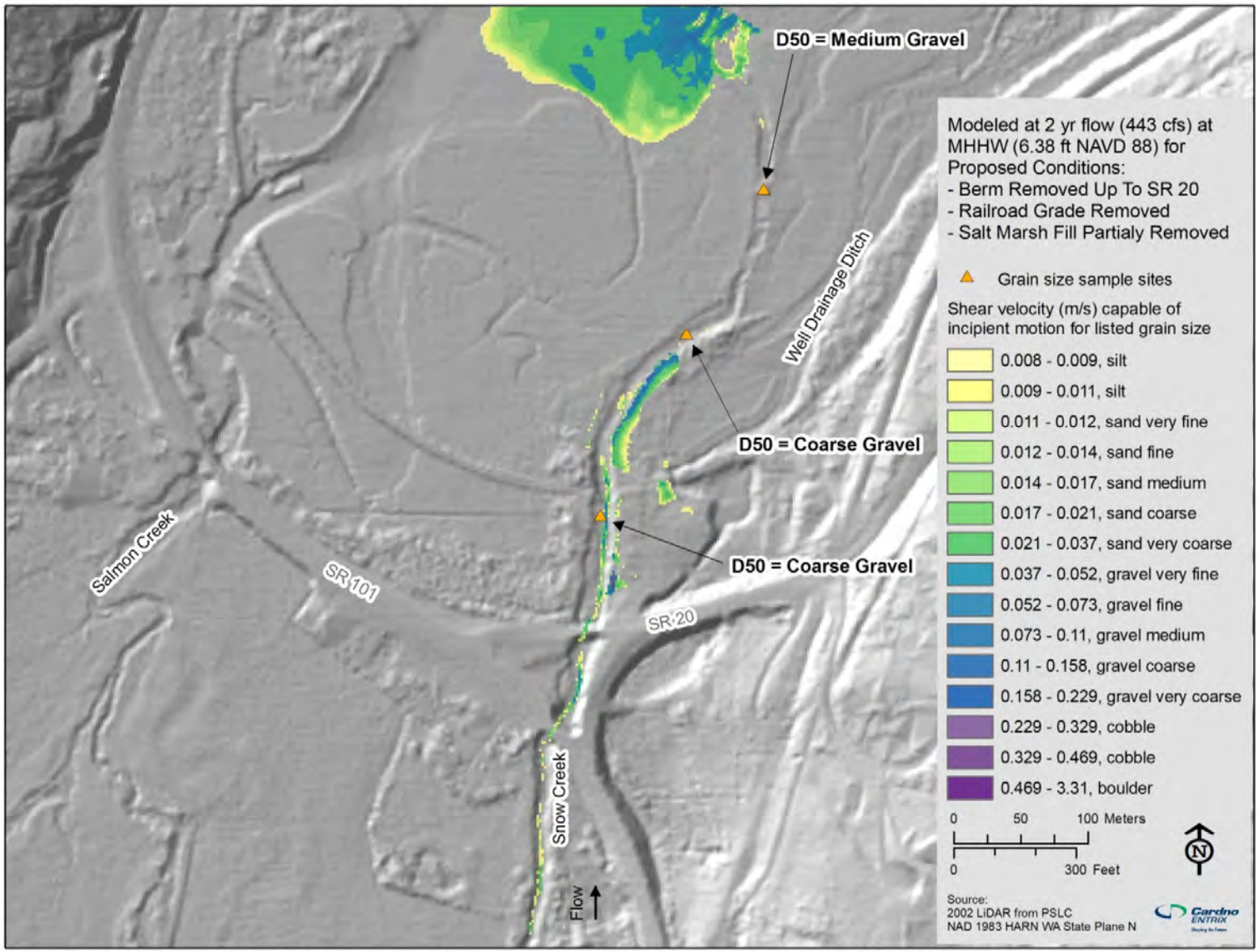


Figure 3: Proposed conditions shear velocity model results in the Snow Creek Project Area for 2-year flow (443 cfs) at MHHW (6.38 ft NAVD 88).

