Feasibility Report Engineering Appendix

Spencer Island Ecosystem Restoration Annex D: Hydrology, Hydraulics and Coastal Engineering

Snohomish County, WA

January 2026 35% ATR

Contents:

Prepared by

US Army Corps of Engineers®

Seattle District

Feasibility Report Engineering Appendix

Spencer Island Ecosystem Restoration HH&C Annex D1: Hydrology & Hydraulics for Feasibility Phase

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Contents

Figures

Tables

1. Overview

This hydraulics, hydrology and coastal (HH&C) Annex compiles existing conditions hydrologic, hydraulic, coastal, topographic and geomorphic data at the Spencer Island project site. This annex also compiles preliminary hydraulic modeling performed to refine the design of the Tentatively Selected Plan. This annex also includes a GIS analysis of the Spencer Island marsh tidal channel network and topography relevant for ecosystem restoration project design. The same analysis was performed on nearby Snohomish River estuary reference sites including the north tip of south Spencer Island, Otter Island, Mid-Spencer, Smith Island (Figure 1) to differentiate sites that are higher functioning ecologically and to develop restoration metrics from that data.

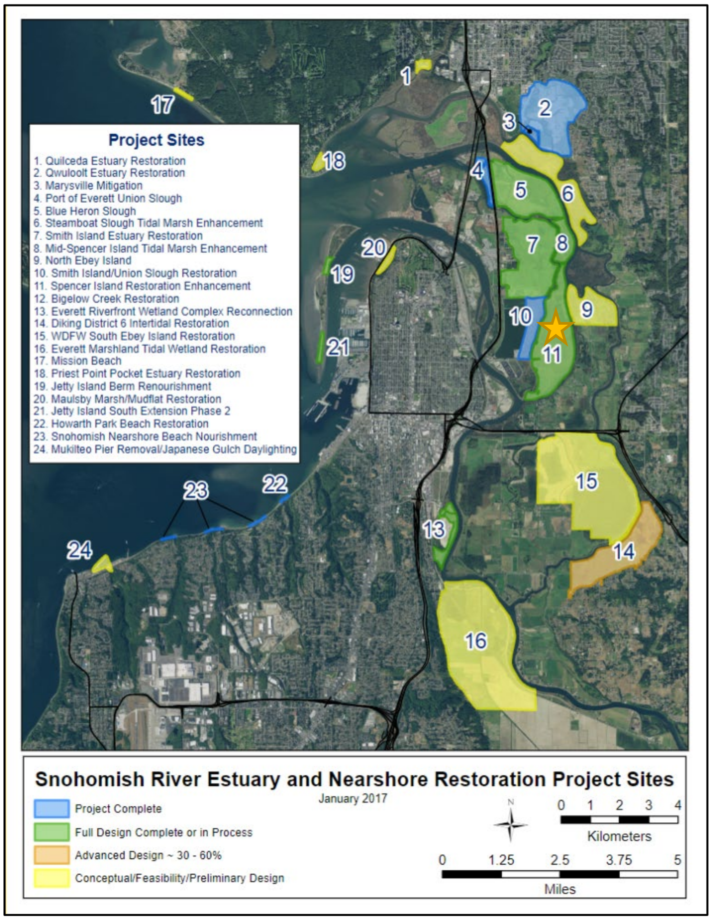


Figure 1. Spencer Island ecosystem restoration project in context with nearby completed and proposed projects. Spencer Island is starred (site 11).

2. Site Data

2.1. Project Area

The Spencer Island ecosystem restoration project (project) drains a combined 1,665 square miles of the Snohomish River basin (Figure 2). The project area (Figure 3) is bounded by the City of Everett wastewater treatment plant and Union Slough ecosystem restoration project to the west, the north tip of Ebey Island and southern half of Otter Island to the east, Ebey Island and US Highway 2 to the south and west, and the Buse Cut and Mid-Spencer Island to the north. The entire island is part of unincorporated Snohomish County. Land ownership is divided roughly equally in terms of area between Snohomish County and the State of Washington (WDFW). The municipal boundary between the City of Everett and State and County land is the centerline of Union Slough. The County has zoned the island and surrounding area as density fringe (Figure 4), which strictly limits development, due to the importance of the island for conveying floodwaters.

According to Table 2 of the WDFW Desktop Review (WDFW, 2023), several easements are present on the site. Easements have been granted to the WA DNR, Northwest Pipeline Corp., Puget Sound Energy, Dike District #5, Snohomish County PUD, and the RCO.

Location data:

PLSS: Township 29N, Range 5, Portions of sections 10, 15, 16, 21, 22

City: Unincorporated

County: Snohomish County

State: Washington

Basin: Snohomish

River: Snohomish River, Union Slough, Steamboat Slough

Tributary drainage area: 1,665 square miles

River Mileage: Steamboat Slough: 3.65 to 5.95; Union Slough: 2.86 to 5.03.

Land Ownership: State of Washington, Snohomish County

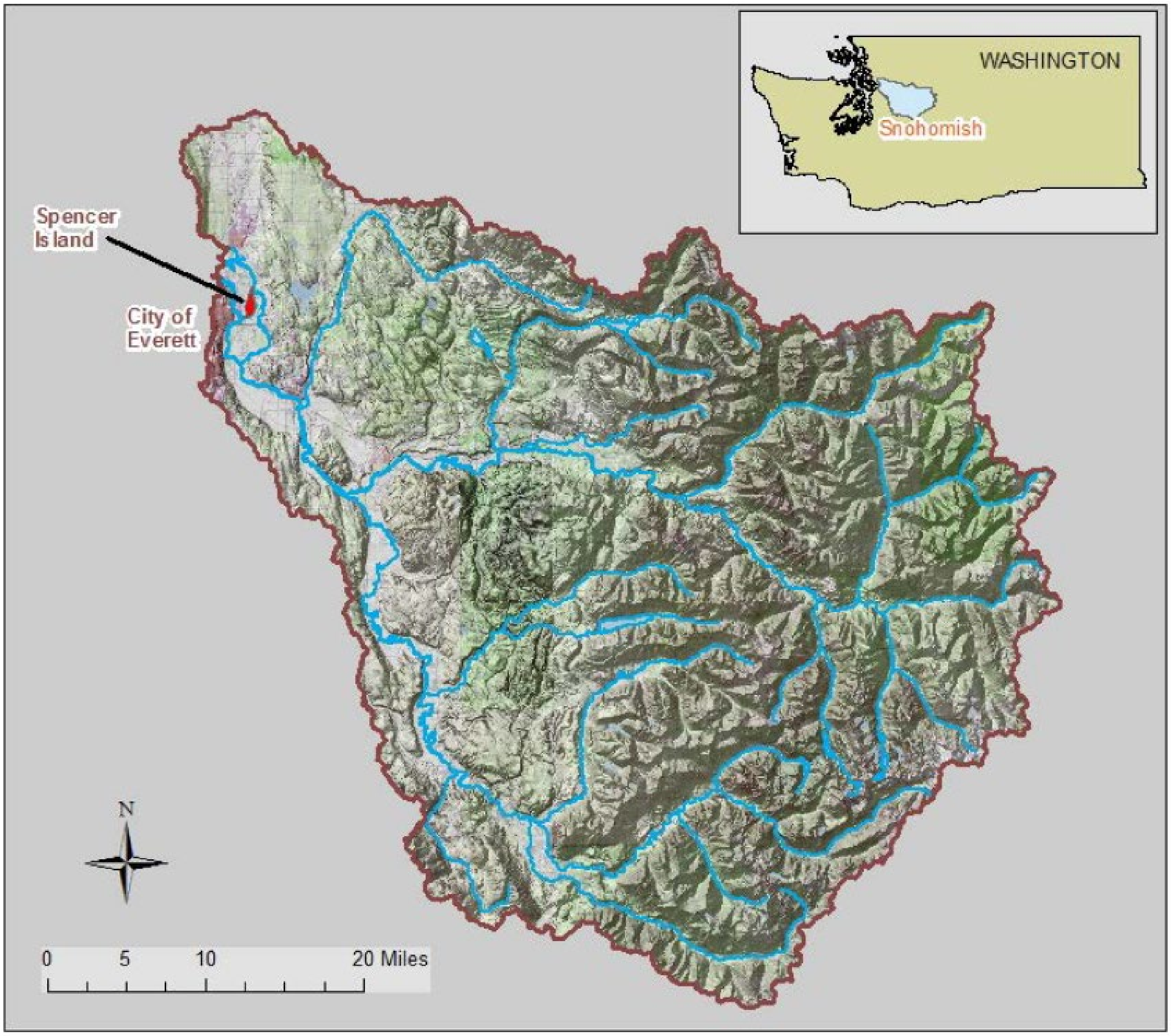


Figure 2. Spencer Island and Snohomish River watershed

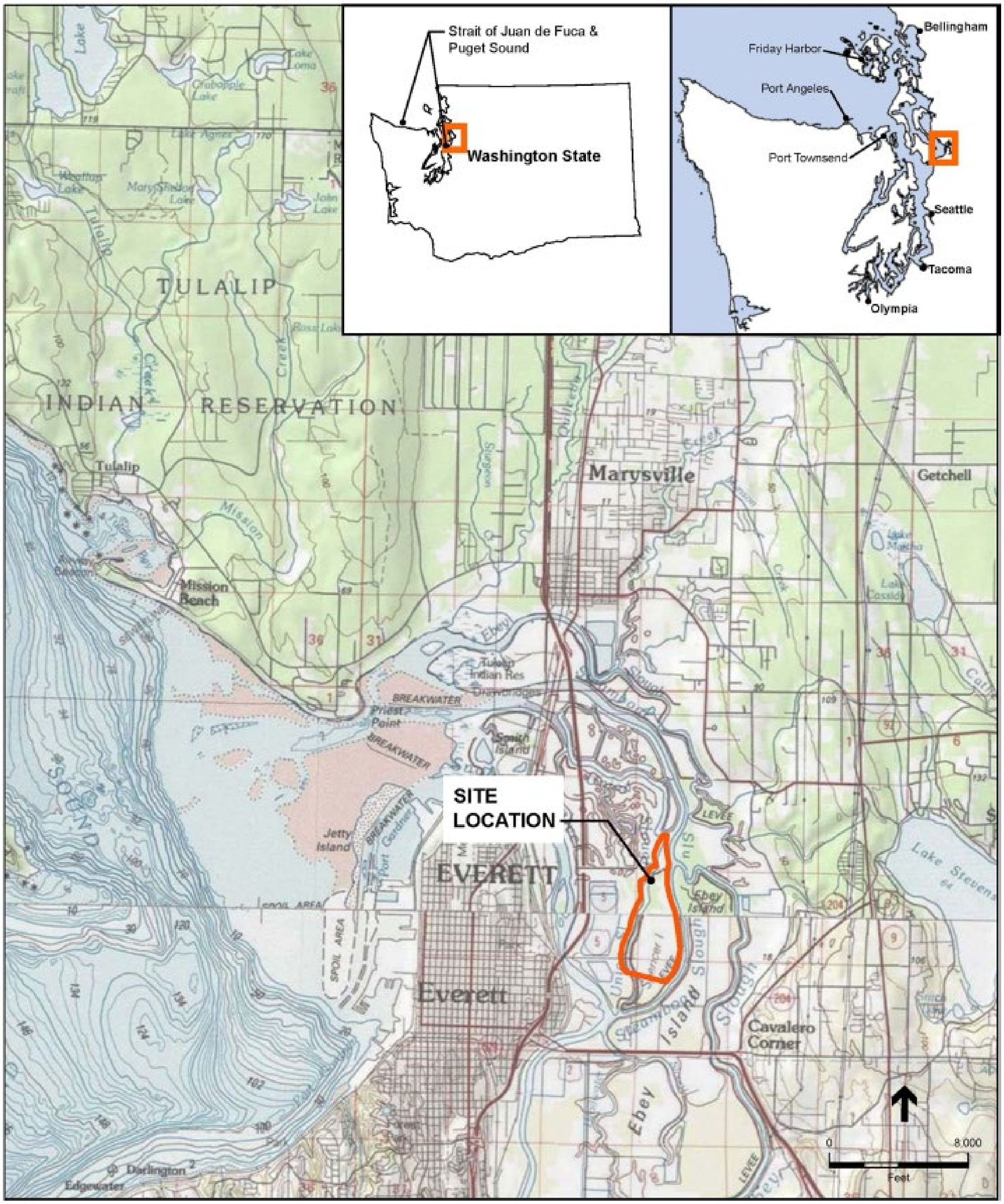


Figure 3. Spencer Island and Vicinity

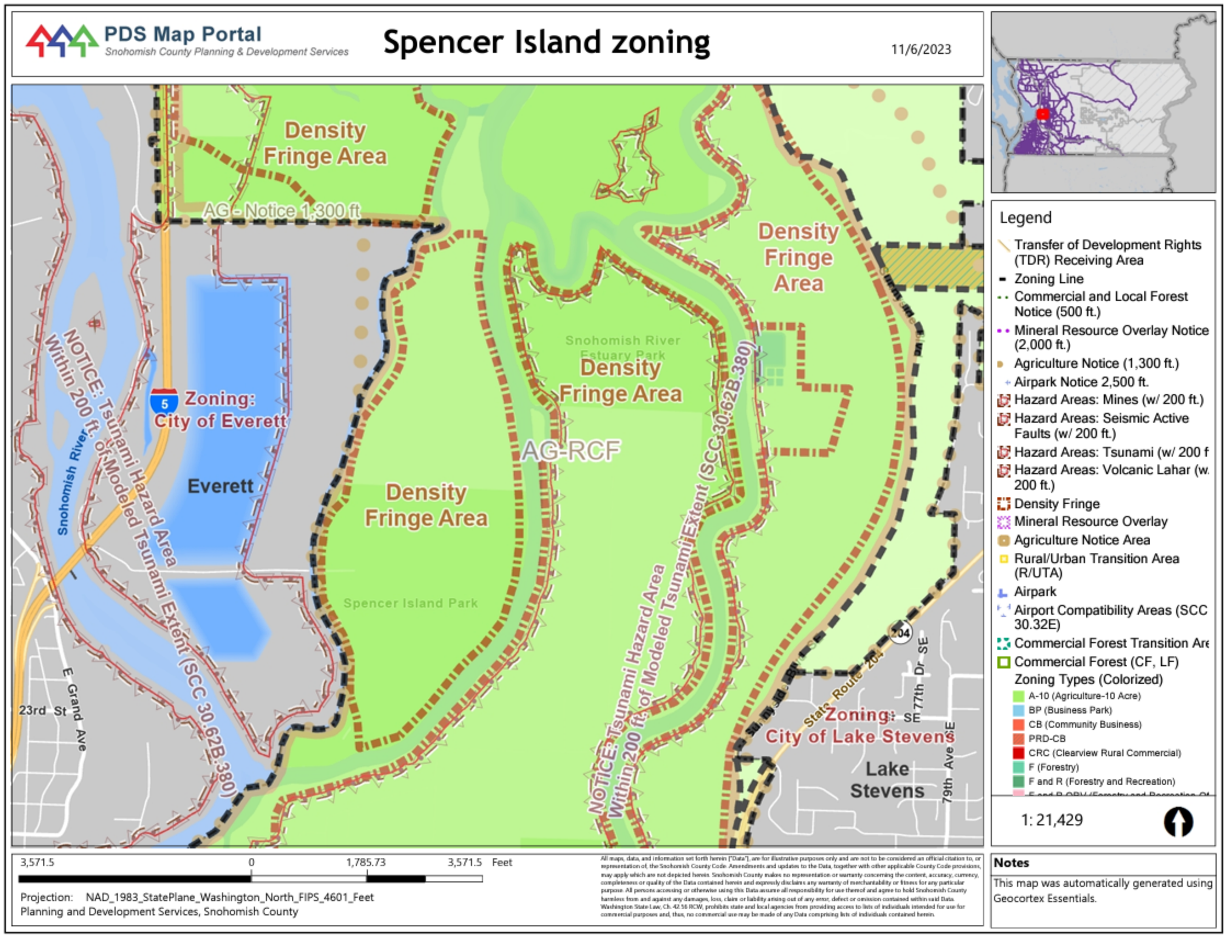


Figure 4. Snohomish County zoning in the vicinity of Spencer Island

2.2. General Site conditions

Per Salish Sea Wiki:

> *The Snohomish is one of the largest river delta sites in Puget Sound. Recovery of historical wetland area is a target of Salmon Recovery in the Snohomish Watershed. Portions of the Estuary are in the City of Everett but most are in Snohomish County. It is in usual and accustomed harvest areas of the Tulalip Tribes of Washington with portions within the tribal reservation. The lower delta is being modified under a series of large scale restoration projects including Qwuloolt Restoration, Smith Island Restoration, and Blue Heron Mitigation Bank among others. These projects are reestablishing a large area of tidal inundation in the saline mixing zone, and when complete will be the largest estuary restoration by area in Puget Sound. Upstream, freshwater tidal lands are in agricultural production, divided into diking districts such as Marshlands and Ebey Island, and depend on diking and pumping to lower water tables. There is controversy over the loss of agricultural lands as Snohomish County works to increase Snohomish Agricultural Resilience. Sea Level Rise effects may be important to long term planning. The Estuary is a study area of the Snohomish Sustainable Lands Strategy.*

3. Hydrology

Spencer Island is located between two Snohomish River distributary channels (Union Slough to the west, Steamboat Slough to the east). Union Slough reportedly forms the natural boundary between fresh water tidal wetland zone and the brackish tidal wetland zone (Collins 2002). The site and connected slough channels experience daily tidal fluxes from Puget Sound. Due to the difference in channel length and size between the mainstem and distributary channels, high and low tides occur at slightly different times. This results in dynamic conditions where upstream and downstream tidal fluxes can occur simultaneously in the mainstem and slough channels on incoming and outgoing tides depending on the location and phase of the tide cycle.

3.1. Tides

For feasibility level analysis and design tidal datums for the site are based on Seattle. Tidal hydrology is summarized below in Table 1 and Table 2. Note that the influence of backwater in the Sloughs likely results in a vertical shift upwards in these datum planes as well as a phasing lag for tides. Stage recorders can be installed in the site to provide a local to Seattle correlation to transfer the datum planes with more reliability.

Modeling work completed by USACE for the nearby Qwulloolt project indicates that the Seattle tide station best captures the tidal amplitude at the site, although the phasing can differ by up to an hour. Conversations with Watershed Science and Engineering, Inc who developed a fully 2D HEC-RAS model for the valley (WSE 2021) confirmed the validity of this observation.

Table 1. Seattle Tidal datums used for project site

Datum	Value	Description
MHHW	9.02	Mean Higher-High Water
MHW	8.15	Mean High Water
MTL	4.32	Mean Tide Level
MSL	4.3	Mean Sea Level
DTL	3.34	Mean Diurnal Tide Level
MLW	0.49	Mean Low Water
MLLW	-2.34	Mean Lower-Low Water
NAVD88	0	North American Vertical Datum of 1988

Table 2. Seattle tide station extremes

Max Tide	12.77	Highest Observed Tide
Max Tide Date & Time	12/27/22 8:36	Highest Observed Tide Date & Time
Min Tide	-7.38	Lowest Observed Tide
Min Tide Date & Time	1/4/1916 0:00	Lowest Observed Tide Date & Time

Tidal extreme water level frequency data are shown below for the Seattle gage using the peak over threshold method (Table 3, Figure 5). The latest total water level flood frequency estimates include the December 2023 flood of record. That event exceeds the largest previously observed event by more than 0.5 feet and is higher than the previous 500-year tide estimate. The flood was a combination of annual king tides and a storm that had one of the lowest atmospheric pressures on record.

Table 3. ***Seattle (NOAA #9447130) extreme water level frequency curve, Peak over threshold method***

% annual exceedance	Return period (year)	Total Water Level (feet, MLLW)	Total Water Level (feet, NAVD88)	±95% Confidence Interval (feet)
99	1.01	13.34	11.0	0.0354
50	2	13.6	11.26	0.0638
10	10	14.05	11.71	0.0954
2	50	14.54	12.2	0.1204
1	100	14.77	12.43	0.1307
0.2	500	15.37	13.03	0.1542

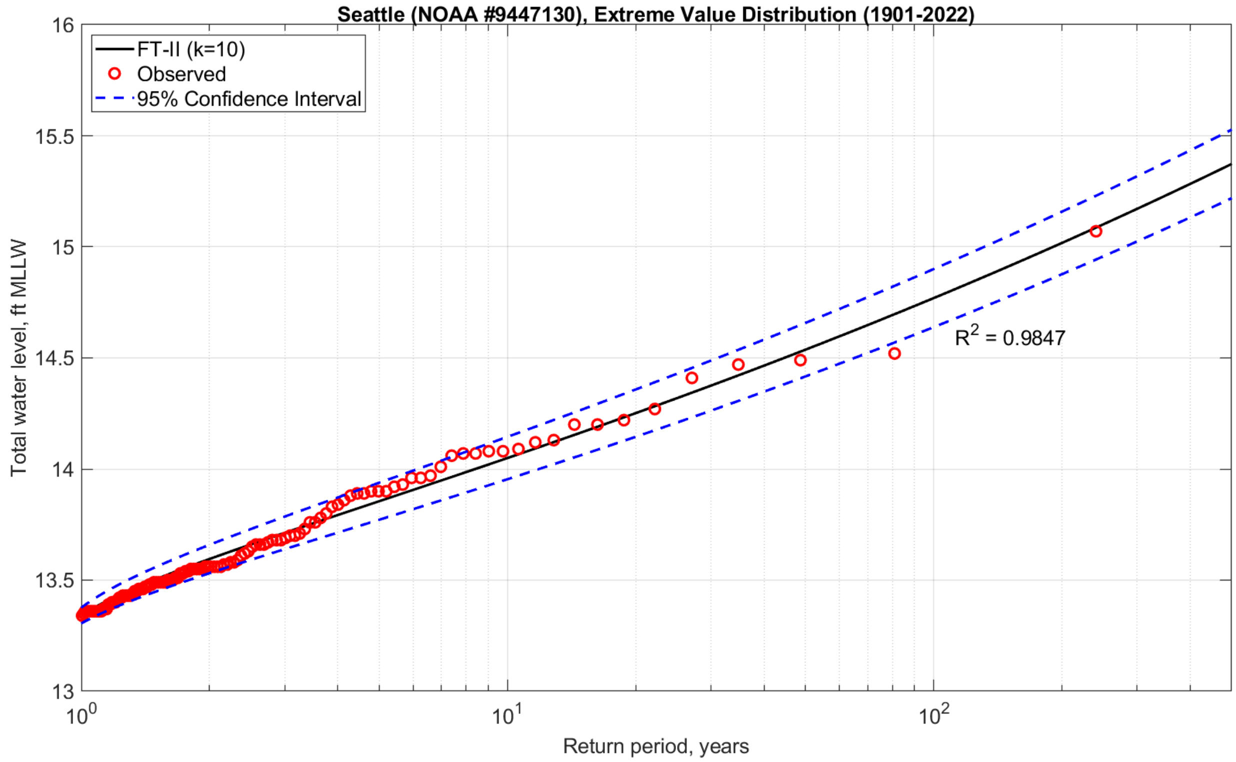


Figure 5. ***Extreme water level frequency curve following the Weibull distribution using peak over thresholds method (period of record = 116 years; N = 194)***

3.2. Snohomish River Basin

Spencer Island is also subject to frequent fluvial flooding from the Snohomish River basin, which drains the combined flows of the Snoqualmie, Skykomish, Tolt, Sultan and Pilchuck Rivers (Figure 2). Real time stages and streamflows are measured at Monroe (RM 20, DA 1,536 sq. mi.), upstream of the tidal backwater zone and on the Pilchuck River near Snohomish (DA 129 sq. mi.). The total drainage area of the gaged proportion of the watershed tributary to the mainstem at the split to Union Slough and Steamboat Slough is 95% (1,665 sq. mi. of 1,749 sq. mi.). Tidal backwater extends upvalley past the City of Snohomish (river mile (RM) 13). The USGS gage at Snohomish was stage only until 2022. Now the gage measures both streamflow and stage. The streamflow period of record at the Pilchuck, Snohomish at Snohomish and Snohomish at Monroe gages are shown below in Figure 6 and Figure 7.

Note that flood stage data go back to 1906 at Snohomish. Flow and stage were measured in the 1940s through 1960s at Snohomish, however flow measurement at this site is difficult because of the influence of tides (flow reversals) and upstream levee overtopping that diverts flow through the floodplain (unmeasured at gage) . The 1906 flood is reported to have had a stage of 35 feet which would likely qualify as a historical event (exceeding a 1% annual chance of exceedance). If the available gaged stage and flow data pairs from the 1940s through 1960s are used to derive a flow-stage rating curve at Snohomish, the peak discharge for the 1906 flood ranges from 130,000 to 180,000 cfs (Figure 8). The switch to the Monroe site for gaging in the 1960s makes sense given the wide variation in flood discharge for a given stage at Snohomish. Note the small to negligible increase in flood discharge at

Snohomish relative to Monroe for the four years of overlapping record (1966-1968, 2023). Between October 2022 and April 2024 USGS measured streamflows at Snohomish in addition to Monroe, and this data is used for stage-flow calibration of the larger HEC-RAS model (Figure 9).