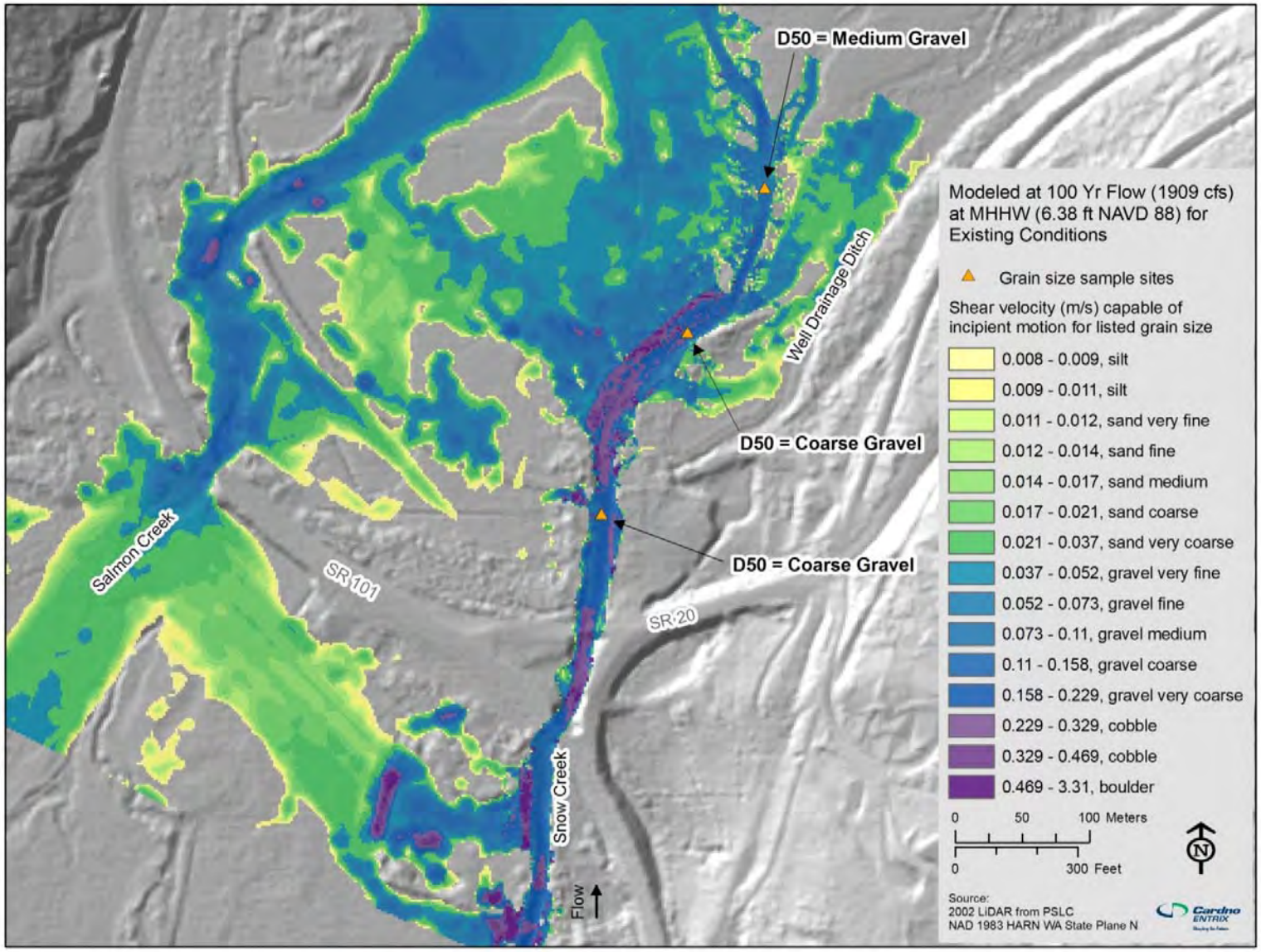


Figure 4: Existing conditions shear velocity model results in the Snow Creek Project Area for 100-year flow (1909 cfs) at MHHW (6.38 ft NAVD 88).