Damaging floods recorded by the Monroe occurred in water year 1991, 2009, 1996, 2007, and 1976. The Snohomish gage was operational prior to the Monroe gage and recorded two large floods of comparable magnitude in 1951 and 1960. USGS published peak flood stages (without flows) for very large floods that occurred in 1905, 1916, 1920, 1932. As part of the FEMA FIS historical floods for 1898, 1907, and 1918 were estimated by regression to build out the historical record which was then used to compute annual peak flow frequency statistics. There is considerable uncertainty in the methods and data used in the FIS, and 24 years have elapsed since that analysis was completed.

For the time being, the best estimates for peak flood discharge should be derived from either the WSE 2D HEC-RAS model or the FEMA UNET model. The WSE model has the advantage of including the effects of potential increased streamflow resulting from climate change, and accounts for valley storage effects.

Future revisions of peak flow frequency estimates (for PED phase) should focus on analyzing spring and fall/winter flood events separately (mixed population), investigate the validity of the 1906 data, and combine all valid records for the Snohomish and Monroe gages to maximize the period of record and improve the Bulletin 17C analysis and the balanced hydrographs used in the FEMA unsteady flow UNET model.

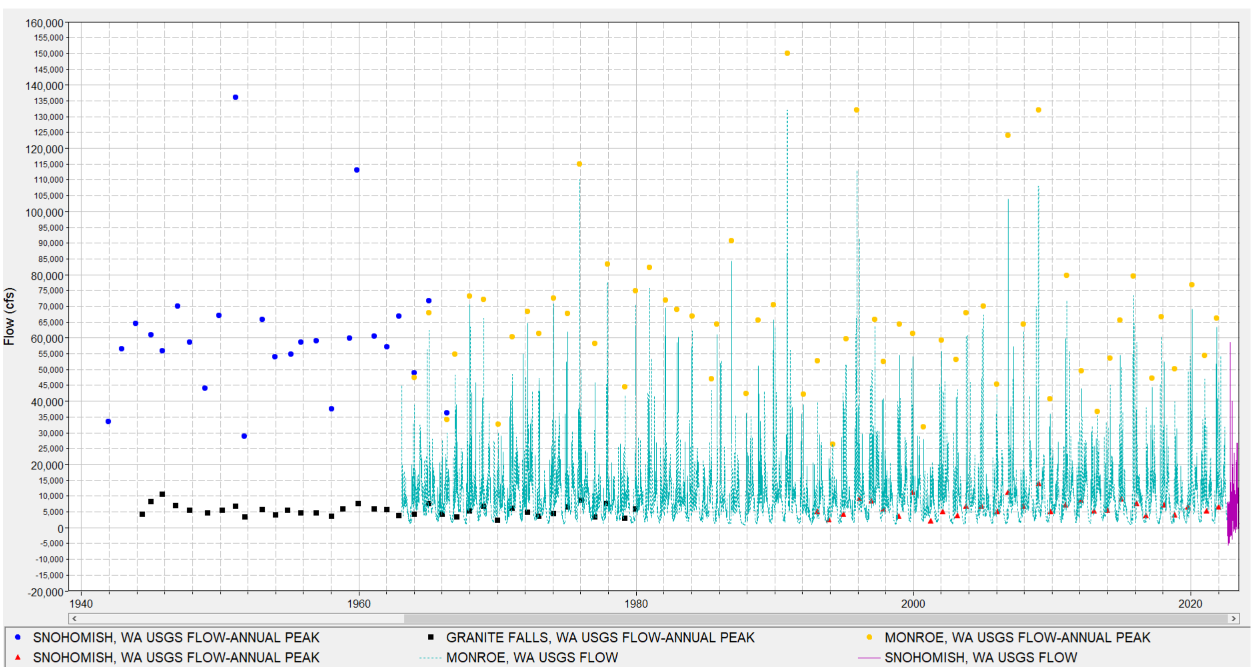


Figure 6. Systematic period of record streamgage data for the Snohomish River at Monroe (orange circles, turquoise dashed line) Snohomish River at Snohomish (blue circles, purple line), and Pilchuck River at Granite Falls (black squares) and near Snohomish (red triangles), 1941-2023

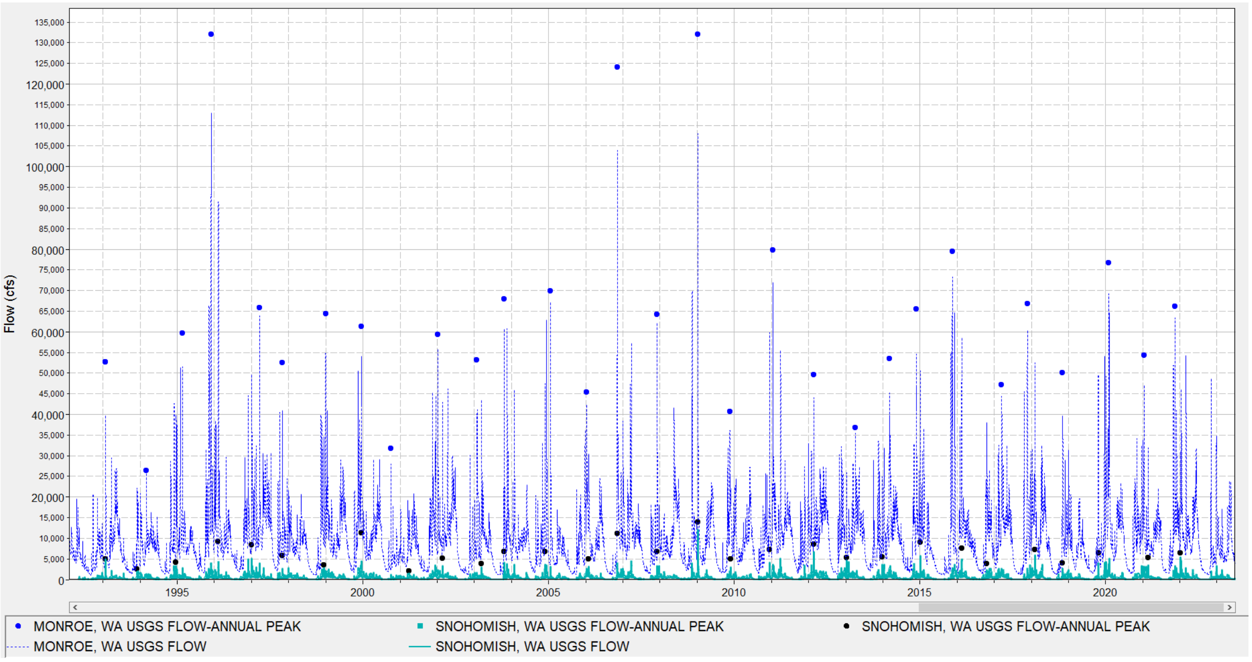


Figure 7. Period of record of Pilchuck River near Snohomish compared with Snohomish at Monroe indicating weak correlation of timing of Pilchuck River annual peaks with mainstem Snohomish River annual peaks (peak discharges often occur months apart)

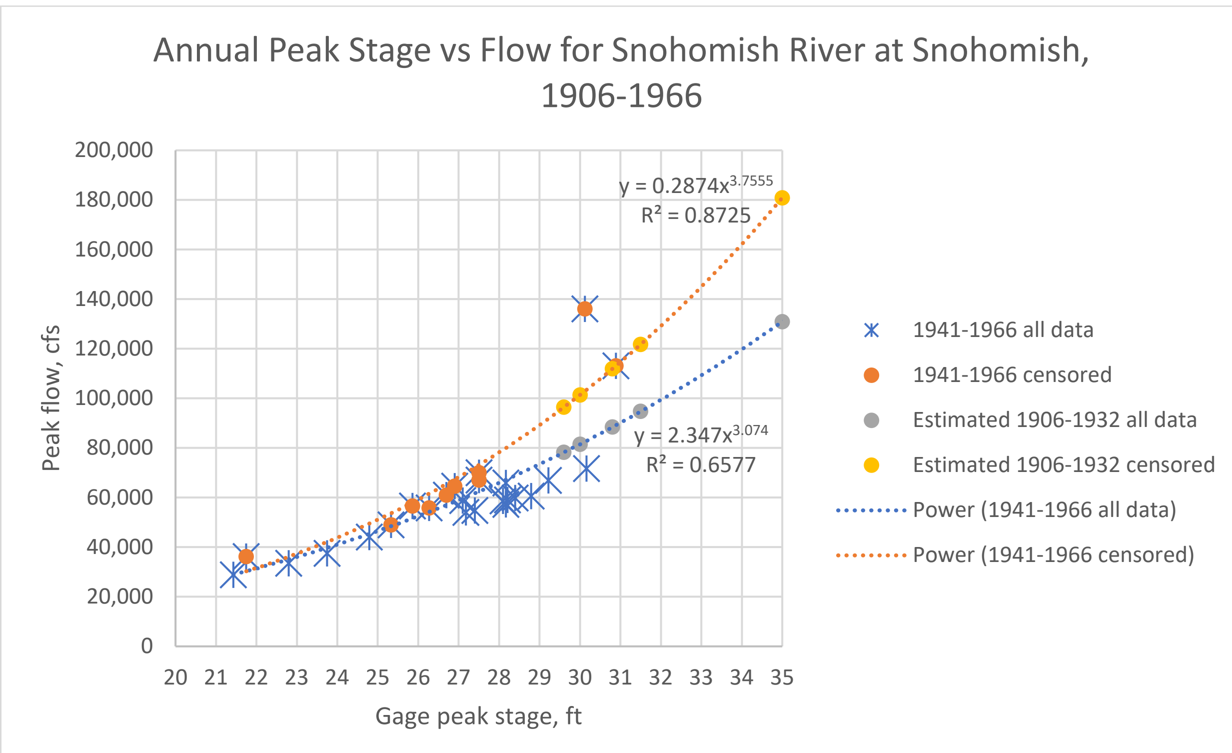


Figure 8. Snohomish River at Snohomish historical flows, 1906-1966

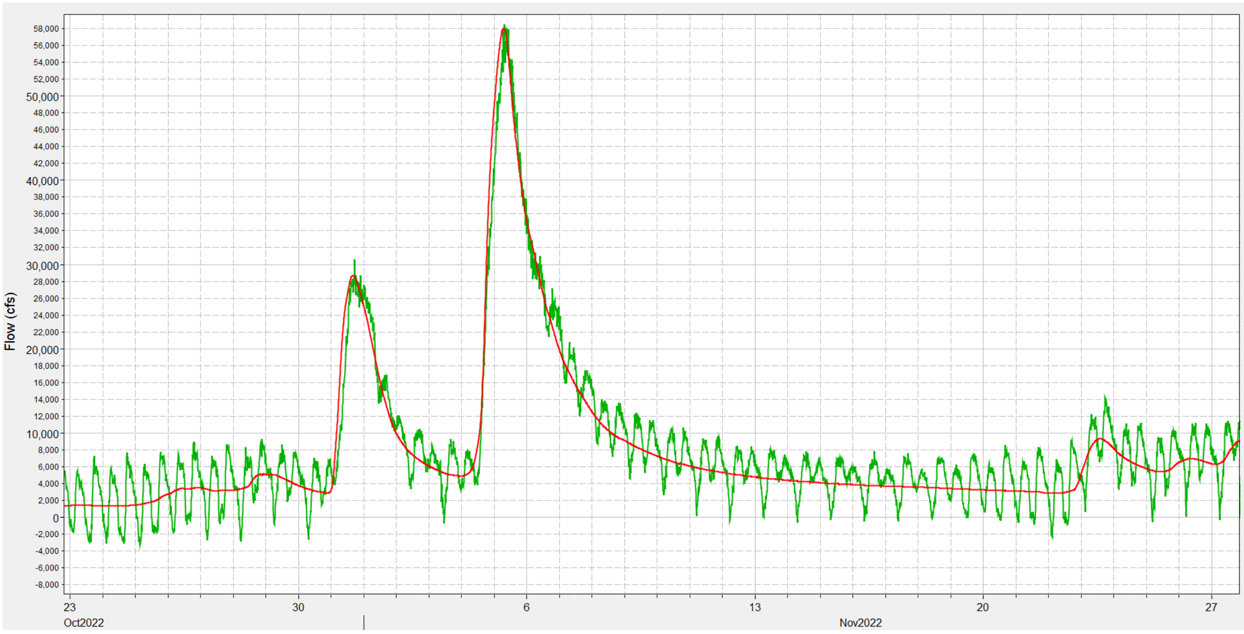


Figure 9. Comparison of real time flows on the Snohomish River at Snohomish (RM 13) and Monroe (RM 20) for October-November 2022 showing very close agreement with peak discharge and effects of daily tides, resulting in upstream flow reversal

3.2.1. Annual peak flow frequencies

Flood flow frequencies (or annual exceedance probabilities) at Spencer Island are not easy to estimate without modeling as they depend on the flow distribution between the mainstem, Ebey Slough and Steamboat/Union Sloughs,largely uncorrelated effects from tidal elevation and phasing, as well as antecedent flooding/dike conditions and local runoff. Previous modeling for the FEMA FIS indicates that flood discharges in the Sloughs are most strongly influenced by the magnitude and volume of the flood hydrograph at the gages and the amount of floodplain storage/attenuation that occurs as the flood wave progresses downstream. Tides can influence attenuation by increasing stages and dike overtopping. If dikes overtop and floodplain areas fill prior to arrival of the flood peak from upstream, attenuation is lessened, and peaks remain higher than they would if the floodplain areas are dry and begin to fill up during the progression of the main flood wave. Similarly, if dikes fail in a previous but remain unrepaired, downstream flood attenuation can be enhanced in the next flood. If dikes fail prior to floodwater reaching the dike crest, downstream attenuation would also be higher than modeled. The complexities and uncertainties of these effects and conditions result in a need for simplification and use of statistical approaches to define probabilistic flood risk.

For purposes of Feasibility Study H&H analyses, no new hydrologic analyses were performed. Existing studies, data and models are leveraged for purposes of this study. Relevant information is provided below. Shortcomings and limitations of the data and approaches that may warrant updates as part of 35% to 65% PED work are highlighted.

Table 4. WSE estimated peak flood flow statistics for the Snohomish River + Pilchuck River based on historical data as compared with effective FEMA FIS estimates and USGS regression equation estimates for the mainstem Snohomish upstream of Spencer Island

Flood Event		Snohomish River at Monroe (DA 1,536 sq. mi.)		Pilchuck River near Snohomish (DA 129 sq. mi.)		Snohomish + Pilchuck (DA 1,665 sq. mi.) (1) (2)		Snohomish mainstem upstream of Spencer Island (DA 1,749 sq. mi.) (1)(3)	
Return Period (Years)	Annual Exceed. Probability (%)	WSE (cfs)	FEMA (cfs)	WSE (cfs)	FEMA (cfs)	WSE (cfs)	FEMA (cfs)	USGS Drain. Area ratio (cfs)	USGS Ungaged regres. (cfs)
1	99%					*49,865*	*54,759*	*50,862*	*47,853*
2	50%	62200		5970		68,170	*77,561*	69,900	71,300
10	10%	101,700	120,700	10,300	8,900	112,000	129,600	117,000	130,000
50	2%	139,200	174,400	13,900	12,100	153,100	186,500	160,000	183,000
100	1%	156,100	196,800	15,400	13,300	171,500	210,100	180,000	208,000
500	0.2%	197,700	242,900	18,900	17,200	216,600	260,100	227,000	266,000

Notes:

1. Estimated by linear regression of peak flow frequency estimates to fill data gaps.

2. FEMA and WSE peak flows near Spencer (Snoh + Pilchuck) are not routed from gages to site and do not include local runoff or attenuation.

3. USGS regression-based estimates do not include drainage area tributary to Ebey Slough/Ebey Island

Flood frequency statistics as reported by WSE (2021) are provided below for the Monroe and Pilchuck gages. Total storm runoff volume, valley floor flood storage capacity and tides influence the ultimate peak discharge at the project site. Model runs that include observed tidal fluctuations preserve valley floor flood storage capacity and have smaller flood peak discharges than models that maintain a constant downstream tidal elevation. A steady tide assumption is reasonably conservative to estimate peak flood stages as it recognizes the probabilistic coincidence of peak tides and peak river flows, but it creates a physically unrealistic water surface elevations in some locations and does not provide reasonable estimates of velocity or tidal flux in the tidal zone. Note that the peak flood flows estimated by WSE are about 20% lower than the FEMA FIS peak flows for the same recurrence interval event (Table 4). It should be noted that the FEMA hydrologic period of record noted in the Technical Support Data Notebook (WEST 2001, Figure 2-3) combines Monroe gage data from 1964-1999 with historic flood estimates (developed by USACE) for 1898, 1907, 1918 and 1922.

Note that the WSE model combines balanced inflow hydrographs for the Skykomish River near Gold Bar, Snoqualmie River near Carnation, N. Fork Tolt River near Carnation, Sultan River below Power Plant, and Pilchuck River near Snohomish plus local runoff scaled by drainage area to the upstream inflow hydrographs, based on the November 2006 storm pattern. Thus, flows at the Monroe gage in the model are not based on estimates from the gage record, but from hydraulic routing.

Table 5. WSE estimated flood flow statistics for the Snohomish River based on historical data

Snohomish River near Monroe

Return Period	Instantaneous Peaks	1 hour Dur.	3 hour Dur.	6 hour Dur.	12 hour Dur.	1 day Dur.	3 day Dur.	7 day Dur.
2	62,200	62,100	61,900	61,200	59,900	56,500	47,800	35,900
5	85,500	85,400	85,300	84,500	82,800	77,700	64,800	47,100
10	101,700	101,600	101,500	100,400	98,500	91,800	75,900	53,900
25	122,800	122,600	122,600	121,300	119,100	109,900	89,600	62,100
50	139,200	138,900	138,800	137,300	135,000	123,400	99,700	67,800
100	156,100	155,500	155,500	153,800	151,300	137,100	109,600	73,200
500	197,700	196,600	196,500	194,300	191,600	169,800	132,600	85,300

Table 6. WSE estimated flood flow statistics for the Pilchuck River based on historical data

Pilchuck River near Snohomish

Return Period	Instantaneous Peaks	1 hour Dur.	3 hour Dur.	6 hour Dur.	12 hour Dur.	1 day Dur.	3 day Dur.	7 day Dur.
2	5,970	5,890	5,780	5,540	5,080	4,090	2,900	2,140
5	8,560	8,390	8,220	7,960	7,370	5,850	4,160	2,940
10	10,300	10,000	9,810	9,560	8,900	7,060	5,020	3,460
25	12,400	12,000	11,800	11,600	10,800	8,640	6,140	4,120
50	13,900	13,500	13,200	13,000	12,300	9,860	7,000	4,600
100	15,400	14,900	14,600	14,500	13,700	11,100	7,870	5,080
500	18,900	18,200	17,800	17,700	17,000	14,100	9,990	6,210

3.3. Future conditions hydrology

USACE guidance (ER 110-2-8162, and ECB 2018-14, Rev. 3) provide policy and guidance for consideration of sea level change and climate change effects on inland hydrology for studies and civil works projects. Policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance resilience of communities. Climate change has been considered in H&H evaluations both quantitatively and qualitatively. This Annex is focused on quantitative evaluations. Refer to Section 6 of this Annex and Annex D3 for qualitative discussion of potential effects of future with and without project conditions.

3.3.1. Annual peak flow frequencies

Snohomish County (WSE 2020) updated historical flood frequency curves based on hydrologic modeling work completed by the UW Climate Impacts Group (CIG). As reported by WSE The CIG forecasted increase in peak runoff by mid-century for the Snohomish gage near Monroe is 14.5% and the increase by late century of 24.4%. The mid-century predictions end in 2069 which is less than a decade from the end of the 50-year planning period (2075) and are a reasonable first approximation for purposes of feasibility level analysis.

Table 7 and Table 8 provide flood frequency statistics for the Monroe and Pilchuck gages accounting for mid-century increases in streamflows caused by climate change. Resulting water surface profiles for the mid-century scenario are shown in Figure 47. For reference at the RM 4 split from the mainstem Snohomish River into Steamboat Slough (upstream end of Spencer Island) 1% AEP (100-year) flood levels are forecasted to increase by about 2 feet by mid-century even though modeled sea levels are 1-ft higher. This indicates about half of the increase in future inundation could be attributable to sea level rise and the other half to increases in basin runoff. Refer to Annex H-2 for detailed inundation maps of the project site for future conditions.

Table 7. WSE estimated flood flow statistics for the Snohomish River based on historical data scaled based on climate change impact projections for mid-century

Snohomish River near Monroe

Return Period	Instantaneous Peaks	1 hour Duration	3 hour Duration	6 hour Duration	12 hour Duration	1 day Duration	3 day Duration	7 day Duration
2	71,200	71,100	70,600	70,300	69,300	68,900	58,800	44,800
5	97,900	97,800	97,200	97,100	95,800	94,700	79,800	58,800
10	116,400	116,300	115,700	115,400	113,900	111,900	93,400	67,300
25	140,600	140,400	139,800	139,400	137,800	134,000	110,300	77,500
50	159,400	159,000	158,200	157,800	156,200	150,400	122,700	84,600
100	178,700	178,000	177,300	176,800	175,000	167,100	134,900	91,400
500	226,400	225,100	224,000	223,300	221,600	207,000	163,200	106,500

Table 8. WSE estimated flood flow statistics for the Pilchuck River based on historical data scaled based on climate change impact projections for mid-century

Pilchuck River near Snohomish

Return Period	Instantaneous Peaks	1 hour Duration	3 hour Duration	6 hour Duration	12 hour Duration	1 day Duration	3 day Duration	7 day Duration
2	6,540	6,460	6,360	6,140	5,700	4,710	3,600	2,530
5	9,380	9,200	9,050	8,820	8,270	6,730	5,160	3,480
10	11,300	11,000	10,800	10,600	10,000	8,130	6,230	4,090
25	13,600	13,200	13,000	12,900	12,100	9,940	7,620	4,870
50	15,200	14,800	14,500	14,400	13,800	11,300	8,690	5,440
100	16,900	16,300	16,100	16,100	15,400	12,800	9,770	6,000
500	20,700	19,900	19,600	19,600	19,100	16,200	12,400	7,340

3.3.2. Relative Sea level change

This project incorporates considerations of analysis of sea level rise in accordance with ER 1100-2-8162. USACE estimated sea level change based on low (historical), and medium and high emissions scenarios are shown below in Figure 10. Presuming the project is constructed in 2027 sea levels/ tidal datums at the site could increase by!0.8 to 3.6 feet by 2080 and steadily increase thereafter. Forecasted sea levels based on low, intermediate, and high emissions scenarios are shown below in Figure 8. By 2063 the mean tide level could inundate the average island elevation daily (under high emission scenario) and by 2117 under the intermediate emission scenario. The proposed dike lowering elevation could be exceeded by the MHHW by 2045 under the high emissions scenario and 2081 by the intermediate emissions scenario. Expected sedimentation within and along the island will extend the forecasted time for intersection between these reference elevations and datums, resulting in a project that is expected to provided intended benefits for the duration of the 50-year planning period.

The NOAA Sea Level Rise Viewer tool was used to see how the changes in mean sea level could manifest near Spencer Island by 2080. From inspection of Figure 11 through Figure 14 daily tidal inundation for nearly all conditions appears to result in inundation patters resembling very large floods on the Snohomish River. It is unclear if landowners will adapt by increasing the height of dikes or abandon the low-lying floodplain areas allowing them to convert back to tidal marsh or tide flats.

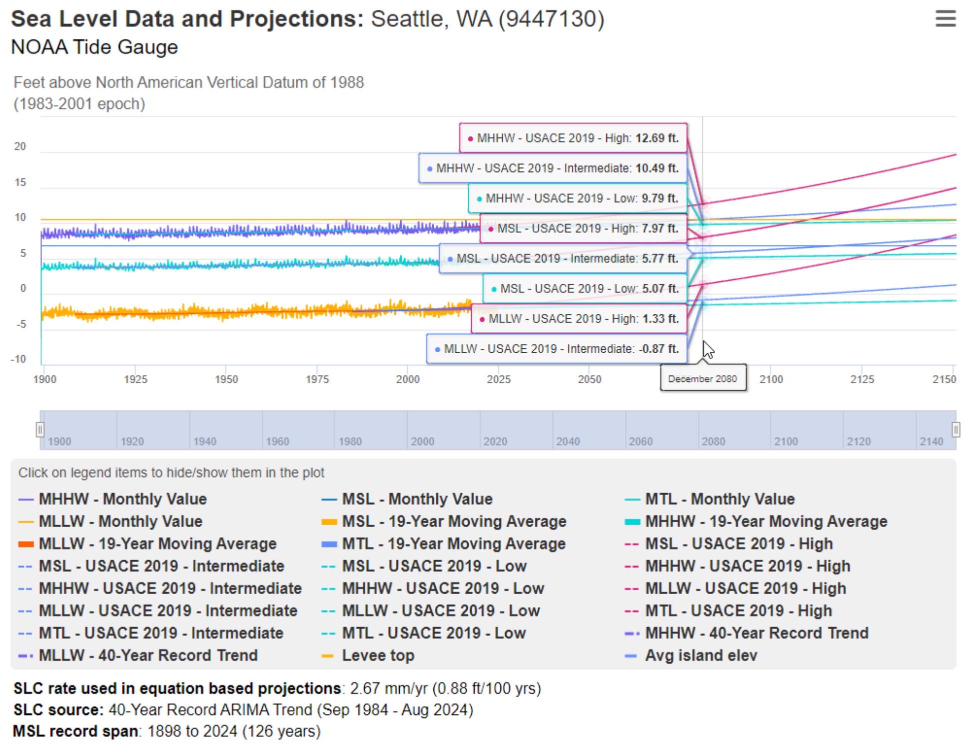


Figure 10. ***USACE low, intermediate, and high sea level change prediction for Seattle, WA (source:*** *https://climate.sec.usace.army.mil/slat/****)***

Table 9. Water Levels (FT, NAVD88) based on Seattle Tide Gauge Annual Exceedance probability water levels including projected Sea Level Change from 2020 to 2120

Return Period, Years	Annual Exceedance Probability (AEP)	water levels in year 2020	water levels + low SLC in year 2120	water levels + intermediate SLC in year 2120	water levels + high SLC in year 2120
100	1%	12.40	13.27	14.72	19.34
10	10%	12.00	12.87	14.32	18.94
2	50%	11.50	12.37	13.82	18.44
1	99%	10.70	11.57	13.02	17.64

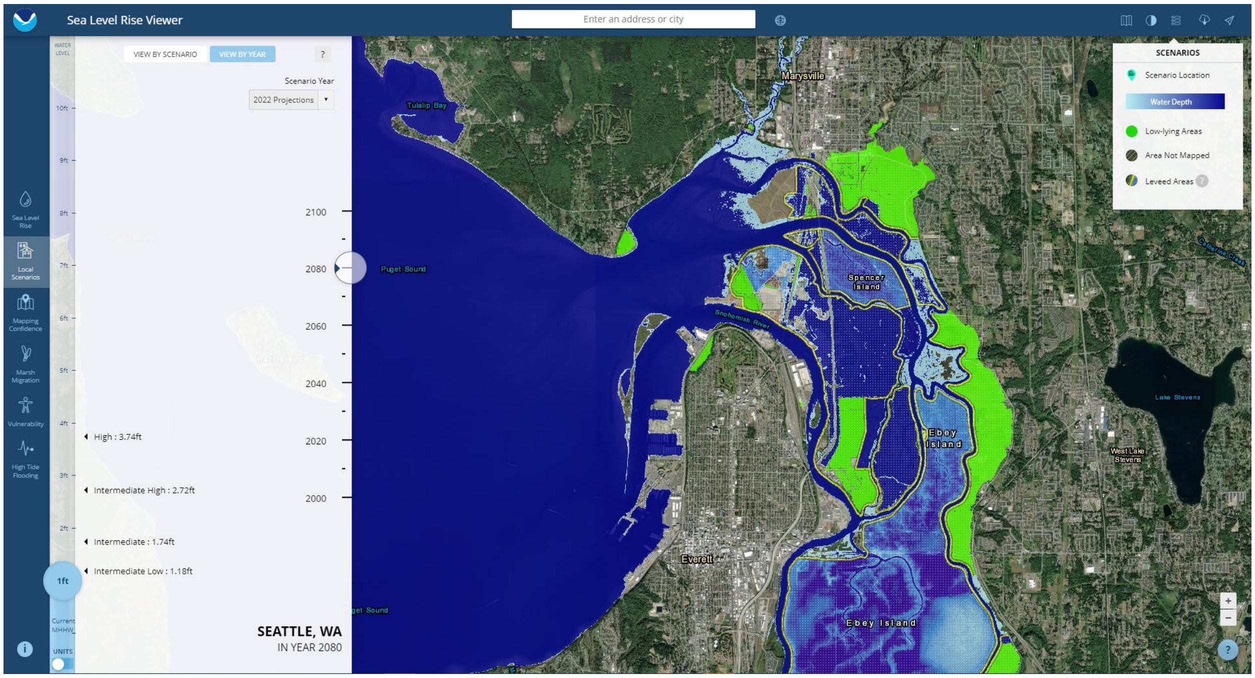


Figure 11. MHHW + 1' (~2080 intermediate low)

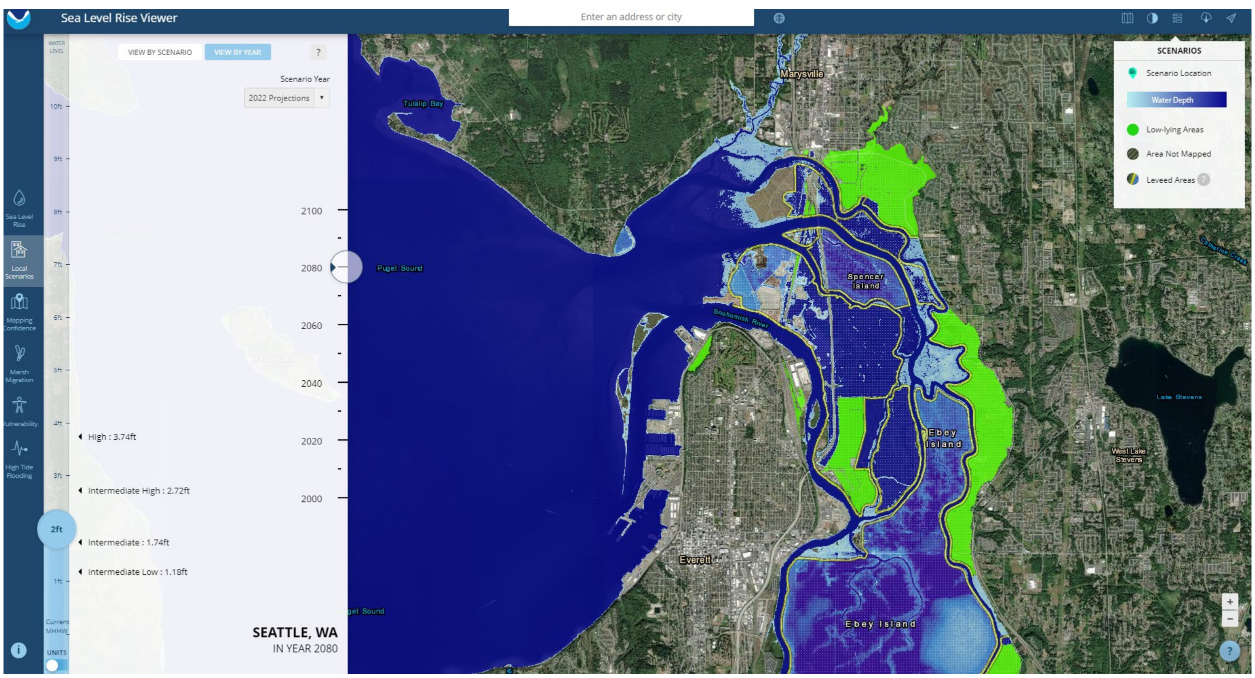


Figure 12. MHHW + 2' (~2080 intermediate)

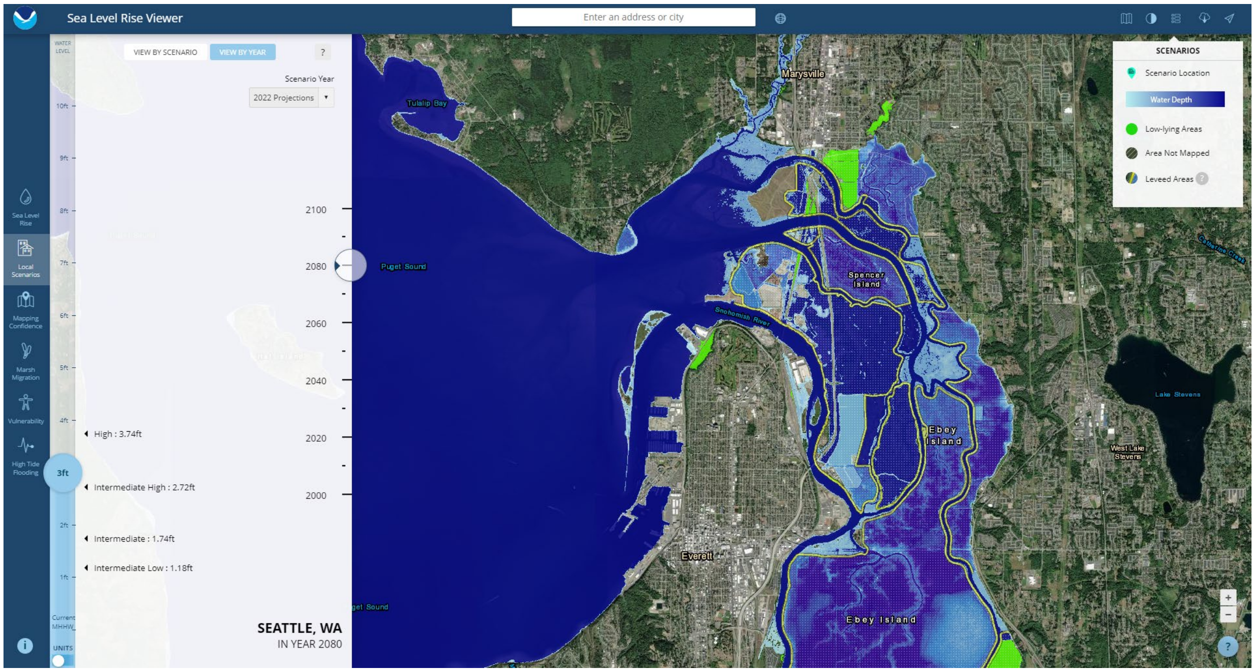


Figure 13. MHHW + 3' (~2080 intermediate high)

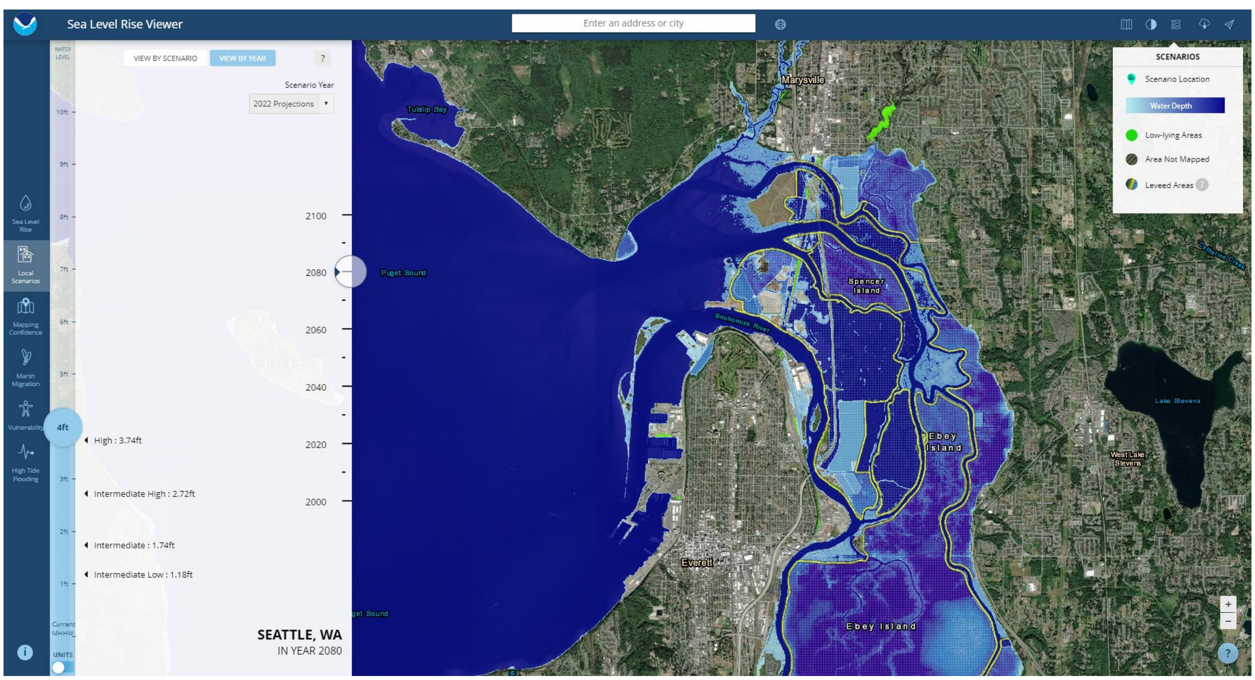


Figure 14. MHHW + 4' (~2080 high)

3.4. Ordinary High-Water Mark

Ordinary high water mark estimation procedures published by Ecology (2016) were employed at Spencer Island using available mapping, topographic, hydrologic, hydraulic and field geomorphic indicators. Site information indicates the OHWM varies across the site due the complex hydrology and hydraulics present. To aid HTRW surveys (where soil (upland) must be distinguished from sediment) a single representative OHW elevation of 11.0 ft NAVD88 was selected to apply to the entire island, which corresponds to the elevations surveyed along Steamboat Slough, the measured monthly high water level averages, and modeled monthly high water level averages, as well as first-order methods (assuming OHWM occurs at an elevation above MHHW).

Ordinary high water (OHW) surveys by USACE, WDFW, and WA Dept. of Ecology were conducted in August 2024 in the south portion of the project are plotted in Figure 15 (overlaid with existing lidar 1-foot contours and the 50% AEP (2-year) river flow inundation) and summarized in Table 10.

The average OHW elevation of the data collected in the south end of Spencer Island is 9.1 feet, with a minimum of 7.73 feet and a maximum of 11.54 feet. Spatial trends in the data show that there is an east-to-west and south-to-north gradient in elevation within the sampling zones caused by existing dikes. The locations of surveyed OHW points track very closely with inundation boundary for the 1-year tidal flood and 2-year river flood scenario (approx. elev. 10 to 11 feet NAVD88).

From inspection of the surveyed elevations by location, there is as much as 1.9 feet of elevation difference between the OHW line along the outboard dike face at Steamboat and Union Slough dikes and about a half foot of fall between the south and north side of the South Cross Dike and the inboard to outboard side of the Union Slough dike. This suggests that dike removal will lower the OHW line along Steamboat Slough and increase it along Union Slough as water will be able to move freely between the sloughs and equilibrate.

The target dike lowering elevation of 10.5 feet used for feasibility level design is based on the average of the daily high tides measured at the Union Slough breach and Snohomish County cross dike bridge tide gages (described in next section). This elevation is higher than the average surveyed OHW but less than the representative OHWM that factors in hydrologic and hydraulic data. Further survey and discussion with the TAG could be conducted to refine this elevation in the design phase.

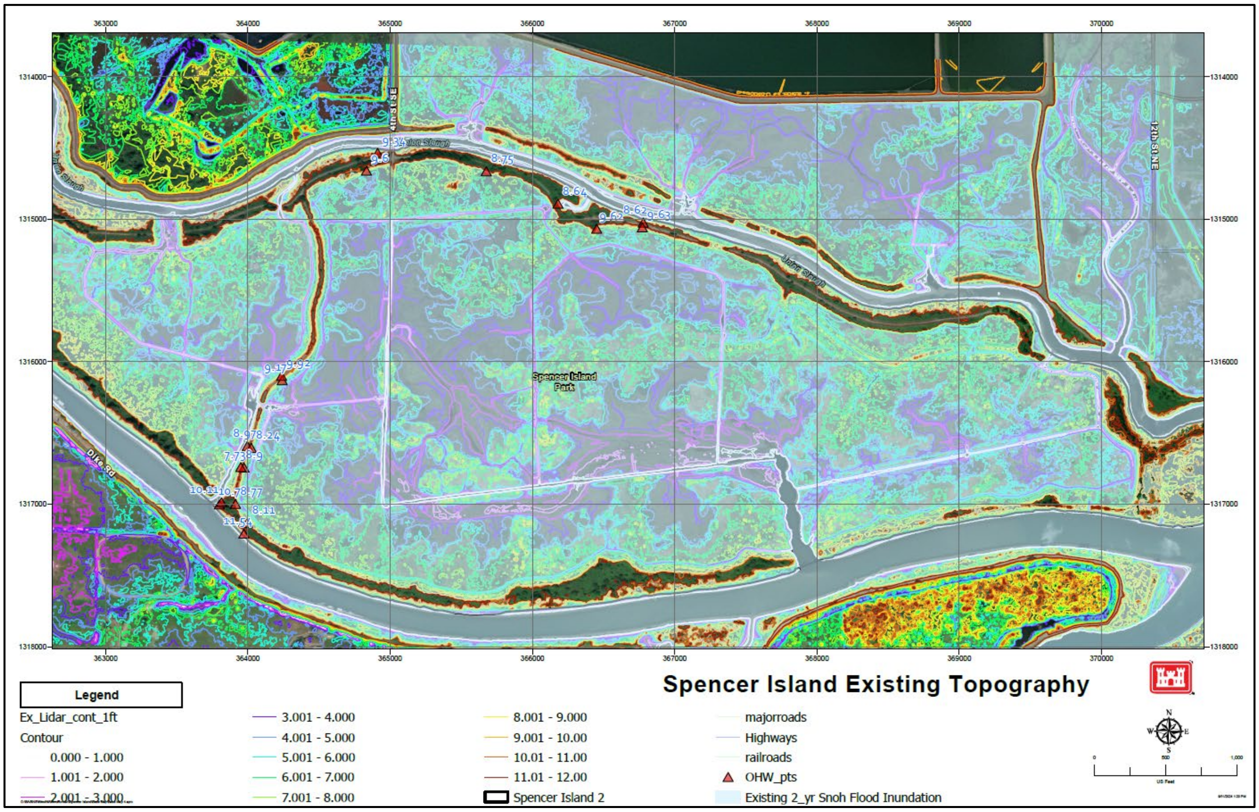


Figure 15. August 2024 OHW data at south end of Spencer Island overlaid with existing lidar and Snohomish River 2-year river flow inundation

Table 10. Statistics for OHW by sampling zone

Statistics by location (elev. feet, NAVD88)	Inboard of Union Slough Dike	Outboard of Union Slough Dike	South of South Cross Dike	North of South Cross Dike	Inboard of Steamboat Slough Dike	Outboard of Steamboat Slough Dike
Min	8.8	8.6	8.9	7.7	8.1	10.1
Max	9.6	9.3	9.2	9.9	8.8	11.5
Avg	9.4	8.9	9.0	8.6	8.4	10.8

3.5. Snohomish Estuary and Water level monitoring

WDFW deployed 6 sensors in and around Spencer Island beginning in March and April 2023 to assist with model calibration and baseline monitoring (Figure 16). The loggers are programed to collect samples every 15 minutes. A barometric pressure sensor is also deployed on the SC bridge south monitoring station. Data collected from March through July are presented in Figure 17 below. This period includes the annual snowmelt freshet and annual June King tides and represents seasonal average high-water conditions (ordinary high water).

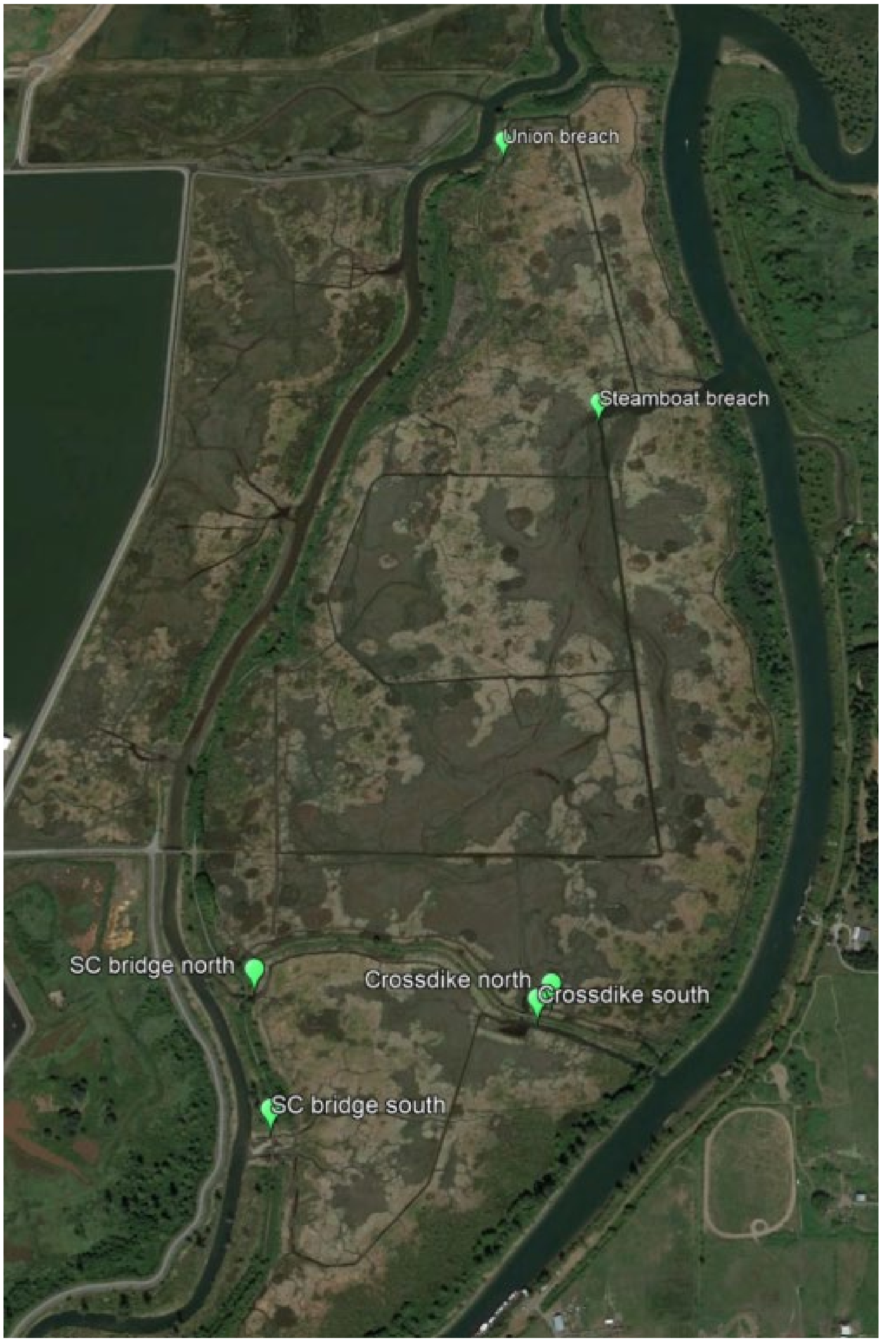


Figure 16. Continuous water sensors deployed on Spencer Island by WDFW

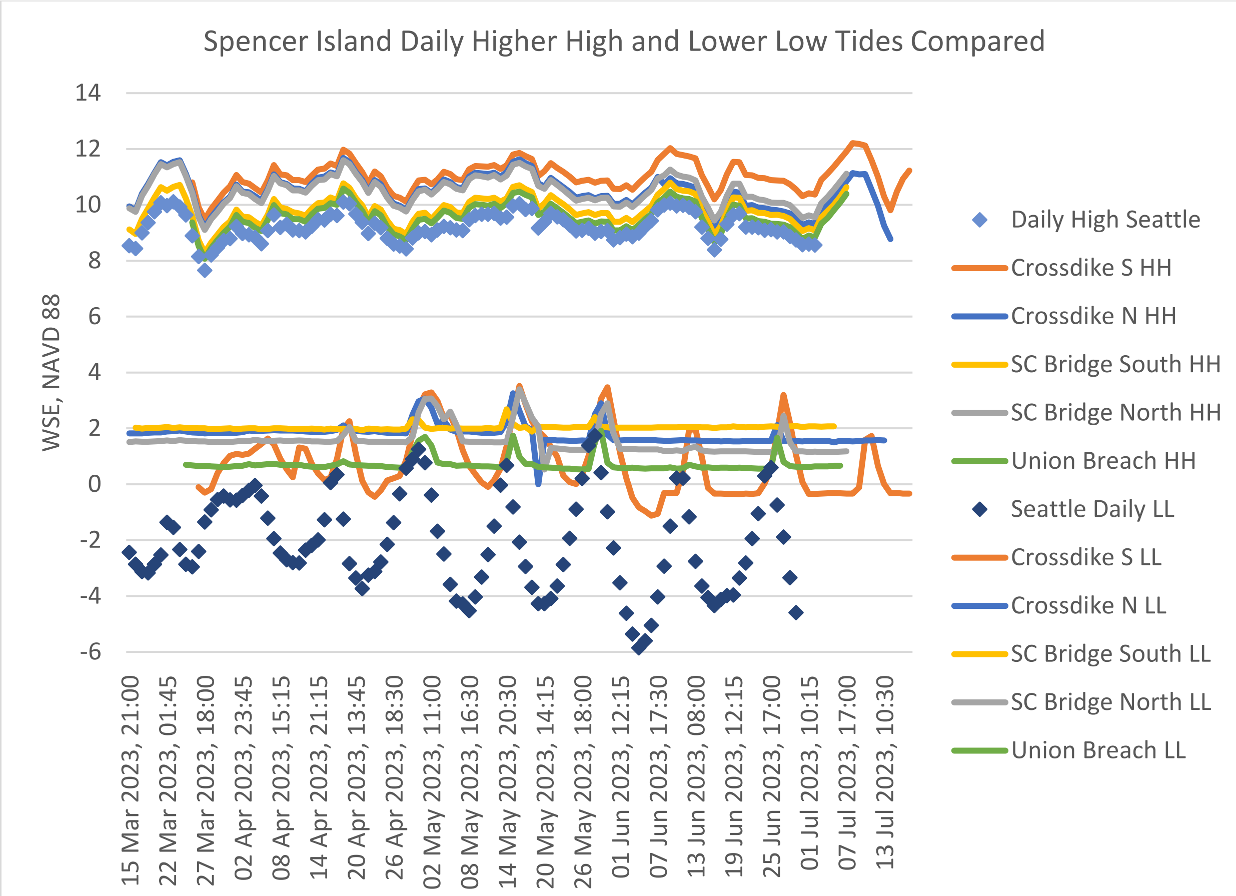


Figure 17. Continuous water sensors deployed on Spencer Island by WDFW

Mean daily higher high tides (MHHW) in the March through June time period at the south end of the site at the south cross dike station (representative of Steamboat Slough) averaged 11.03 feet. At the north end of Spencer Island MHHW averaged 10.6 feet in the same period. MHHW at the site are about 0.2 to 0.5 ft higher at Union Slough and 1.5 to 2 feet higher at the South end of the island at the south cross dike (which is directly connected to Steamboat Slough). Mean daily lower low water (MLLW) elevations recorded by the gages are higher than at Seattle by as much as 5 feet due to fresh water in the sloughs that maintains a higher base level at the site. At Union Slough the gage was not less than 0.5-ft NAVD 88. These averages are in the range of surveyed OHW indicators on the south end of the island. Tides at Seattle during this period were close to long term means (MHHW = 9.2 feet, MLLW = -2.1 feet). Note that anomalies were present in the Steamboat slough breach channel gage, so those data were excluded from the above plot. Sensor drift issues with data after July (after sensors were pulled for download and reinstalled) confound some of the datum calculations so these were excluded.