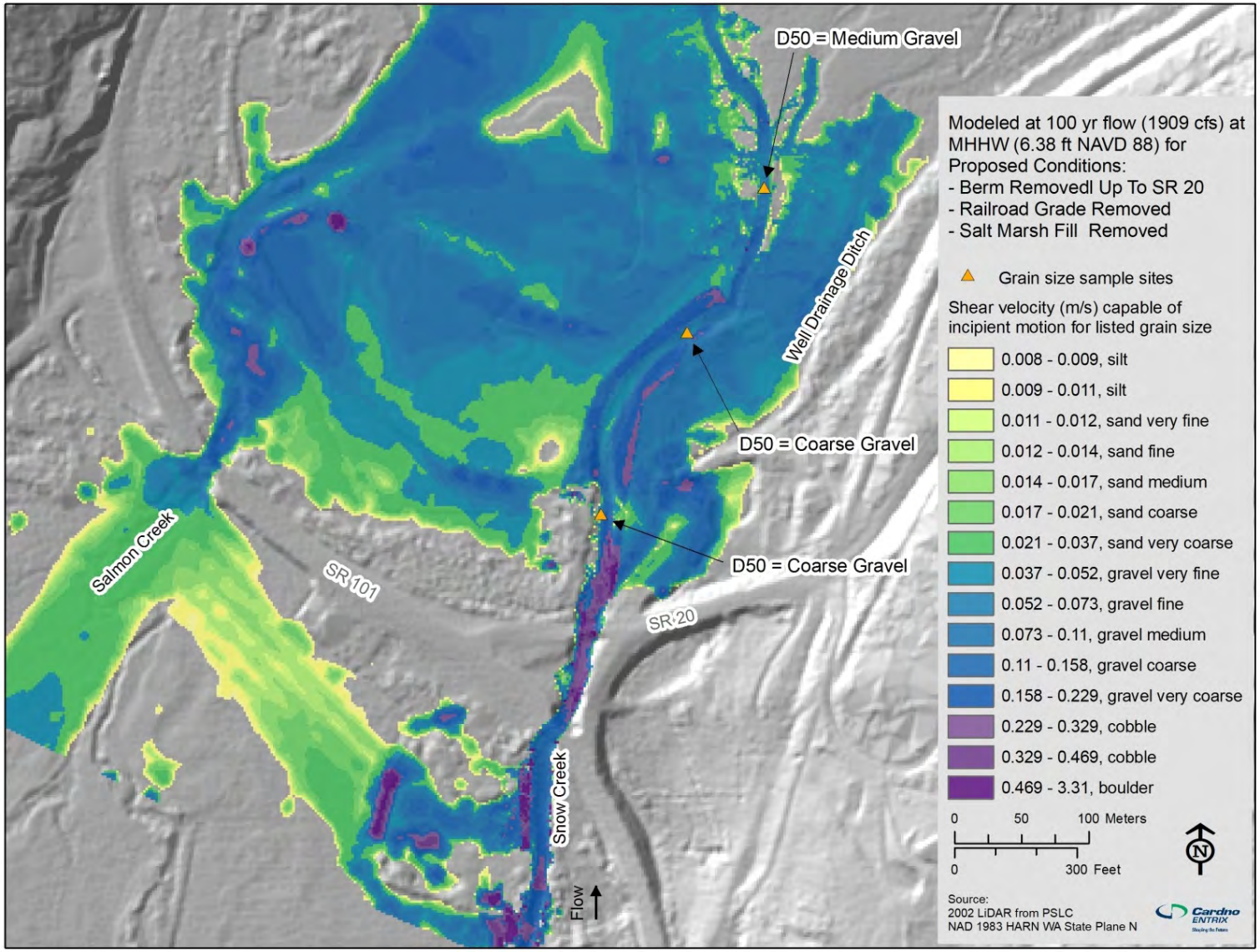


Figure 5: Proposed conditions shear velocity model results in the Snow Creek Project Area for 100-year flow (1909 cfs) at MHHW (6.38 ft NAVD 88).