The City of Everett and their contractor collected 6-minute water level data at three locations along the primary tidal channel constructed at the Smith Island advanced mitigation site, that is located directly west of the north end of Spencer Island and immediately south of the County Smith Island project (Figure 18). Data provided were collected between 22 May and 6 July 2023. Data are shown in Figure 19.

Figure 18. Continuous water sensors deployed on Smith Island by City of Everett at the Advance Mitigation Site

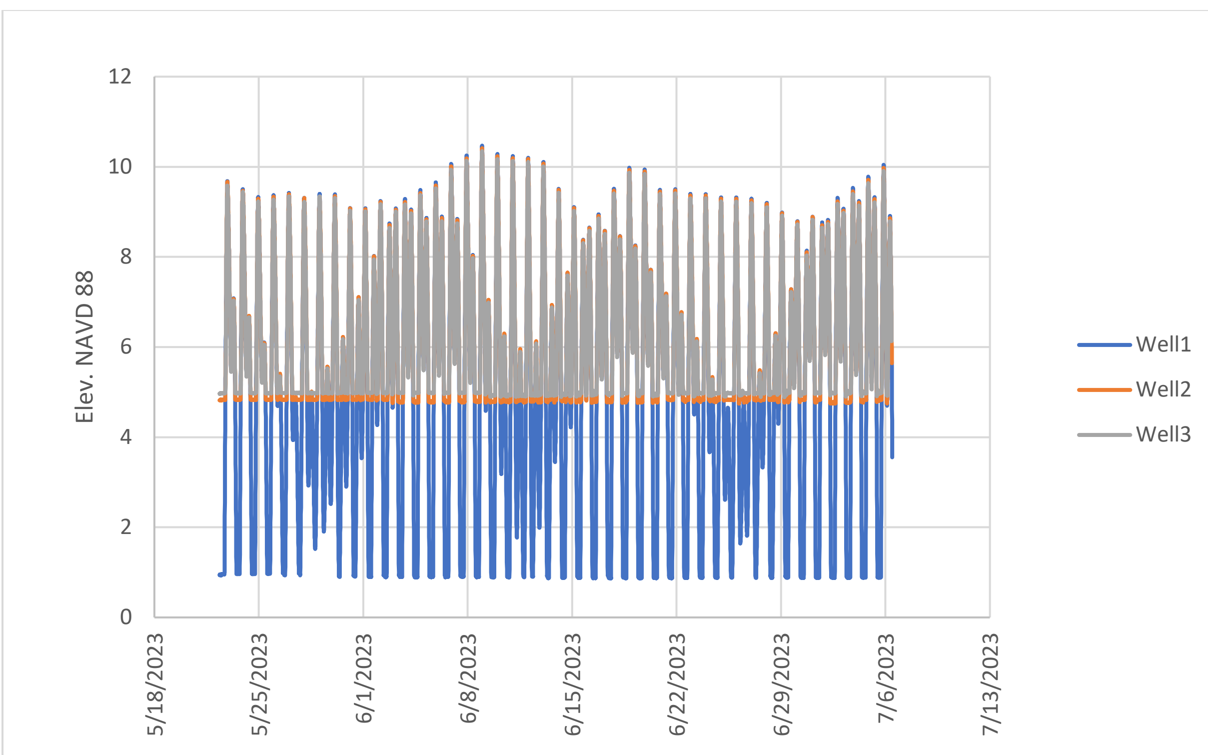


Figure 19. Union Slough Advance Mitigation Site tide measurements May through June 2023

For the period of data provided by the city to the Corps the highest tide recorded at the Advance Mitigation Site was located at the downstream tidal channel Well_1 and occurred on June 8, 2023. The tide reached a maximum of 10.46 feet which was nearly equal to the 10.47 feet recorded at the Union breach station across the river at Spencer Island established by WDFW for the same date. Tides at this site did not drop lower than elevation 0.9 feet, similar to the WDFW Union breach (bottoms out at 0.6 feet).

Since 2013 several water level (depth), conductivity, and temperature sensors (CTD) have been deployed throughout the Snohomish estuary to support monitoring and restoration efforts (Figure 21) by NOAA-NMFS and the Tulalip Tribes. Cramer Fish sciences compiled available data for 24 sites, which was provided to the Corps in July 2023. This data did not extend to the selected validation periods and was not used. WDFW set stage probes throughout the Spencer Island area, however problems with sedimentation inside the probes make it difficult to use for model validation. If this data is cleaned up, it can be applied to future validation.

Snohomish County manages two gages along the study area: Ebey Slough above Highway 2, and Snohomish River at French Slough. The USGS manages two more gages along the Snohomish: Snohomish River at Snohomish, and Snohomish River Near Monroe. These gages are updated in real time and data can be accessed on the internet. These sources were used for model validation (details in section 5.1). Figure 20 shows the gage locations of these four sites.

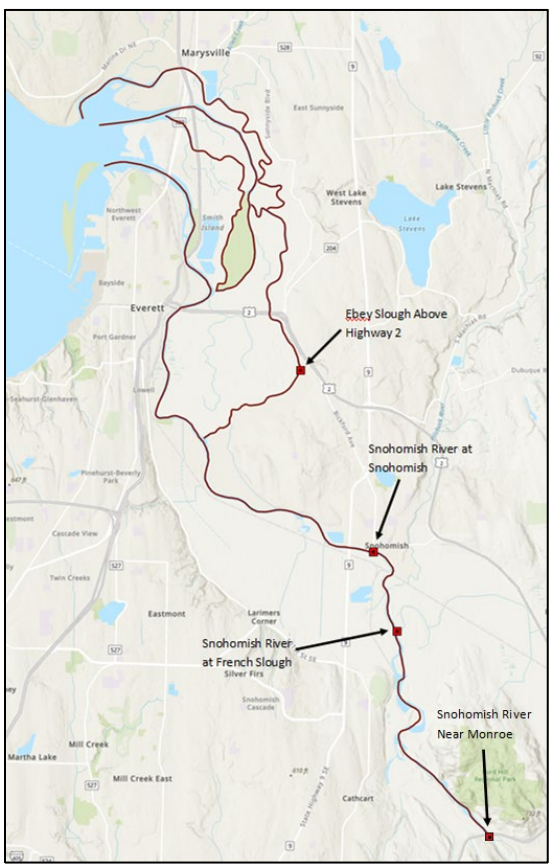


Figure 20. Snohomish County and USGS real time stream gages

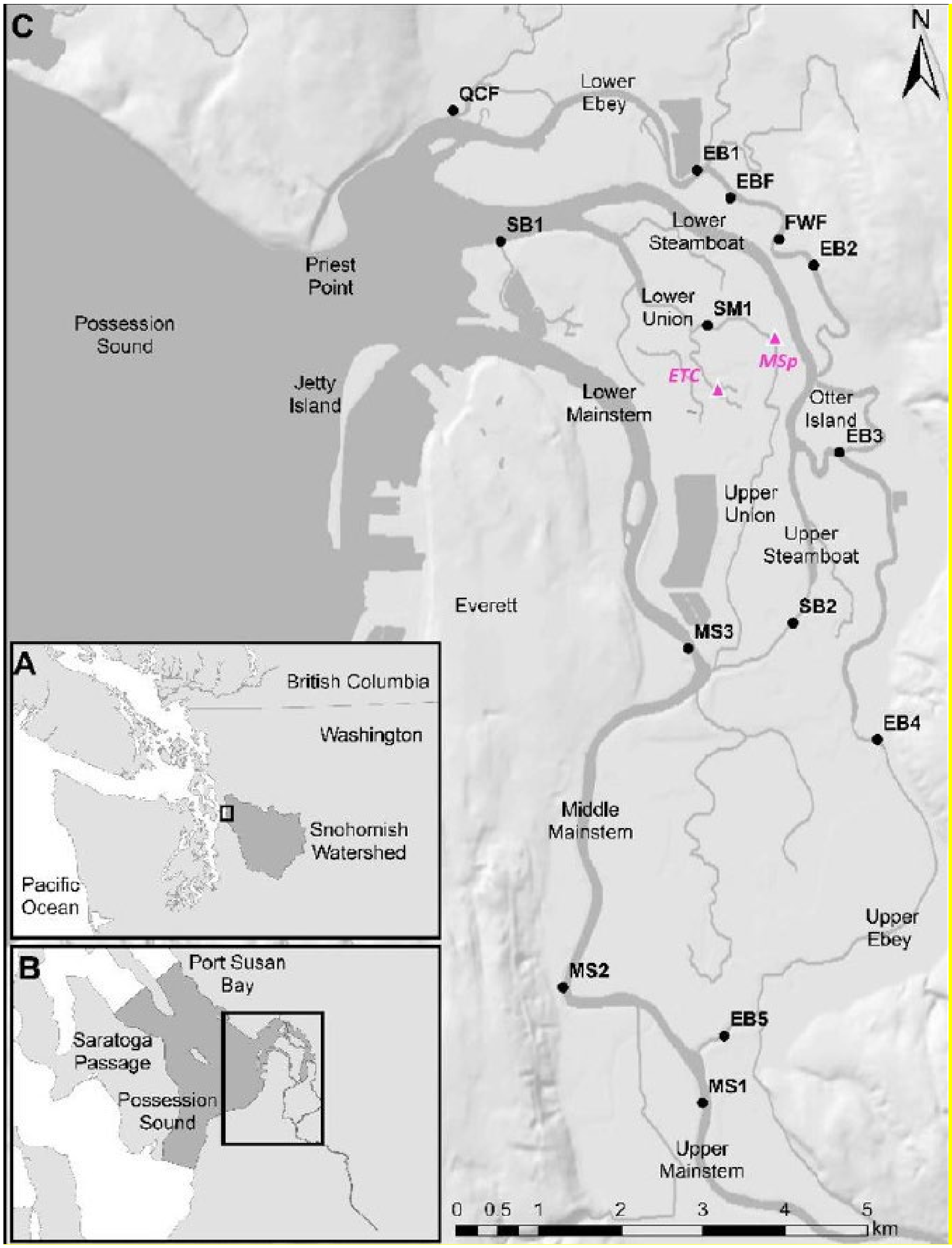


Figure 21. Continuous Water Sensors Network in the Snohomish Delta, Snohomish County sites are labeled ETC (East Tidal Chanel) and MSp(Union Slough at mid-Spencer)

4. Relevant Previous Investigations and Data

4.1. 2001 FEMA flood insurance study

The Corps and WEST Consultants refined previous flood frequency estimates for the mainstem Snohomish River in 1999-2001 as part of the Flood Insurance Study revision work for FEMA. The USACE UNET unsteady flow hydraulic modeling utilized flood frequency statistics for both the volumetric runoff and peak discharge (balanced hydrograph method). Table 11 below provides a summary of the upstream boundary conditions inflow data. Note that the peak flow statistics are strongly influenced by estimates for historical floods at Snohomish using data from upstream gages routed to the site using numerical methods as well as correlation with gages outside the basin. Refer to the Seattle District project files for details of the methods and estimates.

Table 11. Flood frequencies for peak, 1, 3, 5, and 7-day events.

Recurrence Interval (years)	10	20	50	100	500
Exceedance Probability (%)	10%	5%	2%	1%	0.2%
Peak Values for Period of Record (cfs)	100000	115000	135000	150000	189000
Peak Values with Historic Events (cfs)	114000	137000	173000	204000	293000
Scaling Ratio	1.14	1.19	1.28	1.36	1.55
1-Day Average Daily Flow (cfs)	92100	107000	128000	145000	190000
1-Day Average Daily Flow (Scaled) (cfs)	104994	127470	164030	197200	294500
3-Day Average Daily Flow (cfs)	78900	91600	109000	123000	158000
5-Day Average Daily Flow (cfs)	64700	74700	88300	99100	126000
7-Day Average Daily Flow (cfs)	55700	63500	73800	81700	101000

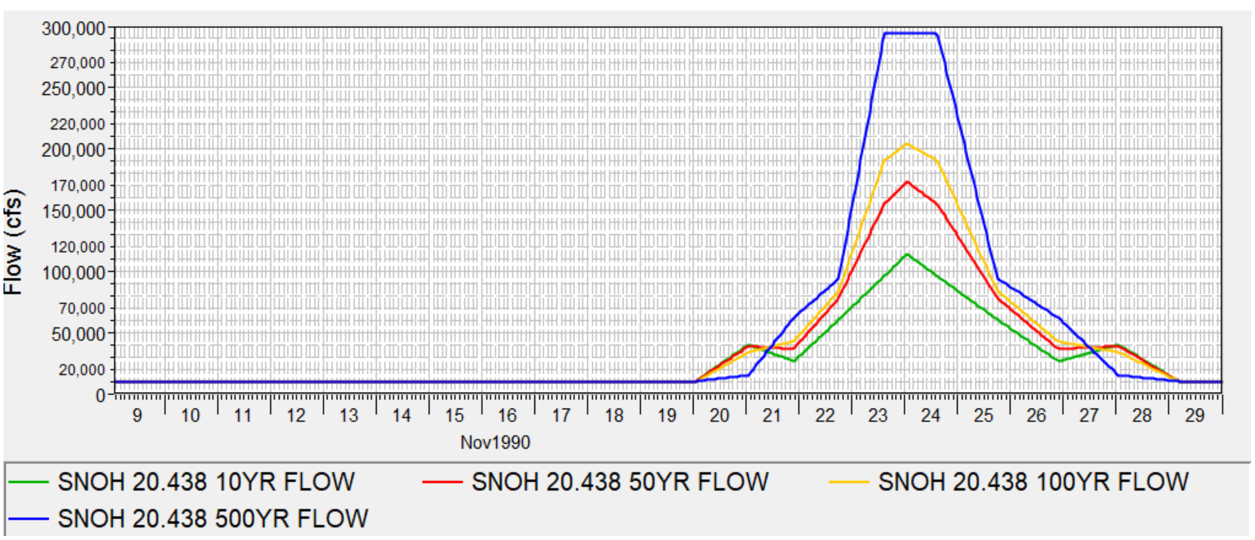


Figure 22. UNET model balanced inflow hydrographs at Monroe gage

The event hydrographs were routed through from the Monroe gage downstream along the approximately 20.5 mile long 1-dimensional reach. The model has lateral weirs along dikes connected to overbank floodplain areas to model flood wave attenuation. The model has interconnected 1-d reaches along all the distributary channels (sloughs) which are also connected to floodplain storage areas. The model includes a constant high tide equal to the MHHW elevation plus 1-foot. The model schematic is shown below in Figure 23.

The FEMA FIS UNET model DSS file was queried to show how event maximum discharge varies between the upstream and downstream ands of each reach. Peak flows are summarized below in Table X. From inspection, the dike system and extensive floodplain of the Snohomish have a significant influence on the peak discharge as flood waves travel downstream. The upstream end of the mainstem has a peak 1% AEP inflow of 204,000 cfs, however by the time the flood wave reaches Spencer Island, the total flow in the river measured at the midpoint of Spencer Island (mainstem and all sloughs) has dropped to 133,180 cfs. Note that the model predicts only 18,900 cfs would flow down Steamboat and Union Sloughs past the upstream (south) end of Spencer Island, however the flow in the sloughs more than doubles (to 40,300 cfs) at the north end of the Island due to floodwaters passing from the Ebey Island storage area into Steamboat Slough.

Spencer Island was modeled as a single 1-dimensional storage area (Figure X). In 1999 when the model was developed the project area was completely ringed with dikes. The crest of the dike controls the amount of overflow into and out of the storage area. Now that the dike is breached in at least two locations it is the storage area connection is outdated, and it is possible that the modeled stage hydrograph could be impacted, however the island has not experienced major changes to topography that are likely to alter the results. A project no-rise analysis will be conducted in PED to verify this assumption.

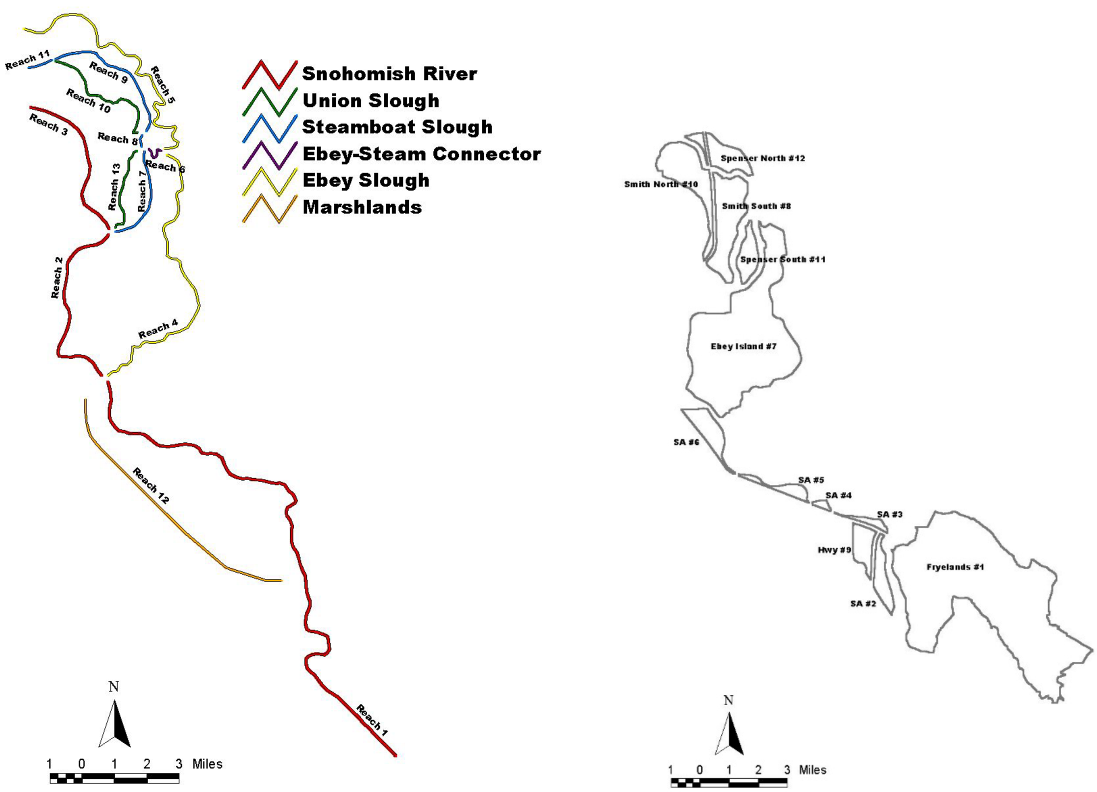


Figure 23. UNET model reaches and storage areas (WEST 2001)

Note that the 64-bit versions of Windows (Windows 10, etc.) are not able to run native UNET models and HEC no longer maintains support for UNET. HEC recommends migration of UNET models to HEC-RAS. FEMA still allows use of UNET but notes that it cannot be used for floodway determination and that it can result in large differences in computed stages relative to other software around bridges and culverts. UNET is not georeferenced and has no inundation mapping capability. As part of the Qwulloolt restoration project on Ebey Slough, USACE conducted a no-rise analysis with the UNET model to analyze the effects of a proposed dike setback. For practical reasons, a no-rise analysis for Spencer Island should plan to utilize a HEC-RAS model based on the effective UNET model. Work completed recently by WEST consultants for Snohomish County (see next section) will facilitate that analysis.

Table 12. 2001 FEMA FIS UNET model reach and Spencer Island peak flow summary for the 0.1, 0.02, 0.01 and 0.002 AEP events

Modeling reach	RM/AEP	Q10 peak (cfs)	Q50 peak (cfs)	Q100 peak (cfs)	Q500 peak (cfs)
		0.1	0.02	0.01	0.002
Reach 1 mainstem US	20.5	113,998	172,933	203,998	294,500
Reach 1 mainstem DS	8.2	107,048	127,869	153,178	224,588
Reach 2 mainstem US	8.2	67,517	79,633	68,711	90,434
Reach 2 mainstem DS	3.8	63,576	76,932	81,954	85,740
Reach 3 mainstem US	3.8	51,604	78,866	89,110	108,567
Reach 3 mainstem DS	0.5	50,441	74,241	89,109	119,784
Reach 4 Ebey Slough US	13.2	39,533	72,489	84,470	134,159
Reach 4 Ebey Slough DS	6.8	28,710	35,490	41,337	73,997
Reach 5 Ebey Slough US	6.8	7,055	14,512	23,814	49,311
Reach 5 Ebey Slough DS	0.5	6,100	10,734	13,704	27,823
Reach 7 Steamboat Slough US	6.25	8,823	9,270	12,819	13,020
Reach 7 Steamboat Slough DS	4.05	9,539	24,406	35,584	51,891
Reach 8 SS-US Connector US	4.04	35,474	55,442	74,875	106,264
Reach 8 SS-US Connector DS	3.76	34,657	52,559	65,500	82,395
Reach 9 Steamboat Slough US	3.75	27,796	44,393	49,690	54,068
Reach 9 Steamboat Slough DS	0.8	28,841	47,578	71,234	91,252
Reach 11 Steamboat Slough US	0.8	35,708	66,287	96,215	119,469
Reach 11 Steamboat Slough DS	0.17	36,404	74,835	101,343	158,220
Reach 13 Union Slough US	4.65	3,156	5,540	6,108	20,019
Reach 13 Union Slough DS	3	3,152	3,401	4,698	4,720
Reach 10 Union Slough US	2.7	6,865	10,526	15,902	28,348
Reach 10 Union Slough DS	0	6,867	18,721	24,983	28,849
Spencer Island US end	**SS 6.25, US 4.65**	**11,979**	**14,810**	**18,927**	**33,039**
Spencer Island DS end	**SS 4.05, US 3.0**	**12,691**	**27,807**	**40,282**	**56,611**
Total system flow Spencer	**S 3, US 4, SS 5, ES 8**	**89,787**	**116,825**	**133,180**	**163,589**

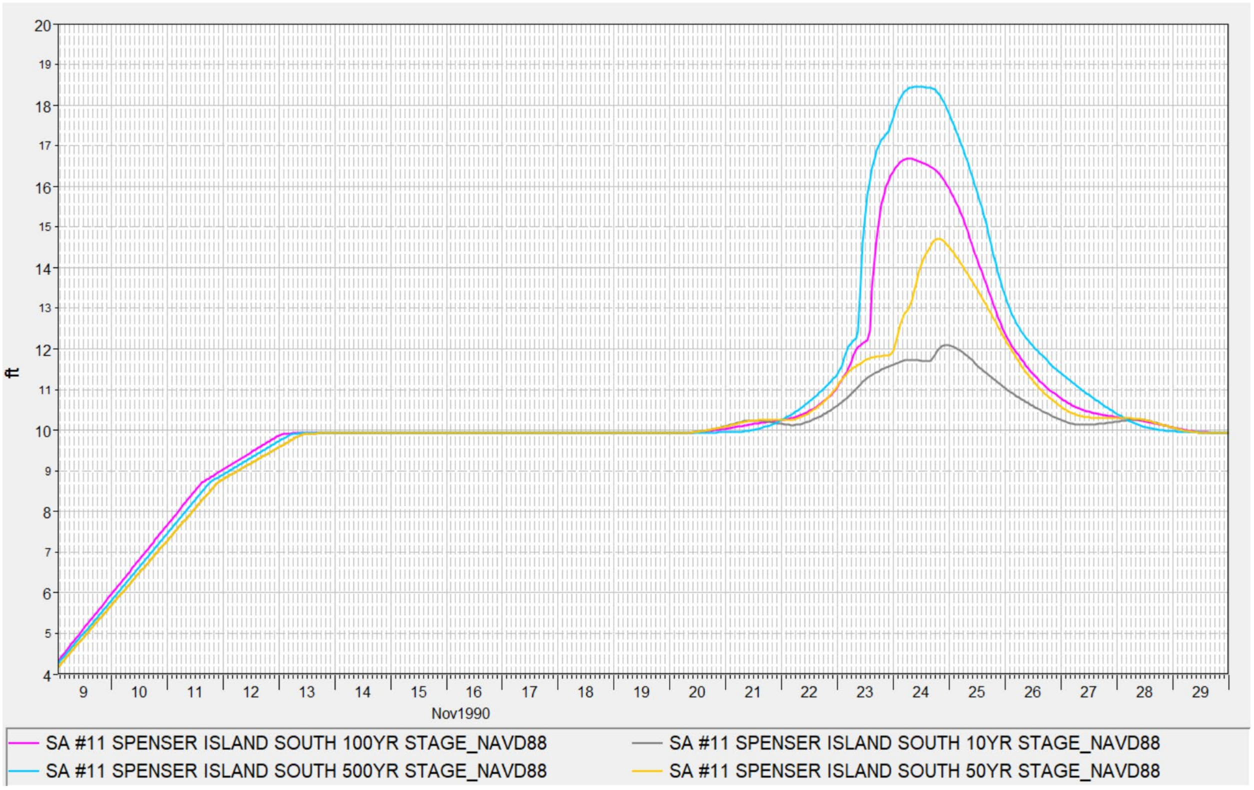


Figure 24. UNET computed stages (NAVD 88) for Spencer Island South storage area #11

4.2. 2012-2016 Smith Island Ecosystem Restoration Project

As part of the adjacent Smith Island ecosystem restoration project Snohomish County and WEST Consultants and Otak, Inc. migrated the UNET model to HEC-RAS unsteady to model the effects of the proposed dike setback and restoration project. This part of the floodplain is administered by the City of Everett. Note that the City of Everett Corporate Boundary extends to the centerline of Union Slough, but the southwest corner of the Smith Island project overlaps with City lands. The Corps and City of Everett constructed ecosystem restoration project at Union Slough adjacent to the Smith Island project and Spencer Island in the mid-2000s Both of these sites were modeled previously as a single storage area (#8). Cross dikes are present within this storage area that affect conveyance. WEST consultants completed the model revisions. A geo-referenced HEC-RAS unsteady flow model was built from the UNET model. This model was updated using new survey data (corrected effective). The final determination letter was received in 2016 from FEMA (FEMA, 2016). The restoration project was constructed by Snohomish County and completed by 2018. As shown below the model revisions resulted in lowering and increasing BFEs by 0.7 feet upstream of I-5.

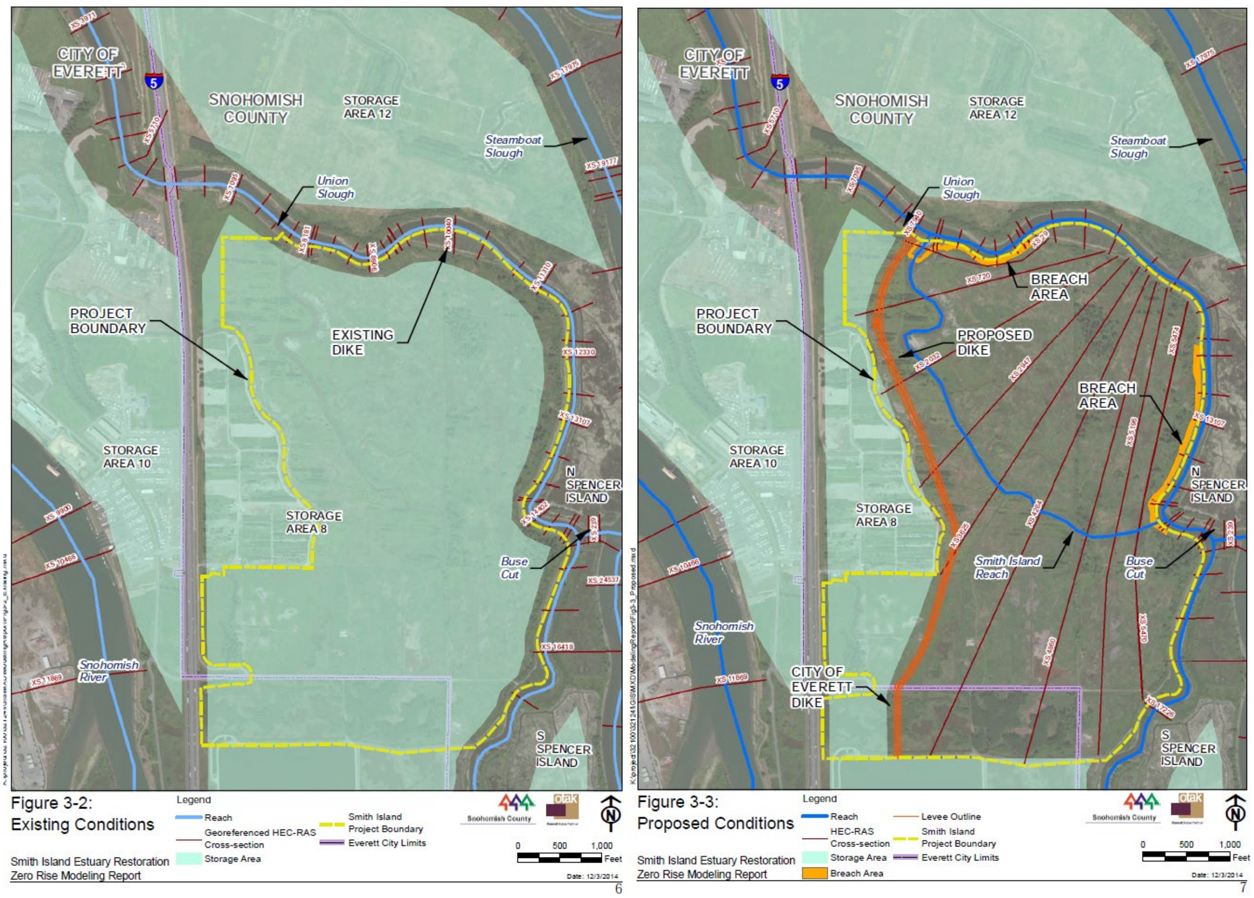


Figure 25. Smith Island restoration project CLOMR HEC-RAS model adjustments

Otak reports modeling result for changes from existing conditions resulting from the Smith Island project as follows:

> The project conditions' decreases in peak water-surface elevations over the upper portion of the reach adjacent to Smith Island are due to the dike breaches that allow more water to flow freely across Smith Island, thus effectively increasing the total conveyance capacity of the reach (Union Slough between overbank dikes and Smith Island). The maximum decrease in water-surface elevation is about 0.5 feet with the decreases extending about 2,600 feet upstream of the Buse Cut located near the upstream end of Smith Island project boundary [emphasis added]. Despite the increased flows across the island, peak water-surface elevations under the project conditions are reduced by about 0.4 to 0.5 feet (Figure 4-2) compared with that under the existing conditions. The breaches in the dike allow water to flow more freely across the area opened east of the dike setback with less backwater and ponding which used to be caused by the existing higher dike profile.
>
> The local increase in project conditions' water-surface elevation just upstream of the East Tidal Channel outlet is about 0.7 feet, with the increase extending about 1,300 feet upstream of the outlet. This local jump in the water-surface elevation appears to be the result of a jump in the discharge resulting from the return flow from the island. As noted above, the dike breaches allow significantly more water to flow freely across Smith Island, with a majority of this flow returning to Union Slough through the low notch created at the East

Tidal Channel outlet (see Figure 4-1). This large increase in flow along Union Slough, from just upstream to just downstream of the dike breach, results in a large value for the convective acceleration term in the momentum equation in the one-dimensional HEC-RAS numerical solution schemes that must be balanced by an increase in the water-surface and/or energy grade slope. The increase in water surface elevation is compensated by the loss of energy across the location of the return flow and caused the increase in the upstream water surface elevation. This is a localized result with the large increases only affecting water-surface elevations along Union Slough near the East Tidal Channel outlet; changes elsewhere are minor and less influenced by the proposed dike setback project in the Smith Island (see discussion below). In Figure 4-3, the water-surface elevations under existing and project condition are shown in comparison with the Base Flood Elevations (BFE) from the FEMA Digital Flood Insurance Rate Maps (DFIRM) near the East Tidal Channel outlet.

At all other locations in the modeled area changes in peak water-surface elevations are very minor. Along Ebey Slough changes range from zero to a 0.03 ft decrease under project conditions. Along the Snohomish River changes under project conditions are less than 0.01 ft., ranging from -0.007 ft. to +0.007 ft. Changes in maximum water-surface elevation are all negative along Steamboat Slough, ranging from -0.001 ft. to -0.046 ft. Changes in maximum water-surface elevations in the storage areas are all zero or negative except for SA12 that shows a small increase of 0.0069 ft. SA 12 [Spencer Island] represents the area between Union Slough and Steamboat Slough just north of Smith Island and the small increase here is related to the local increase along Union Slough at the East Channel outlet.

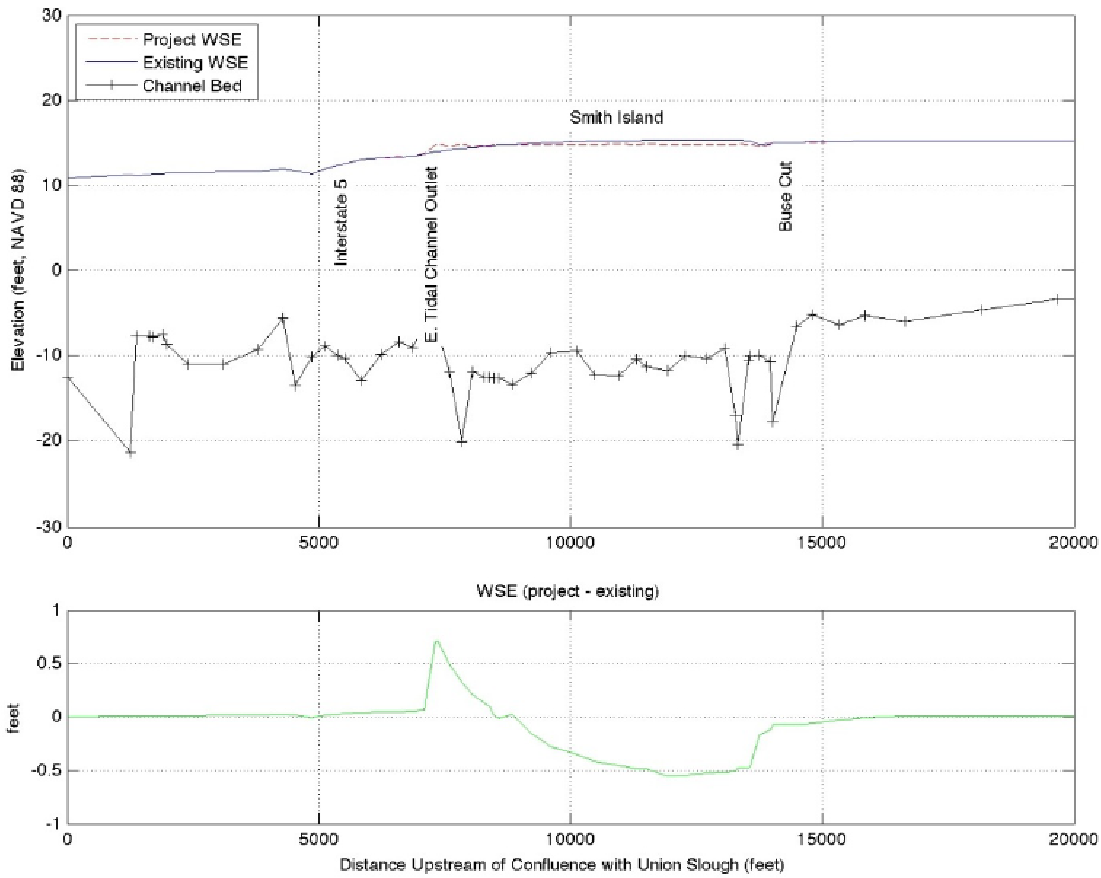


Figure 4-1. Comparison of existing and project conditions computed maximum water-surface profiles along Union Slough.

Figure 26. Modeled WSE changes at Union Slough from CLOMR study

Table 13. BFE comparison table from FEMA 2016 CLOMR

BFE Comparison Table			
Flooding Source: Union Slough		BFE Change (feet)	Location of Maximum Change
Existing vs. Effective	Maximum increase	0.0	N/A
	Maximum decrease	0.7	Approximately 860 feet upstream of Interstate 5
Proposed vs. Existing	Maximum increase	0.7	Approximately 1,990 feet upstream of Interstate 5
	Maximum decrease	0.0	N/A
Proposed vs. Effective	Maximum increase	0.7	Approximately 1,990 feet upstream of Interstate 5
	Maximum decrease	0.7	Approximately 1,220 feet upstream of Interstate 5

In the CLOMR M2 form (request to FEMA to modify the effective flood insurance rate maps), Snohomish County notes the following that are directly relevant to Spencer Island:

> Construction of the new setback dike (dike) will result in floodplain fill with a significant portion of this fill located in the Density Fringe. Development in the Density Fringe is governed by Snohomish County Code (SCC), Chapter 30.65 "Special Flood Hazard Areas", in sections 30.65.240 through

> 30.65.285. It is managed by the Department of Planning & Development Services (PDS), which is the County Department that is responsible for requesting this CLOMR Application as part of their Flood Hazard permit conditions. The Density Fringe is managed to a 1-foot cumulative rise standard (SCC 30.65.240). SCC 30.65 is attached to this application. [emphasis added]
> The new setback dike is not intended to provide 100-year protection but rather is designed to U. S. Army Corps of Engineers (USACE) standards to provide 10-year protection, plus 2.0 feet of freeboard, and to qualify for the USACE PL84-99 maintenance program.

The above implies that any changes resulting from restoration at Spencer Island would be handled in the same manner as those resulting from the larger Smith Island project.

4.3. Effective FEMA Flood Insurance Study

The current effective FEMA flood insurance rate (FEMA, 2023) show that Spencer Island is located entirely within the FEMA AE flood zone, with a mapped floodway that spans the entirety of both Union Slough and Steamboat Slough (between the dikes). Base Flood Elevations for the 100-year flood event are shown on the map, as water surface profiles (Figure 28-Figure 30), and summarized in Table 14 and Table 15. The entirety of island landward of the existing dikes is mapped as a Density Fringe area. Density fringe areas are areas where not more than 2% of the land area can be developed in a manner that displaces floodwaters (Snohomish County Code (SCC) section 30.65.240) and the width of new construction cannot exceed more than 15% of the width of flow through the property or fringe area, whichever is less (SCC 30.65.255). WEST consultants noted in their model files that the 15% reduction was applied when computing the encroached water surface elevations shown in the FIS floodway tables.

Construction within the floodway is generally limited to only those actions that are necessary for public works, provided that the modifications do not worsen flooding (no-rise). In Snohomish County public works such as water dependent utilities and dikes shall not cause a cumulative increase in the base flood elevation of more than 1 foot (SCC 30.65.260). Restoration actions at Spencer will primarily remove fill from the existing dikes/dikes, increasing conveyance in the floodway. Some of these materials will be placed within the density fringe zone, but below an elevation that would restrict the passage of floodwaters. The work would likely be classified as a permitted use per SCC 30.65.280 (3) preserves and reservations, (4) parks and recreational activities, (7) water dependent utilities. SSC 30.65.285 (3) specifically mentions filling of marshlands as prohibited uses. Clarification may be necessary to determine if placement of spoils next to constructed channels is prohibited. Since this has been done at nearby restoration sites the presumption is that it is not prohibited.

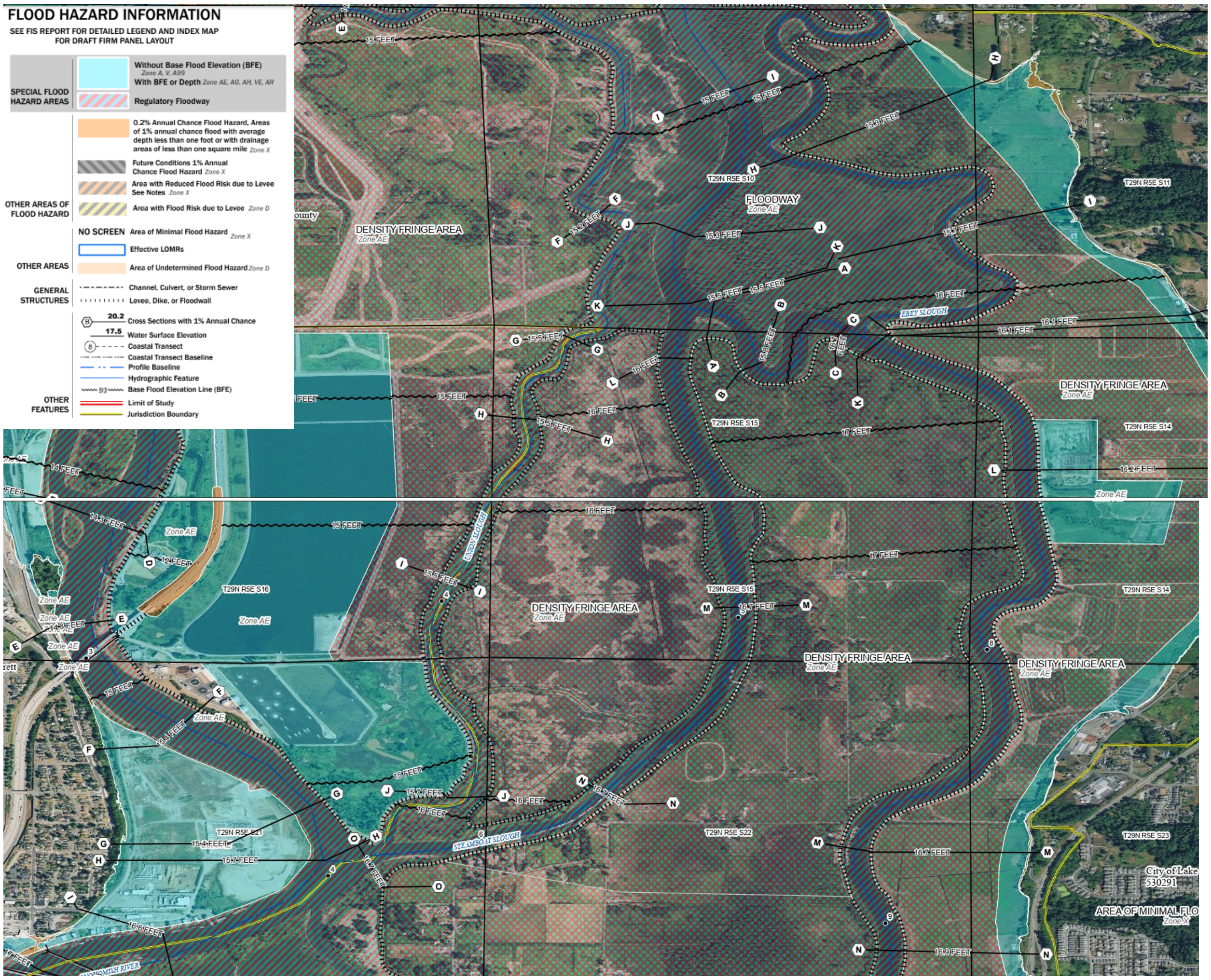


Figure 27. Effective FEMA Flood Insurance Rate Maps (FEMA Flood Hazard Viewer, 2023)

Note that the reported BFEs in the AE zone and on the cross section cut lines reflect the inclusion of a density fringe area (partially blocked storage area). Note in the floodway tables that the lower two miles of Steamboat Slough and lower mile of Union Slough are controlled by flooding from Puget Sound. The published flood elevations are higher along Steamboat Slough than Spencer Island, and higher in Spencer Island than Union Slough. There is about 1.5 feet of fall in the water surface profile along Steamboat Slough and about a half a foot along Union Slough. The FEMA UNET model, while outdated, appears to capture the macro scale differences is water levels between the various sloughs and islands. The BFE for Spencer Island is lower than the 2001 UNET computed WSE by about 0.7 feet, the reason for the discrepancy is not apparent, but could be related to updated hydrology or floodway assumptions.

The FEMA floodway tables show that there is an allowance for 0.5 to 0.6 feet of rise to account for the floodway fringe becoming fully developed subject to the density fringe requirements. In this analysis 15% of the area outside of the floodway boundary is assumed to become developed (block flowing water). Given that two large scale restoration projects have been completed along Union Slough, and Spencer Island is forthcoming, the density fringe areas and floodways could arguably be reanalyzed since new development will be prohibited in these areas in perpetuity (they could be converted to floodway or the development potential / conveyance / storage reduction reduced to 0%). This would have the effect of lowering the published base flood elevations along Union Slough, Steamboat Slough and possibly along the mainstem and Ebey Island.

Discussion and coordination with Snohomish County and FEMA (and likely the city of Everett) will need to be factored into the project schedules especially if map revisions are requested.

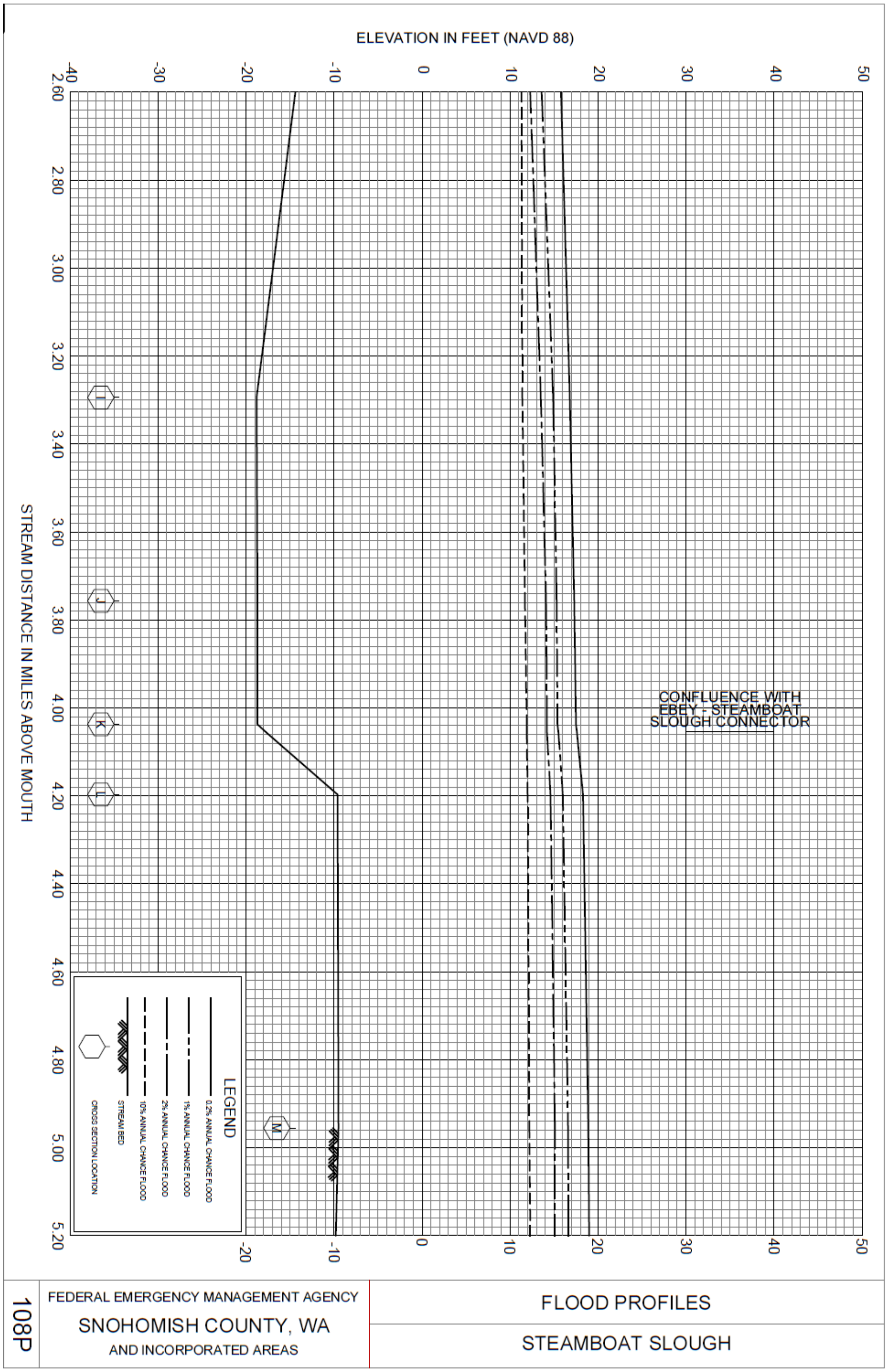


Figure 28. Steamboat Slough flood profiles from effective FEMA FIS (1 of 2)