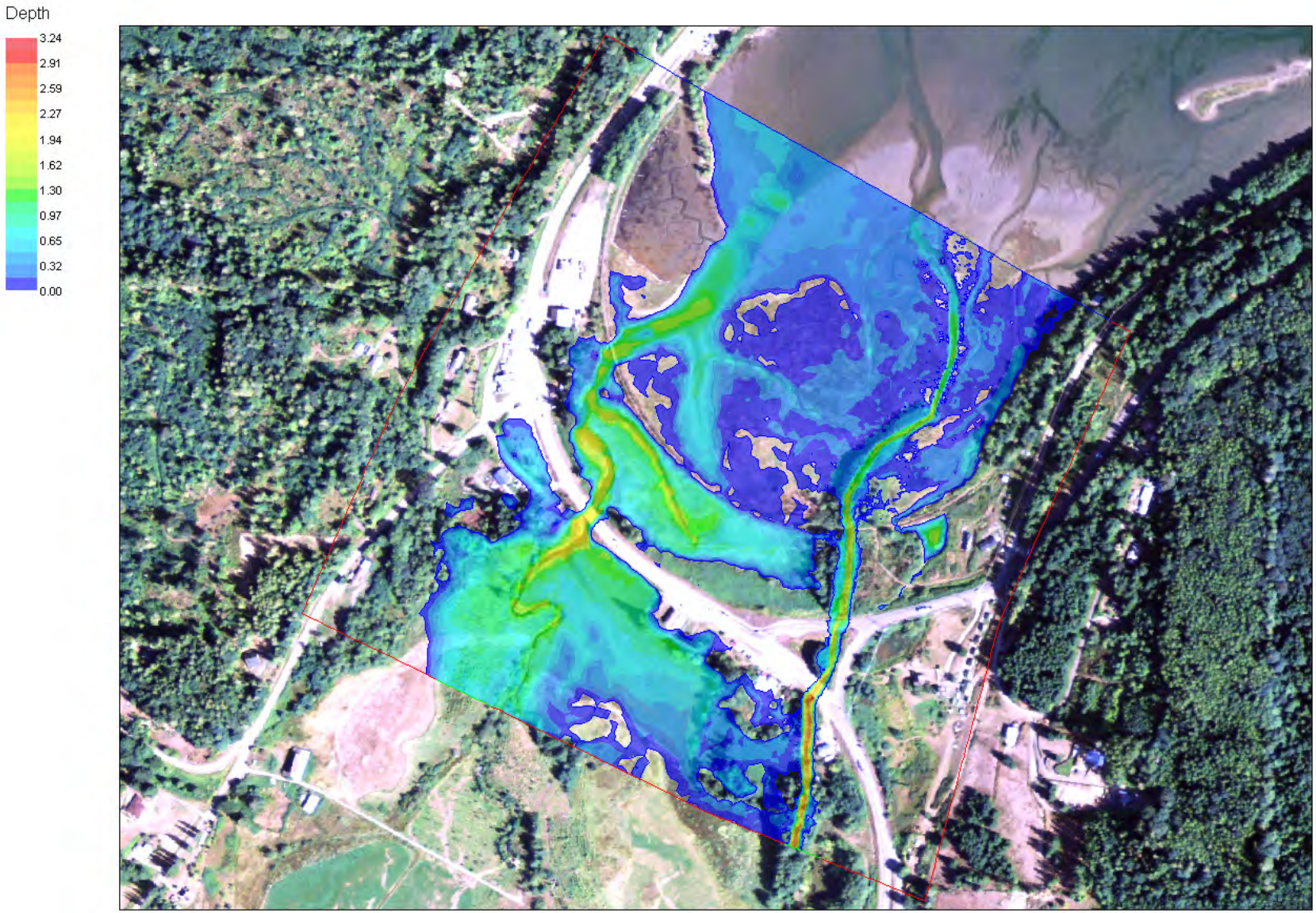


Figure 6: Existing conditions flow depth model results in the Snow Creek Project Area for 100-year flow (1909 cfs) at MHHW (6.38 ft NAVD 88).