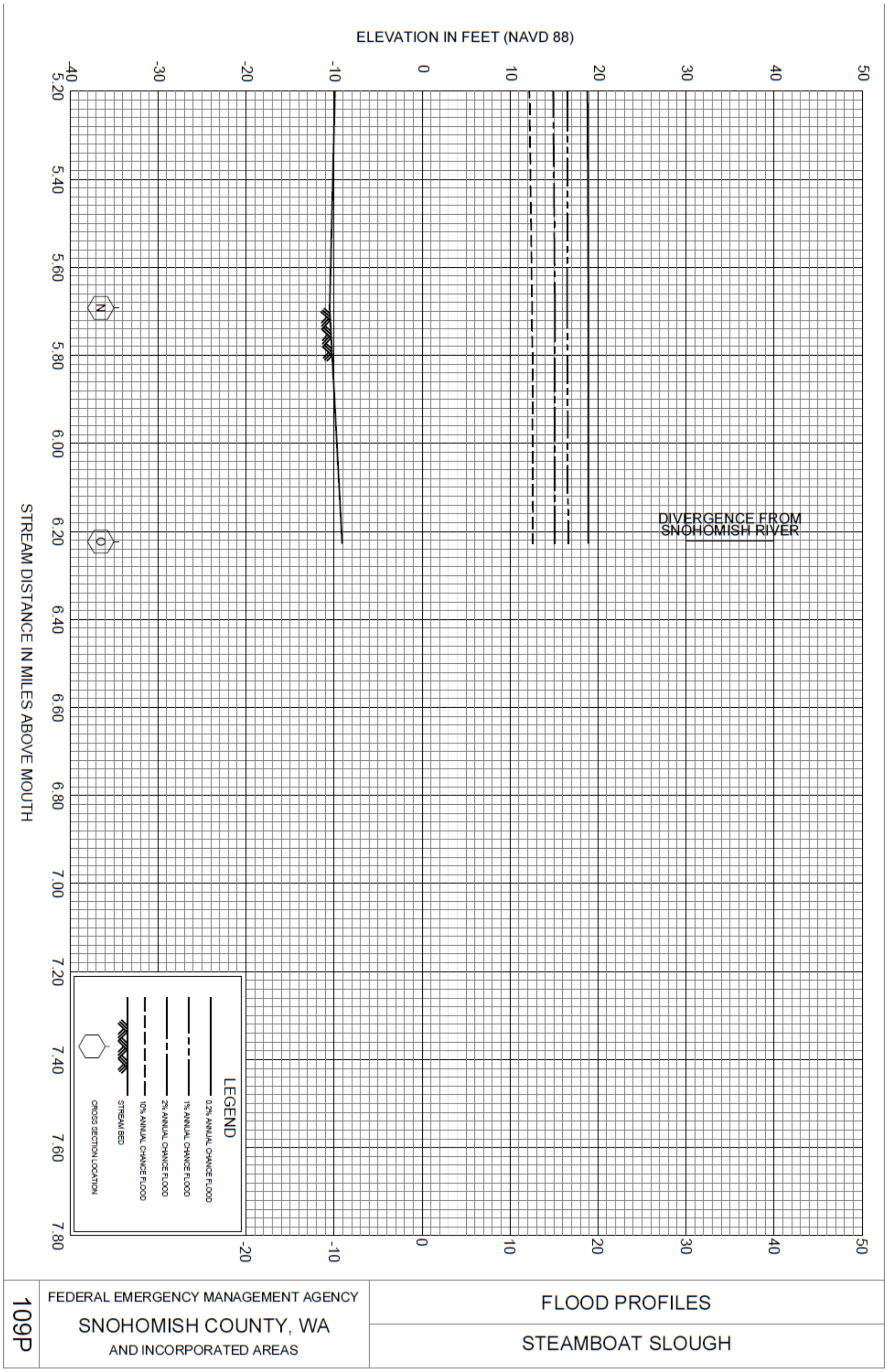


Figure 29. Steamboat Slough flood profiles from effective FEMA FIS (2 of 2)

LOCATION		FLOODWAY			1% ANNUAL CHANCE FLOOD WATER SURFACE ELEVATION (FEET NAVD88)			
CROSS SECTION	DISTANCE[1]	WIDTH (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET PER SECOND)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
A	0.16	2,917	30,510	3.9	*	9.9[2]	9.9[2]	0.0
B	0.80	1,353	21,730	4.7	*	10.9[2]	10.9[2]	0.0
C	1.12	2,889	17,842	4.4	*	11.6[2]	11.9[2]	0.3
D	1.49	1,368	19,526	5.3	*	12.0[2]	12.3[2]	0.3
E	1.62	596	12,265	5.9	*	12.1[2]	12.6[2]	0.5
F	1.72	626	12,730	5.1	*	12.4[2]	12.9[2]	0.5
G	2.15	1,309	17,342	4.8	13.1	13.1	13.8	0.7
H	2.60	1,148	13,451	5.6	13.8	13.8	14.5	0.7
I	3.30	1,150	16,315	4.5	15.0	15.0	15.5	0.5
J	3.76	2,145	22,823	4.5	15.3	15.3	15.9	0.6
K	4.04	2,772	26,253	4.9	15.5	15.5	16.1	0.6
L	4.20	350	6,490	3.5	16.0	16.0	16.6	0.6
M	4.96	349	5,844	2.9	16.7	16.7	17.2	0.5
N	5.70	240	4,566	3.4	16.7	16.7	17.2	0.5
O	6.23	742	10,093	1.6	16.7	16.7	17.2	0.5

[1]STREAM DISTANCE IN MILES ABOVE MOUTH

[2]ELEVATION COMPUTED WITHOUT CONSIDERATION OF BACKWATER FROM PUGET SOUND

*CONTROLLED BY COASTAL FLOODING – SEE FIRM FOR REGULATORY BASE FLOOD ELEVATION

TABLE 25	FEDERAL EMERGENCY MANAGEMENT AGENCY **SNOHOMISH COUNTY, WASHINGTON** AND INCORPORATED AREAS	**DENSITY FRINGE AREA DATA** FLOODING SOURCE: STEAMBOAT SLOUGH

Table 14. FEMA FIS floodway table for Steamboat Slough, extents of Spencer Island highlighted

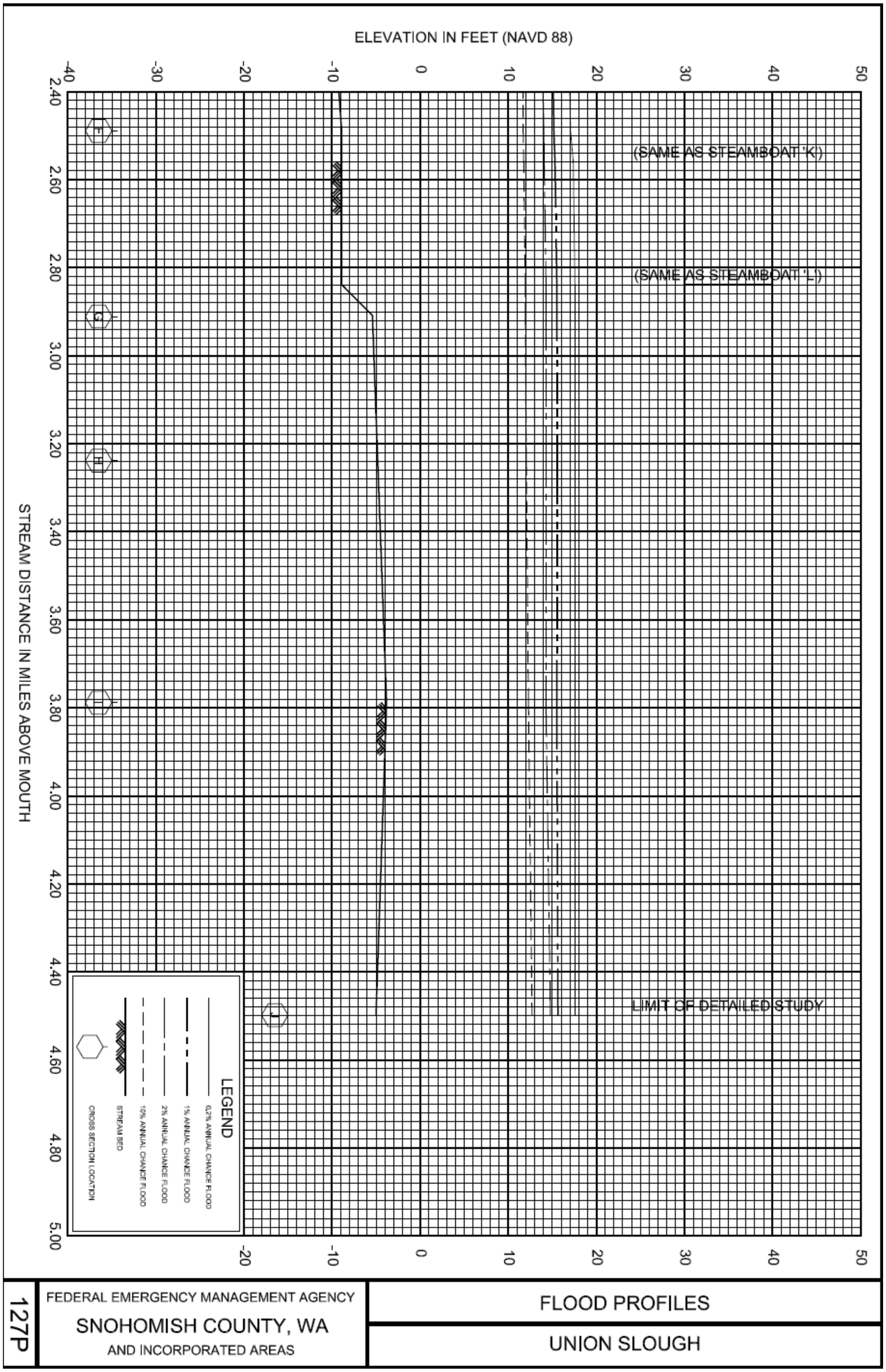


Figure 30. Union Slough flood profiles from effective FEMA FIS

LOCATION		FLOODWAY			1% ANNUAL CHANCE FLOOD WATER SURFACE ELEVATION (FEET NAVD88)			
CROSS SECTION	DISTANCE[1]	WIDTH[2] (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET PER SECOND)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
A	0.17	610	7,084	3.6	*	10.9[3]	10.9[3]	0.0
B	0.23	505	4,798	5.3	*	11.5[3]	11.6[3]	0.1
C	0.88	278	4,356	5.8	*	12.5[3]	13.2[3]	0.7
D	1.08	382	4,948	3.8	13.8	13.8	14.8	1.0
E	1.35	207	3,281	4.9	14.4	14.4	15.0	0.6
F	2.49	309	4,189	4.5	15.2	15.2	15.7	0.5
G	2.91	260	3,250	2.1	15.5	15.5	16.1	0.6
H	3.24	259	3,086	2.1	15.5	15.5	16.1	0.6
I	3.79	272	2,925	2.7	15.5	15.5	16.1	0.6
J	4.50	364	3,413	2.2	15.7	15.7	16.3	0.6

[1]STREAM DISTANCE IN MILES ABOVE MOUTH
[2]WIDTHS TAKE INTO ACCOUNT FLOODWAY FRINGE AND DENSITY FRINGE
[3]ELEVATION COMPUTED WITHOUT CONSIDERATION OF BACKWATER FROM PUGET SOUND
*CONTROLLED BY COASTAL FLOODING – SEE FIRM FOR REGULATORY BASE FLOOD ELEVATION

TABLE 25

FEDERAL EMERGENCY MANAGEMENT AGENCY
SNOHOMISH COUNTY, WASHINGTON
AND INCORPORATED AREAS

DENSITY FRINGE AREA DATA

FLOODING SOURCE: UNION SLOUGH

Table 15. FEMA FIS floodway table for Union Slough, extents of Spencer Island highlighted

4.4. 2021 Watershed Science and Engineering Study

In 2021 Snohomish County retained Watershed Science and Engineering (WSE) to update existing floodplain modeling with modern channel and floodplain topographic data using the 2D version of HEC-RAS to:

> *"…characterize current floodplain hydraulic conditions in the Snohomish River watershed and assess the projected impacts of climate change on flood depths and inundation extents along the Skykomish, Snoqualmie, and Snohomish rivers. The study area included the Skykomish River as far upstream as Gold Bar, the Snoqualmie River as far upstream as the King-Snohomish County Line, and the entire length of the Snohomish River from near Monroe to Possession Sound.*
>
> *Hydrologic and hydraulic analyses were conducted to characterize floodplain conditions within the study area for historical, mid-century (2040-2069), and late-century (2070-2099) time periods. USGS streamflow records were used to perform flow frequency analyses and create balanced hydrographs representing historical hydrologic conditions. Climate scalars were developed from hydrologic modeling of climate projections and used to scale the historical balanced hydrographs to represent floodplain hydraulic conditions for each of the two future time periods.*

> *A detailed two-dimensional HEC-RAS hydraulic model was developed, calibrated, and applied to evaluate river-related flooding throughout the study area, with a particular focus on the Skykomish and Snohomish Rivers. The model was configured to directly use observed streamflow data as its hydrologic inputs, allowing users to simulate any flood event in the historical record. The model's computational mesh contained approximately 330,900 cells and covered a combined total of approximately 76 river miles and 70,560 acres of floodplain. The calibrated model was run to produce flood depths, velocities, water surface elevations, and inundation extents, for the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood events for historical, mid-century, and late-century time periods.*

This model usedHEC-RAS version 5.0.7 and a bathymetric surface based on 2019 single beam sonar data (of the mainstem and slough channels merged with 2019 terrestrial Lidar data. To aid in analysis of the Spencer Island site the WSE HEC-RAS 2D model, which can take more than 24 hours to run depending on the simulation period, was truncated at the Snohomish River Monroe gage, leaving all other boundary conditions downstream of this cutoff the same. The model was then run with either observed or synthetic flows at the Monroe gage depending on the scenario of interest. A small, detailed model of the Spencer Island site and adjacent slough channels was developed that uses the truncated model for boundary conditions. These model boundaries are shown below in Figure 31.

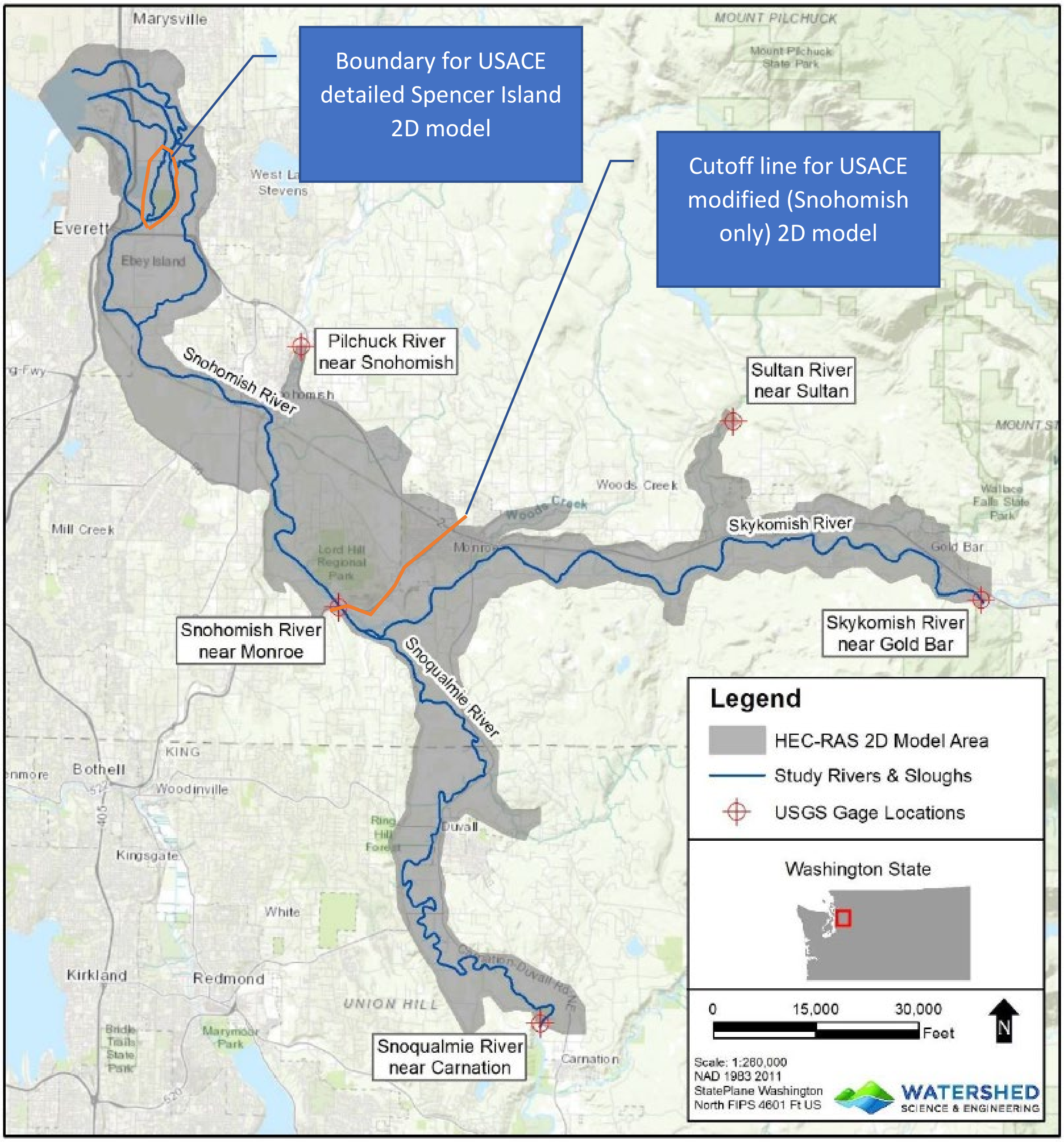


Figure 31. HEC-RAS 2D model extents and stream gage locations

4.5. PSNERP Draft Feasibility Report & EIS Engineering Appendix

USACE Seattle District summarized previous hydraulic studies as part of the original PSNERP feasibility study. Flood flows and elevations are as reported in the FEMA FIS. Impacts of restoration were qualitatively assessed and expected to be minimal but it was recommended that that PED phase activities verify this assumption.

5. Spencer Island Hydraulic Analysis

5.1. Spencer Island 2D Modeling to Support Conceptual Design

The purpose of this 2D HEC-RAS unsteady flow modeling is to compute inundation areas and velocity changes for 8 separate action alternatives and the no action alternative to compute benefits needed to identify a preferred alternative. The model is based on the WSE 2021 model, described previously, truncated to Spencer Island and adjacent sloughs. Boundary conditions (stage-flow time series) were extracted from a Snohomish River only existing conditions 2D model created by USACE run for the same time period (June 2022). The analysis is documented in Annex D4. Refer to the civil design annex for a description of the pertinent features of the conceptual alternatives. The terrain created for the Alternative 8 model was used to develop the grading plan for the selected alternative and is the basis for the 35% design analyzed in the full model and described below.

5.2. Spencer Island 2D Modeling for Feasibility Level H&H Analysis

The purpose of this modeling is to understand on and off-site hydraulic changes and to help inform design phase refinements.

5.2.1. Survey & Terrain data

Several sources were used to build a suitable terrain for our model. This involved multiple surveys, multiple LiDAR sources, and processing using GIS software. LiDAR of the entire Snohomish basin from the Watershed Sciences and Engineering (WSE) model makes up most of the terrain (WSE 2021). The Tulalip Tribe produced rasters of the surrounding sloughs from a multibeam survey (Tulalip Tribes 2020). Inside the Island, survey data was obtained (by USACE) for the bathymetry of some existing channels. Our proposed condition terrain has a modified LiDAR raster that includes proposed changes and disposal areas of the moved material. These sources were all compiled and mosaicked into two rasters (proposed and existing conditions). The cell size for the rasters ranges from about 1.5 to 3. The coordinate reference system is set to NAD83 Washington State Plane North (EPSG 4601) in US feet. The vertical datum is NAVD88.

Terrain modifications were added to both terrains to add dikes and high points throughout the study area. This data came from the National Dike Database (NLD). See Figure 32 for the full terrain. See Figure 33 for the modified proposed conditions LiDAR and the multibeam survey around the Sloughs.

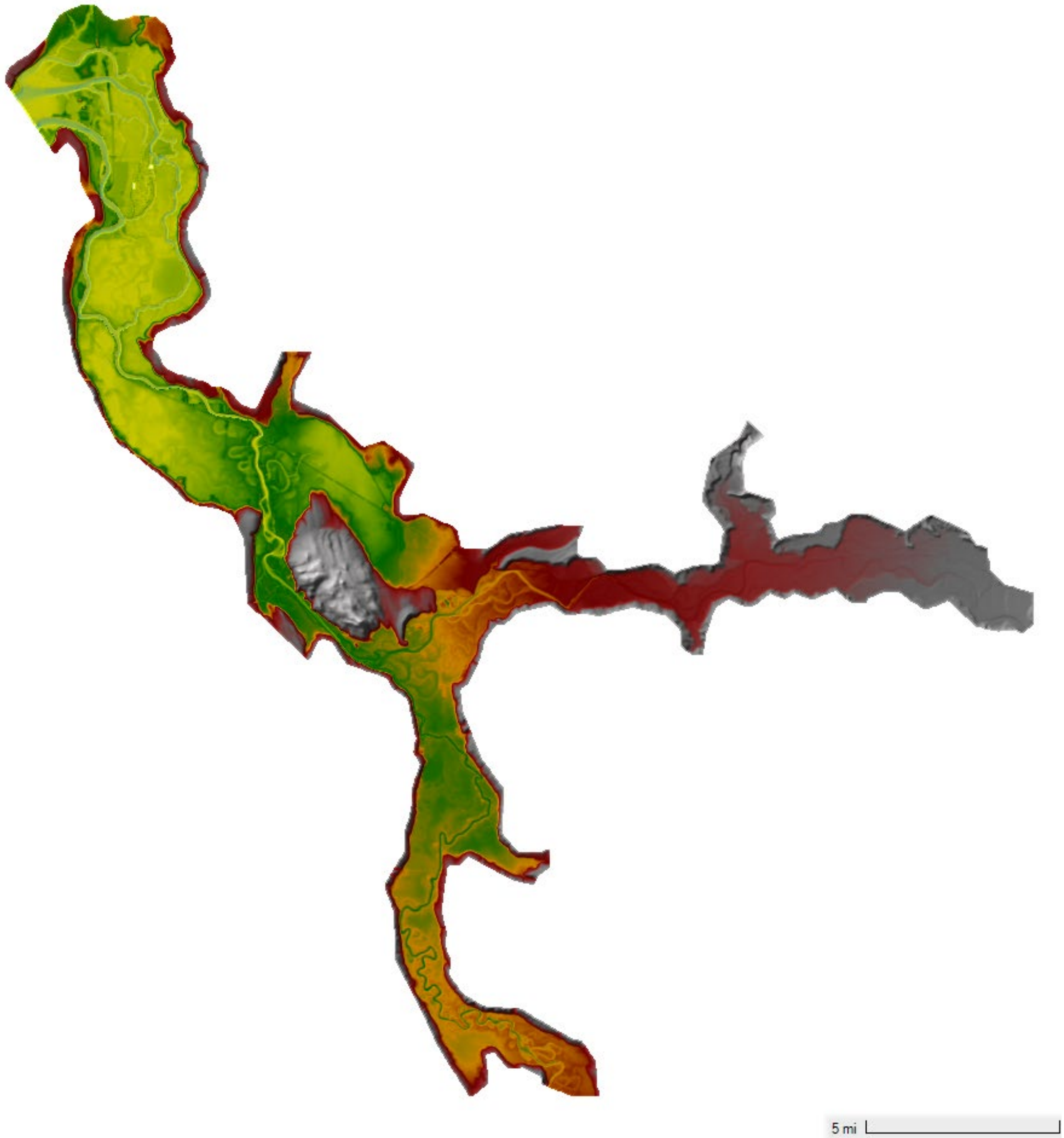


Figure 32. Full Terrain Extent

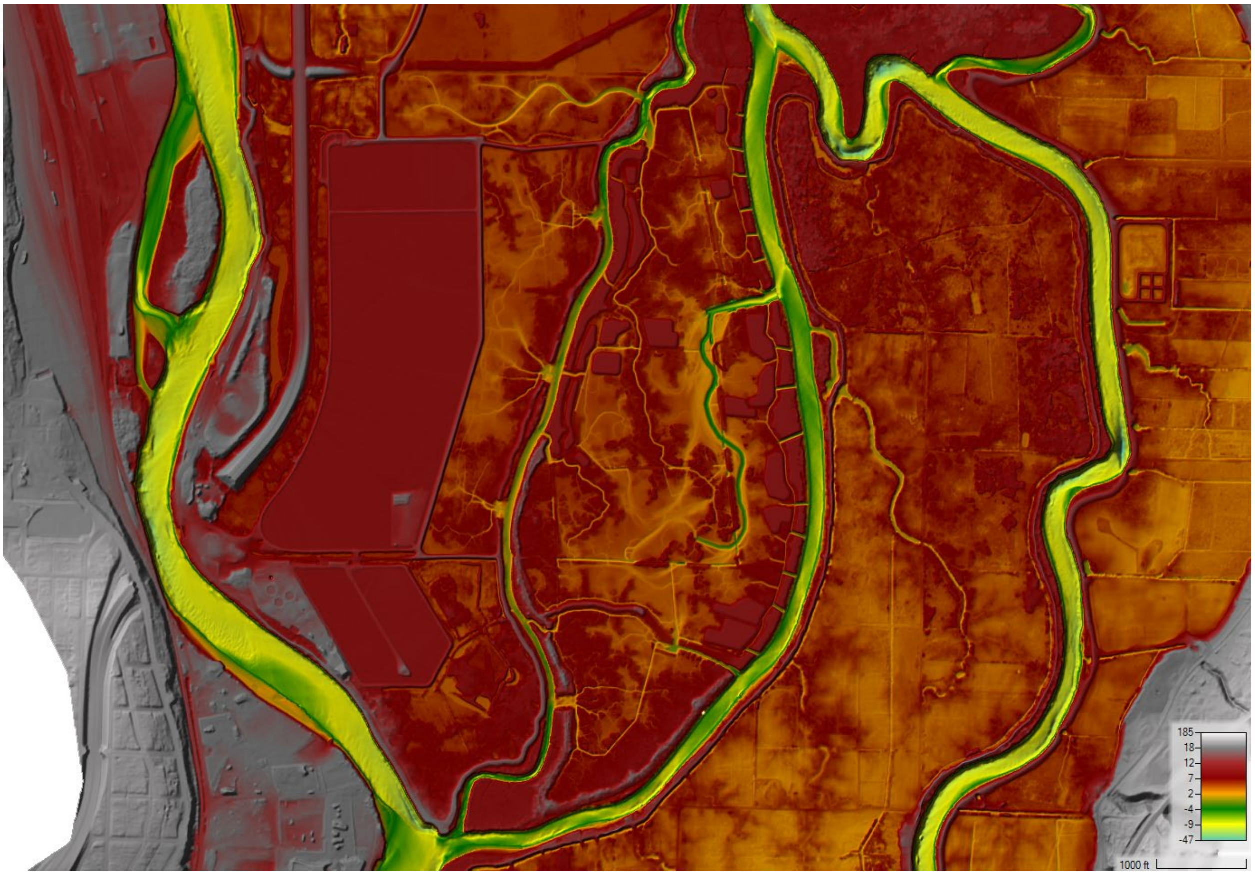


Figure 33. Proposed Conditions terrain. Note the multibeam surveys of the Sloughs.