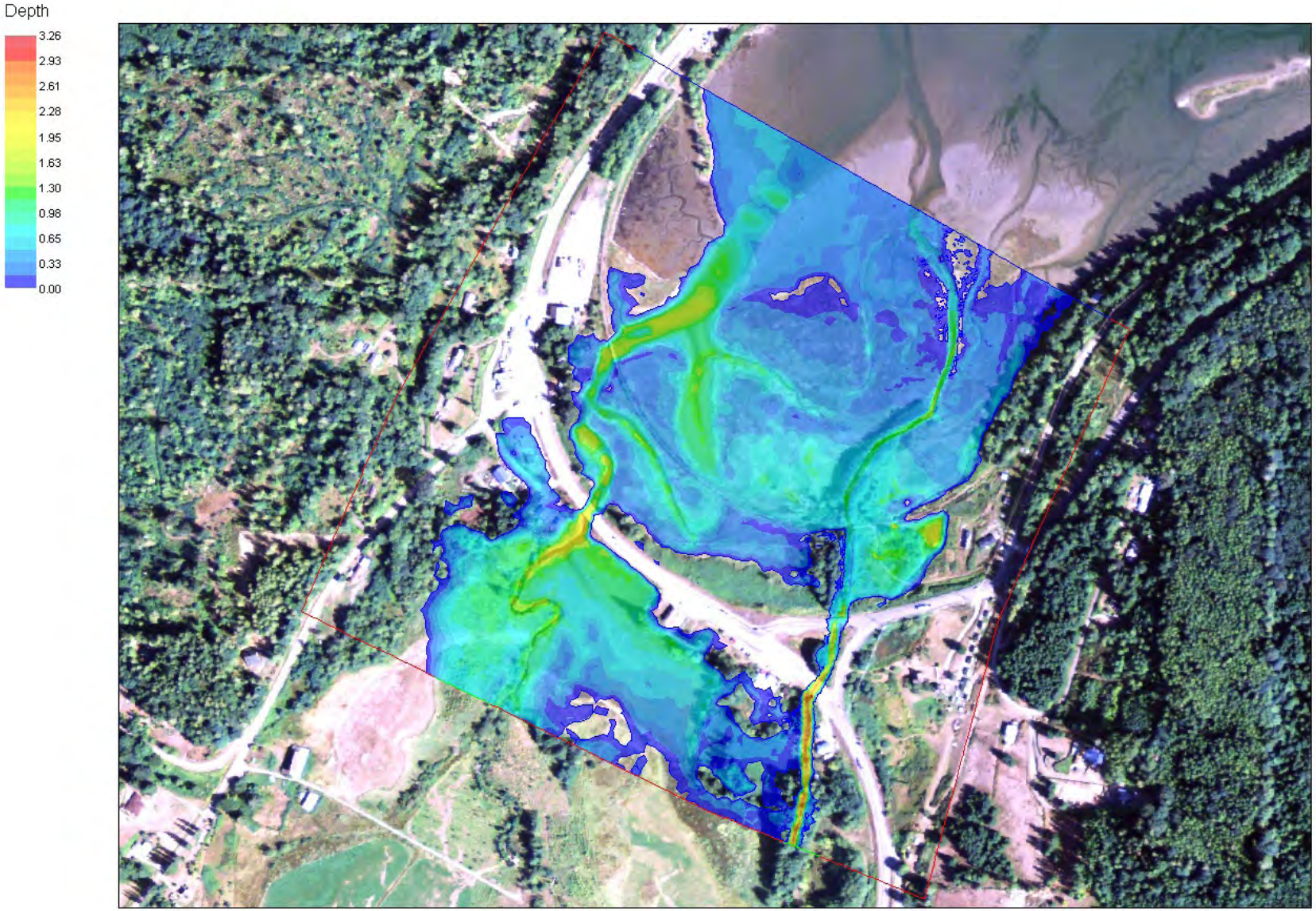


Figure 7: Proposed conditions flow depth model results in the Snow Creek Project Area for 100-year flow (1909 cfs) at MHHW (6.38 ft NAVD 88).

References

Fischenich, C. 2001. Stability Thresholds for Stream Restoration Materials. USAE Research and Development Center, Environmental Laboratory. ERDC TN-EMRRP-SR-29

Cardno ENTRIX

Shaping the Future

Down to Earth.

Down to Business.™



Toll-free 800 368 7511
www.cardnoentrix.com
www.cardno.com