5.2.2. Geometry

Three versions of the geometry were developed for this model. First, a geometry was used for the validation runs. The validation runs use the original larger model from the 10% Design phase. It did not include the finer geometry features of the actual island itself. This geometry was meant to simulate the surrounding areas to assess our model's accuracy against observed conditions. The remaining two geometries were for the proposed 35% design and the existing conditions scenarios. These two geometries have the same larger basin mesh, with a finer mesh for the Spencer Island area have. For both models, the minimum cell size was 55 sq ft, and the maximum was 70000 sq ft. The maximum cell sizes occur near the downstream tidal boundary condition. The average cell size is approximately 8400 sq ft, and the total ranges from 183650 (existing conditions) to 187441 (proposed conditions) cells. The difference in total cells is due to differences within the island itself.

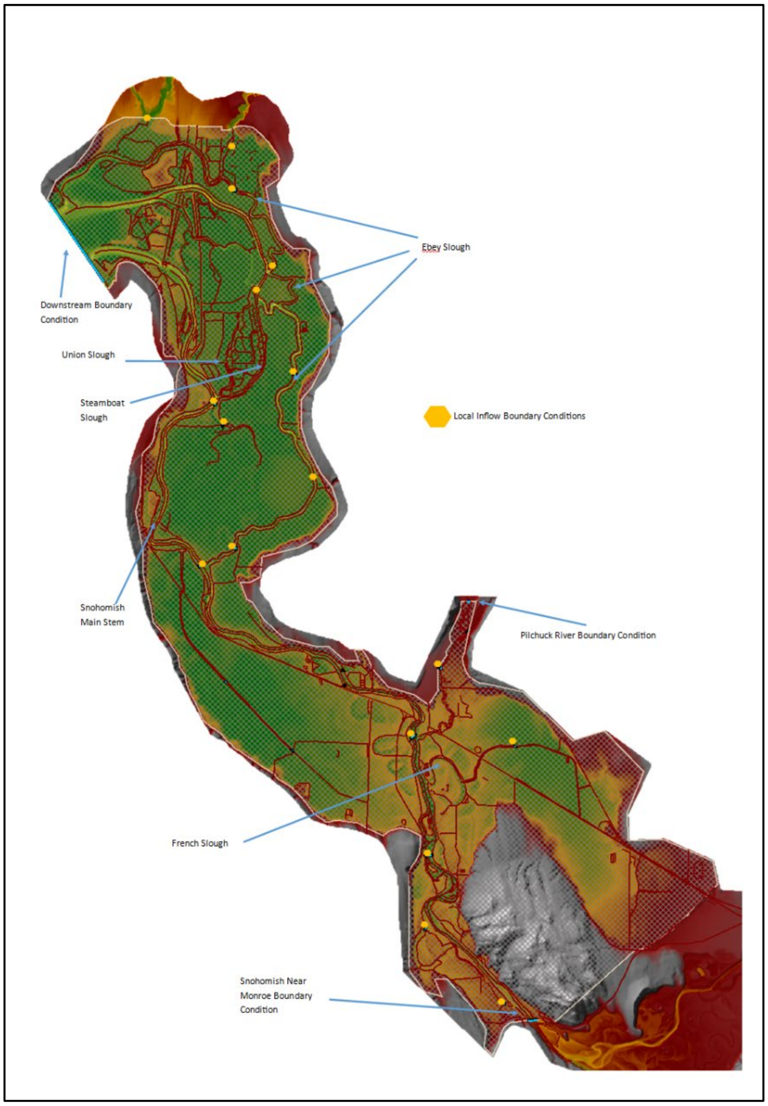


Figure 34. Full Mesh

The larger basin geometries are based on the full Snohomish Basin model from Watershed Science and Engineering. The geometry was modified to start at the USGS Snohomish near Monroe gage, which serves as our upstream boundary condition. Mesh refinements were made throughout the model to accurately model flow around NLD dikes. The Spencer Island area meshes were developed during the 10% design phase. The larger mesh and the finer island area meshes were combined, so the final meshes for the proposed and existing design have both the larger basin mesh as well as the fine Island mesh. The proposed conditions' land use required some roughness overrides inside Spencer Island. See Figure 35 for a comparison of the Spencer Island land use and meshes for both conditions.

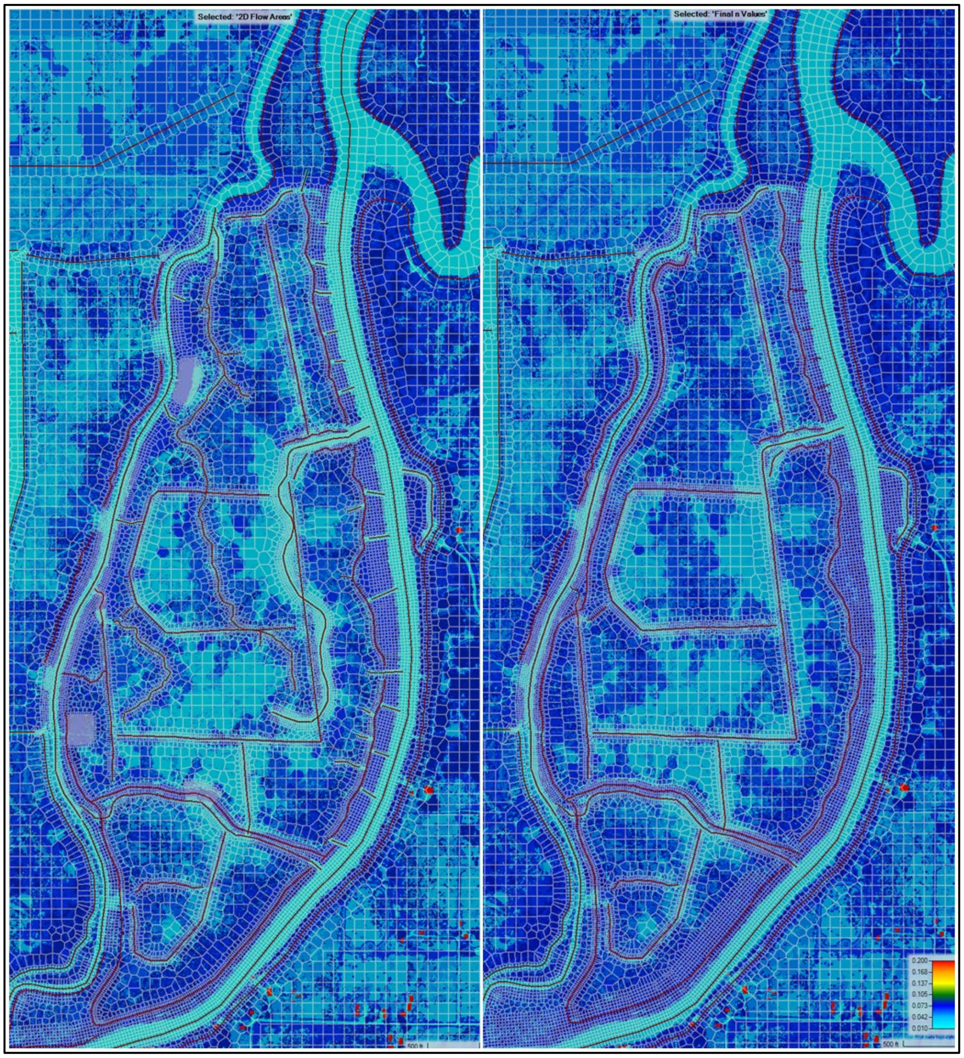


Figure 35. Proposed (left) vs Existing (right) meshes and land use

5.2.3. Model parameters and setup

The latest version of HEC-RAS was utilized (version 6.5, Feb. 2024) for all model runs. All models use the Shallow Water Equations (Eularian/Langrangian Method). Turbulence model is non-conservative, with longitudinal and transverse mixing coefficients set to 0.6. Initial Conditions time is 4 hours, with a ramp up fraction of 0.1. A maximum Courant is set to 2, and a minimum of 0.5. Other adaptive timestep settings vary between the models. Corresponding proposed and existing model runs were set to the same settings. Computation interval was set to 10 seconds. Model run times took anywhere from 18 hours to 38 hours, depending on the amount of inundation throughout the study area and the type of computer used. Because of the long run time, some models were run using restart files.

5.2.4. Boundary conditions and modeling scenarios

The feasibility level modeling includes two validation scenarios, and 30 production runs focused on understanding changes to flood levels resulting from historical and future sea levels and river flows. The production runs were split into 15 scenarios, each with a proposed conditions and existing conditions version.

Model Validation

USACE made several major changes to the existing WSE model and verified model calibration using data from December 2022 and December 2023. December 2022 king tide of record caused widespread flooding near Spencer Island. This event was coupled with high (but not flood) flows on the Snohomish River of 36,000 cfs at the Monroe gage. In December 2023 a high flow of 65,000 cfs occurred at the Monroe gage that had a recurrence interval estimated to be 2.3 years. The Snohomish gage is affected by both tidal backwater and upstream dike overtopping making it a difficult location for reliable measurements.

Two stage gages were used to validate the results: Ebey Slough near Highway 2, and mainstem Snohomish River at French Slough near the pumping station. Both Ebey Slough and Snohomish near Snohomish required conversion from their original datums to the NAVD88. The Ebey Slough conversion was +3.668 feet. The Snohomish near Snohomish conversion was +6.43 feet.

Table 16 shows the maximum observed values in the three gages, as well as the modelled values at the same locations for the two validation events. The delta row is the modelled value subtracted from the observed value. The validation results are illustrated in Figures 33 through 40.

Table 16. Validation maximum WSE results

	2022				2023			
	Max WSE (ft NAVD88)			Flow (cfs)	Max WSE (ft NAVD88)			Flow (cfs)
Condition	French	Snoho	Ebey	Snoho	French	Snoho	Ebey	Snoho
Observed	19.06	16.44	13.82	37800	25.58	21.26	13.14	64,800
Modelled	19.05	16.42	13.39	41100	25.58	21.35	13.01	67800
Delta	0.01	0.02	0.43	-3300	0	-0.09	0.13	-3000

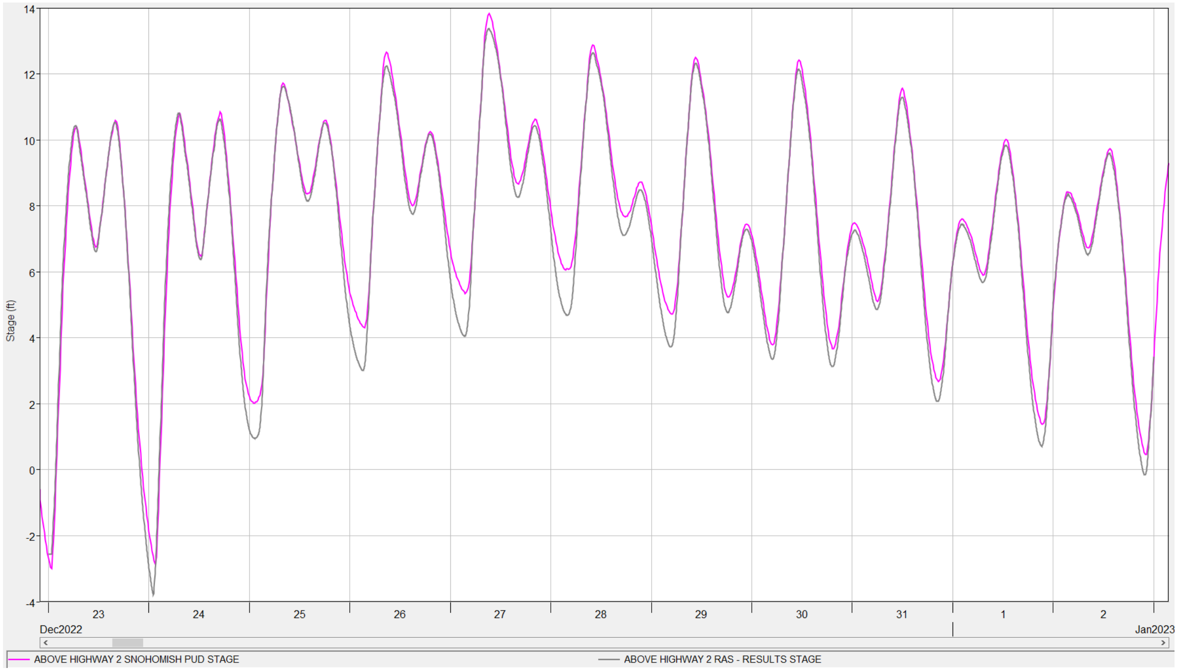


Figure 36. 2022 Validation Run Stage vs Observed Stage, Ebey Slough above Highway 2 gage

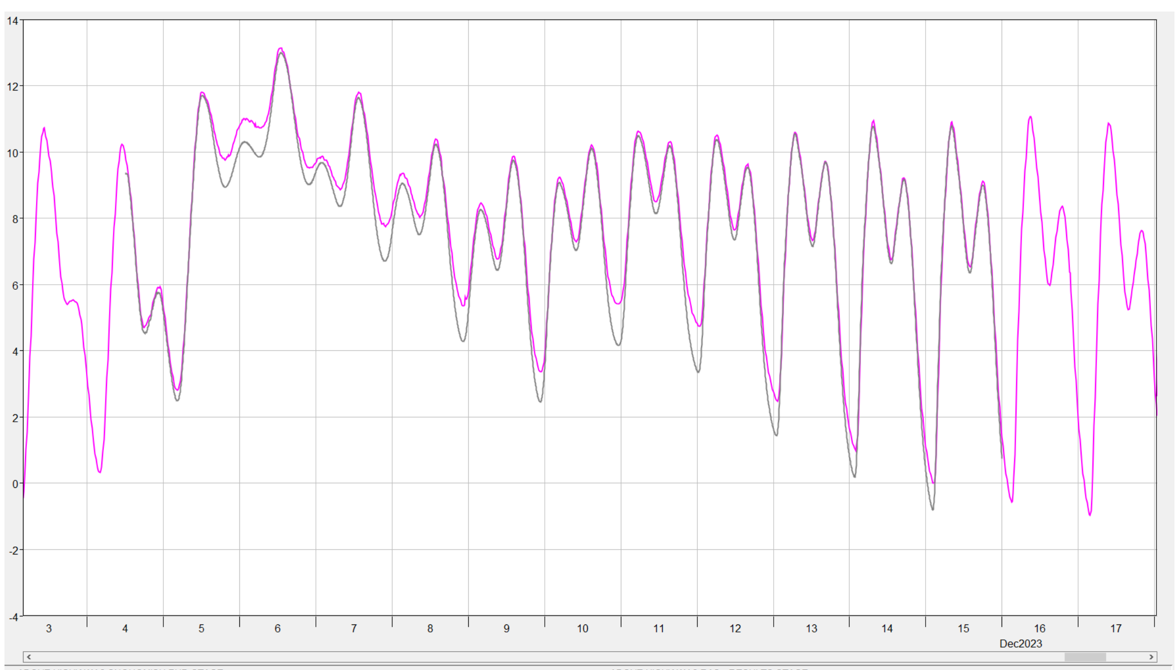


Figure 37. 2023 Validation Run Stage vs Observed Stage, Ebey Slough above Highway 2 gage

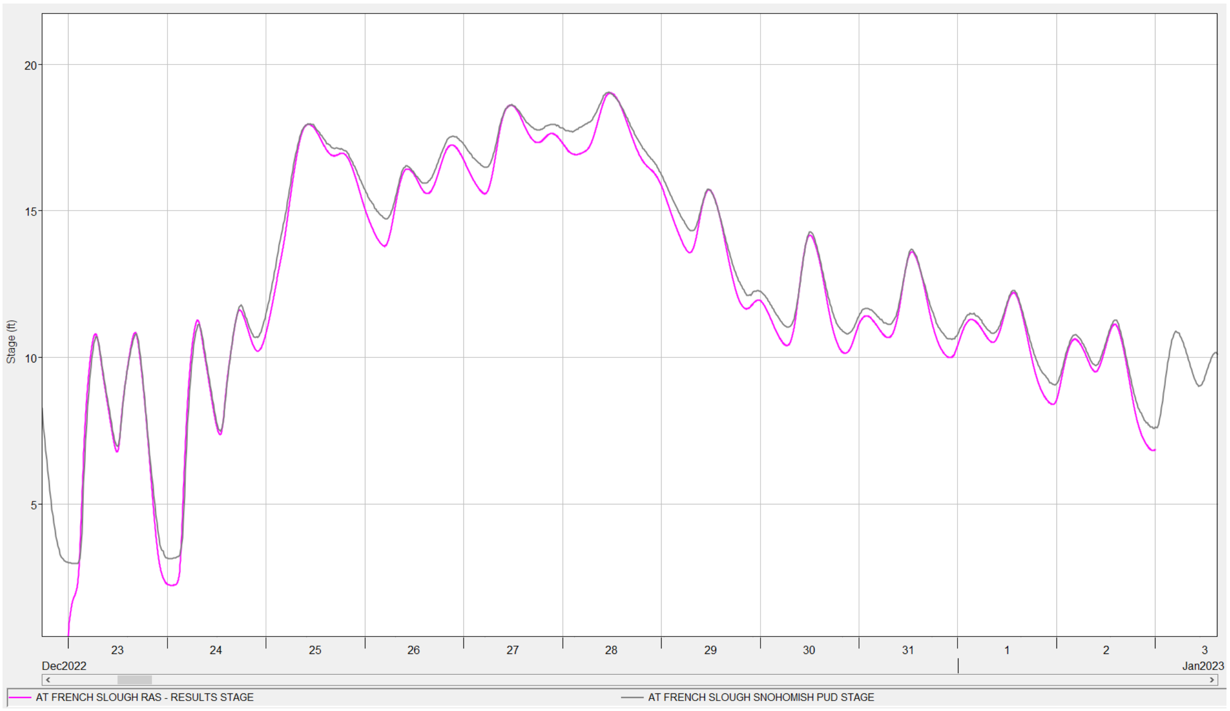


Figure 38. 2022 Validation Run Stage vs Observed Stage, Snohomish River at French Slough gage

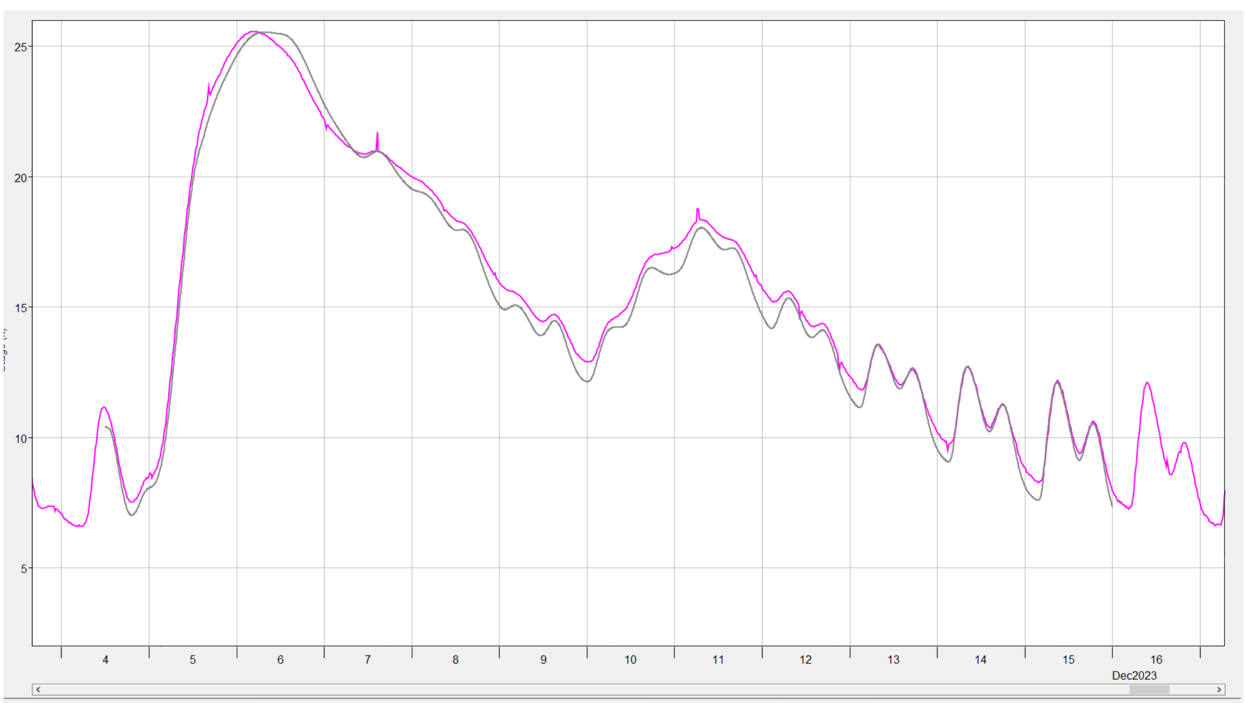


Figure 39. 2023 Validation Run Stage vs Observed Stage, Snohomish River at French Slough gage

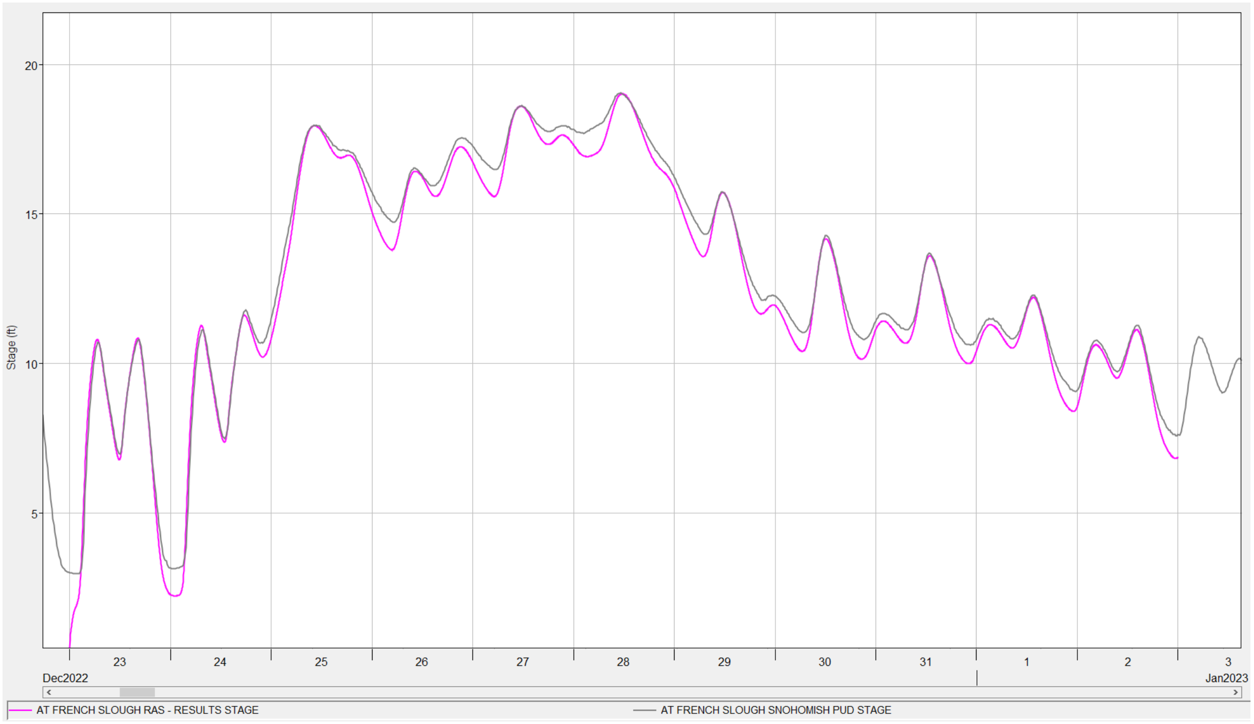


Figure 40. 2022 Validation Run Stage vs Observed Stage, Snohomish River at Snohomish gage

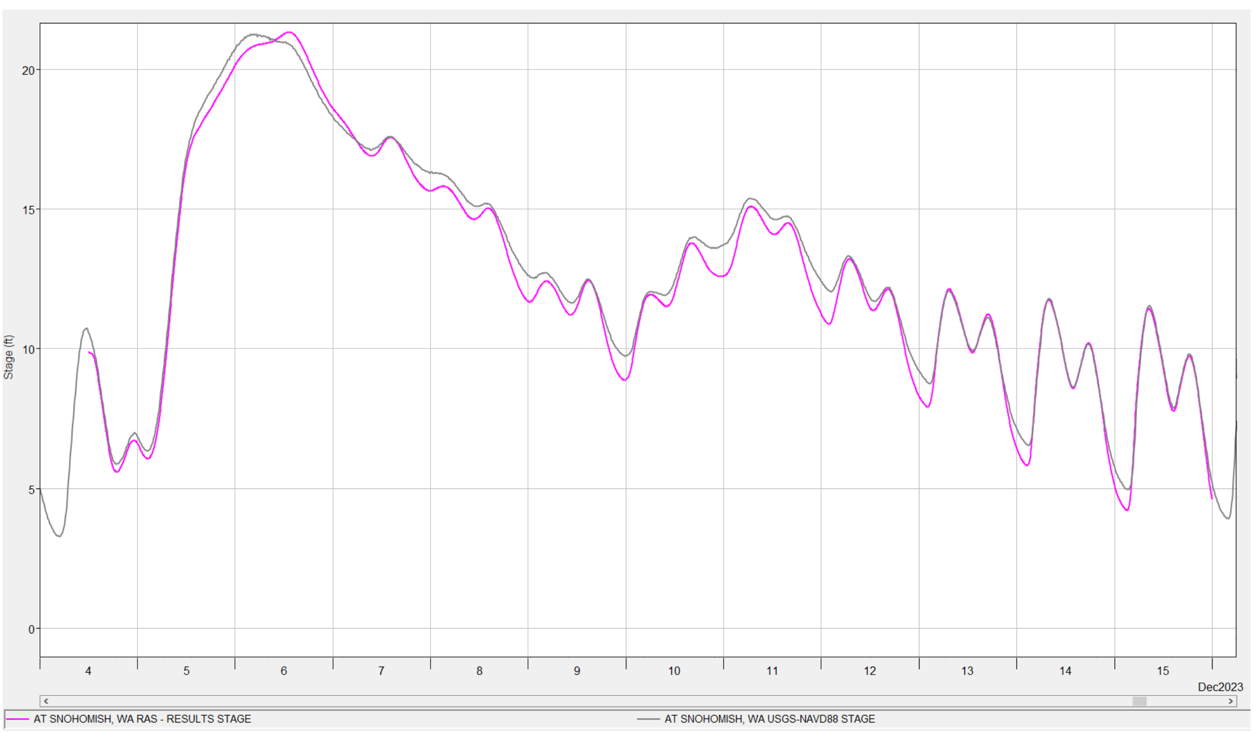


Figure 41. 2023 Validation Run Stage vs Observed Stage, Snohomish River at Snohomish gage

Figure 42. 2022 Validation Run Flow vs Observed Flow, Snohomish River at Snohomish gage

Figure 43. 2023 Validation Run Flow vs Observed Flow, Snohomish River at Snohomish gage

Existing and proposed conditions (historical) flood risk scenarios

Changes in potential flood risk due to the proposed project are analyzed in the following scenarios (Table 17). Scenario designated with an E refer to existing scenarios, scenarios with a P designation refer to proposed scenarios. Scenarios 1 through 11 are intended to bracket the full range of flood stages expected in the project lifetime, assuming stationarity of coastal and riverine boundary conditions, which is consistent with most USACE feasibility level investigations. WSE hydrology refers to flow values from the 2021 study for Snohomish County by WSE. FEMA FIS estimates refer to peak flow estimates provided in the effective FEMA Flood Insurance Study.

Table 17. Existing and proposed historical flood risk scenarios

Scenario	Coastal Boundary Condition	Riverine Boundary Condition	Notes
1E/P	99% AEP / 11.0 feet	99% AEP / 54533 cfs	WSE hydrology
2E/P	50% AEP / 11.26 feet	99% AEP / 54533 cfs	“”
3E/P	10% AEP / 11.71 feet	99% AEP / 54533 cfs	“”
4E/P	2% AEP / 12.2 feet	99% AEP / 54533 cfs	“”
5E/P	1% AEP/ 12.43 feet	99% AEP / 54533 cfs	“”
6 E/P	0.2% AEP/ 13.03 feet	99% AEP / 54533 cfs	“”
7 E/P	MHHW + 1 feet (9.8 NAVD88)	50% AEP / 77562 cfs	FEMA FIS estimates (1)
8 E/P	MHHW + 1 feet (9.8 NAVD88)	10% AEP / 129600 cfs	“”
9 E/P	MHHW + 1 feet (9.8 NAVD88)	2% AEP / 186500 cfs	“”
10 E/P	MHHW + 1 feet (9.8 NAVD88)	1% AEP / 210100 cfs	“”
11 E/P	MHHW + 1 feet (9.8 NAVD88)	0.2% AEP / 260100 cfs	“”

(1) 50% AEP estimate obtained by linear regression of FIS annual peak flow frequency data

All coastal boundary conditions are set as a constant stage (the value on the respective row). Riverine boundary conditions are based on synthetic hydrographs from the FEMA FIS UNET models. The 10% hydrograph was scaled to the 50% AEP flows and 99% AEP flows, which were not a part of the initial UNET model. Note that some UNET flows have higher peaks than listed for volume accounting.

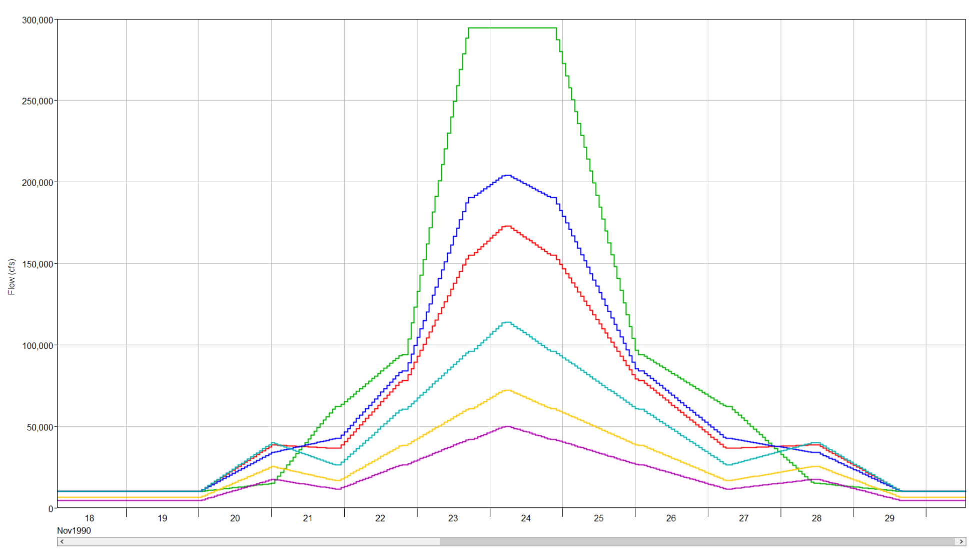


Figure 44. Balanced inflow hydrographs for 99% through 0.02% AEP historical floods at Monroe gage

The figure above shows the hydrographs of the Snohomish River near Monroe. This data forms the upstream most boundary condition, and accounts for most of the flow going into the model.

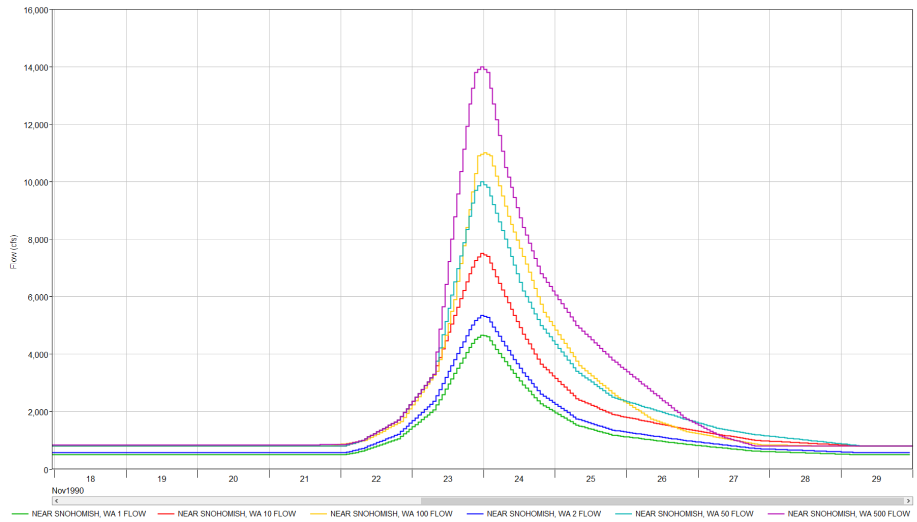


Figure 45. Coincident lateral inflow hydrograph for Pilchuck River for 99% AEP through 0.02% AEP events

The figure above shows the lateral inflow hydrographs for Pilchuck river tributary inflows which enter the model upstream of Snohomish. Lateral inflow hydrographs in the WSE hydrology for smaller ungaged basins scale these hydrographs by drainage area ratio.

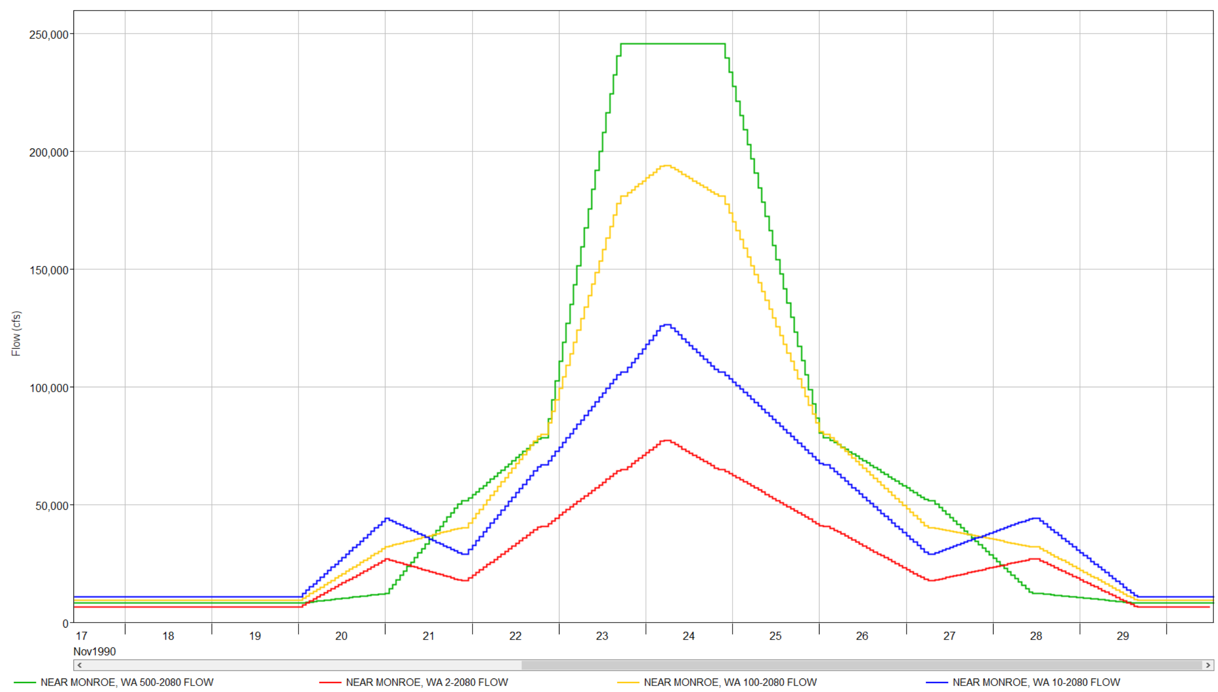
Future flood risk scenarios

WSE completed an evaluation of potential floodplain changes for intermediate SLR estimates of 1.67 feet and scaled peak streamflows based on a UW CIG analysis of climate modified hydrology (UW CIG 2014). Refer to the WSE 2021 report for more details of that analysis. These scenarios are provided for informational purposes (not used for design). The higher projected flows from WSE were used to scale the existing UNET hydrographs to their new values. The 0.2% UNET flows were scaled to the new 2080 0.2% flows, the 1% UNET to the new 2080 1% flows, and so on.

Table 18. 2080s conditions (intermediate scenario SLR) + CIG forecasted inland hydrology

Scenario	Coastal Boundary Condition	Riverine Boundary Condition	Notes
12 E/P	MHHW + 1-foot 2080 (11.47ft NAVD88)	2080 50% AEP / 77,400 + 7,370 cfs	WSE 2021
13 E/P	MHHW + 1 foot 2080	2080 10% AEP / 126,500 + 12,700 cfs	“”

14 E/P	MHHW + 1 foot 2080	2080 1% AEP / 194,200 + 19,000 cfs	“”
15 E/P	MHHW + 1 foot 2080	2080 0.2% AEP / 245,900 + 23,300 cfs	“”



2080s balanced inflow hydrographs for 99% through 0.02% AEP historical floods at Monroe gage based on WSE 2021 hydrology

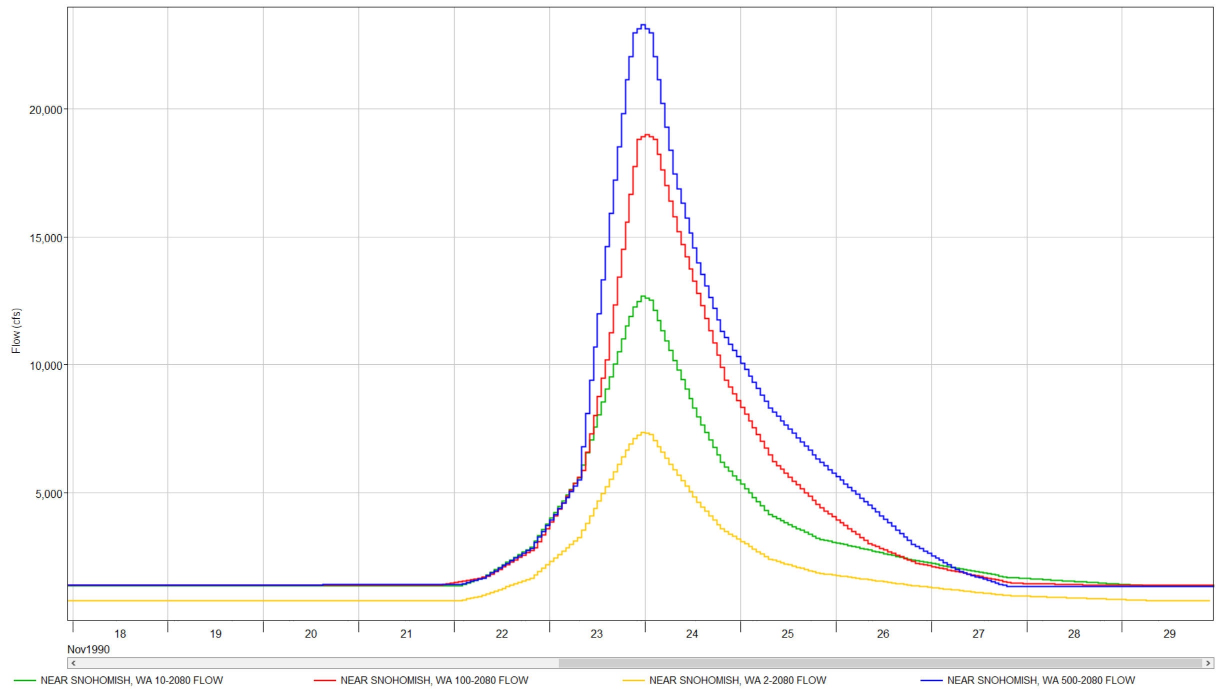


Figure 46. 2080s coincident lateral inflow hydrograph for Pilchuck River for 99% AEP through 0.02% AEP events

6. Existing and Future with and Future Without Project Hydraulic Analysis Results

6.1. Water Surface Profiles and Inundation Maps

This section summarizes the results shown in Annex D2 for the scenarios presented in Table 17 and Table 18. Key results and findings are presented. Note that the modeling shows that water surface elevations do not change for coastal flood scenarios, so only the results for the riverine flood scenarios are discussed here. Refer to Annex D2 for results for all scenarios. For discussions of potential changes in velocity and implications refer to Annex D3.

Along the mainstem Snohomish River between Puget Sound and the Ebey Slough (Figure 47) all riverine flooding scenarios show very small decreases in maximum water surface profiles. The decrease is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Note that the split from the mainstem to Union/Steamboat Slough is river mile 4.

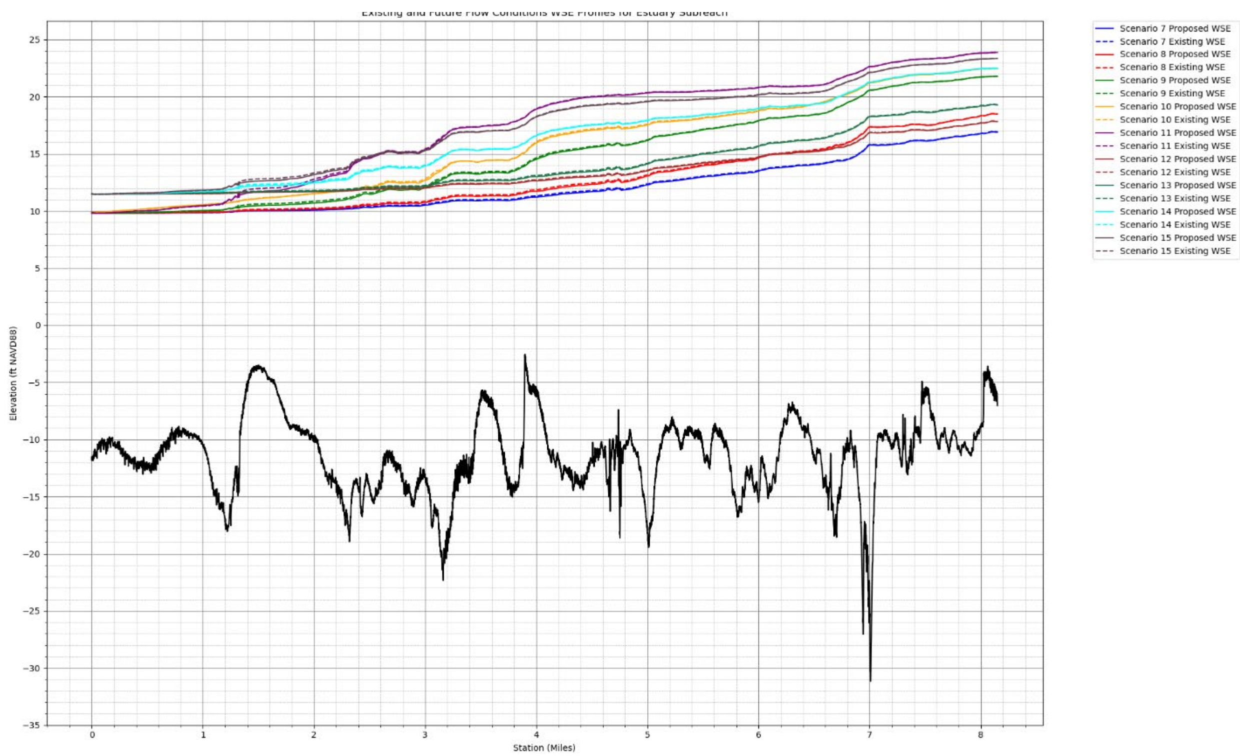


Figure 47. Mainstem Snohomish River water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

Along Steamboat Slough, between Puget Sound and upstream connection with the Snohomish River, modeled flooding scenarios (Figure 47) predict larger decreases in maximum water surface profiles than in other distributary channels. The decrease is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Spencer Island spans from RM 4.5 to 6.6 in the plot below.

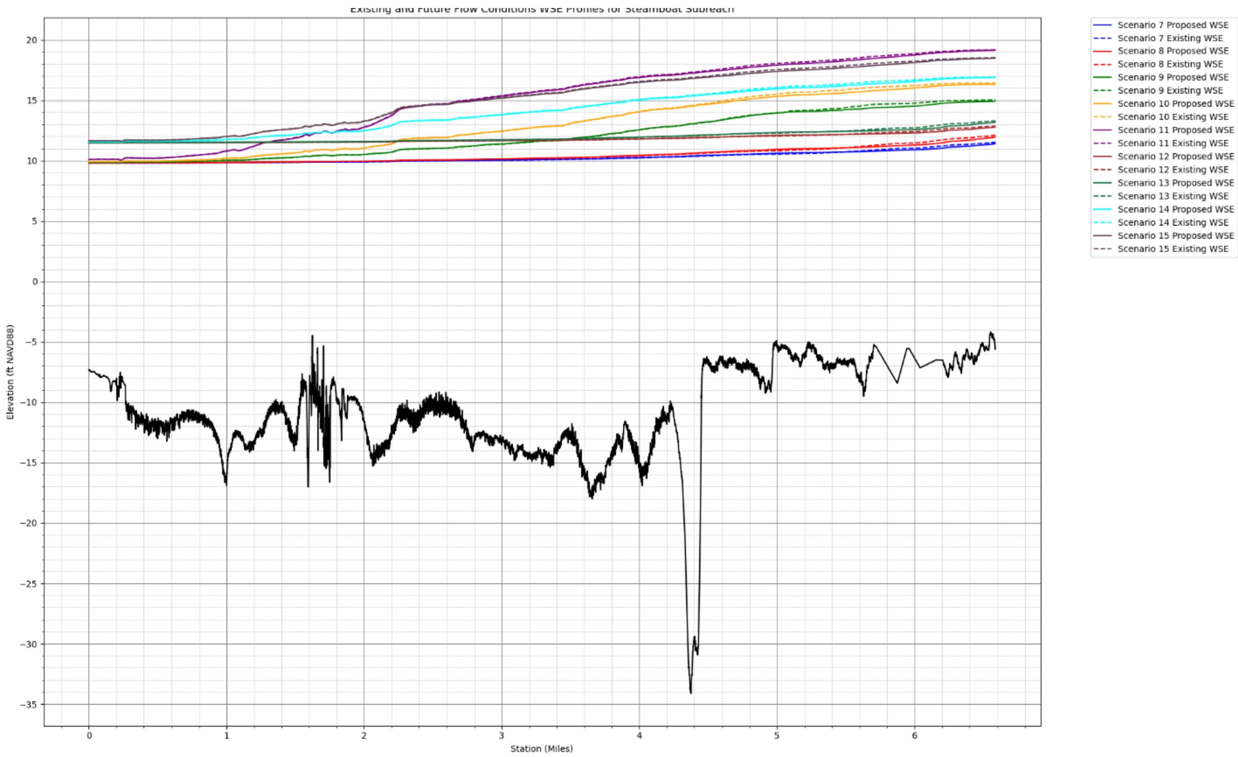


Figure 48. Steamboat Slough water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

Along Union Slough, between Puget Sound and upstream connection with the Snohomish River, modeled flooding scenarios (Figure 48) predict small changes predict small increases and decreases in maximum water surface profiles. Decreases in water surface occur in the upstream most part of Union Slough, immediately after the junction where Steamboat and Union sloughs branch off the mainstem Snohomish. This slight decrease is observed in Scenarios 7, 8, 9, 12, and 13. This decrease in water surface is minimal and is imperceptible in the profile plots. It can be seen in an inundation/depth difference plot. Figure 50 plots the differences in depth between proposed and existing conditions for scenario 8. In Figure 50 existing water surface elevations are subtracted from 35% conditions. Areas that are shaded blue are deeper, and orange are shallower. Grey areas fall between +/- 0.1 feet, in recognition of typical survey tolerances and modeling accuracy limitations.

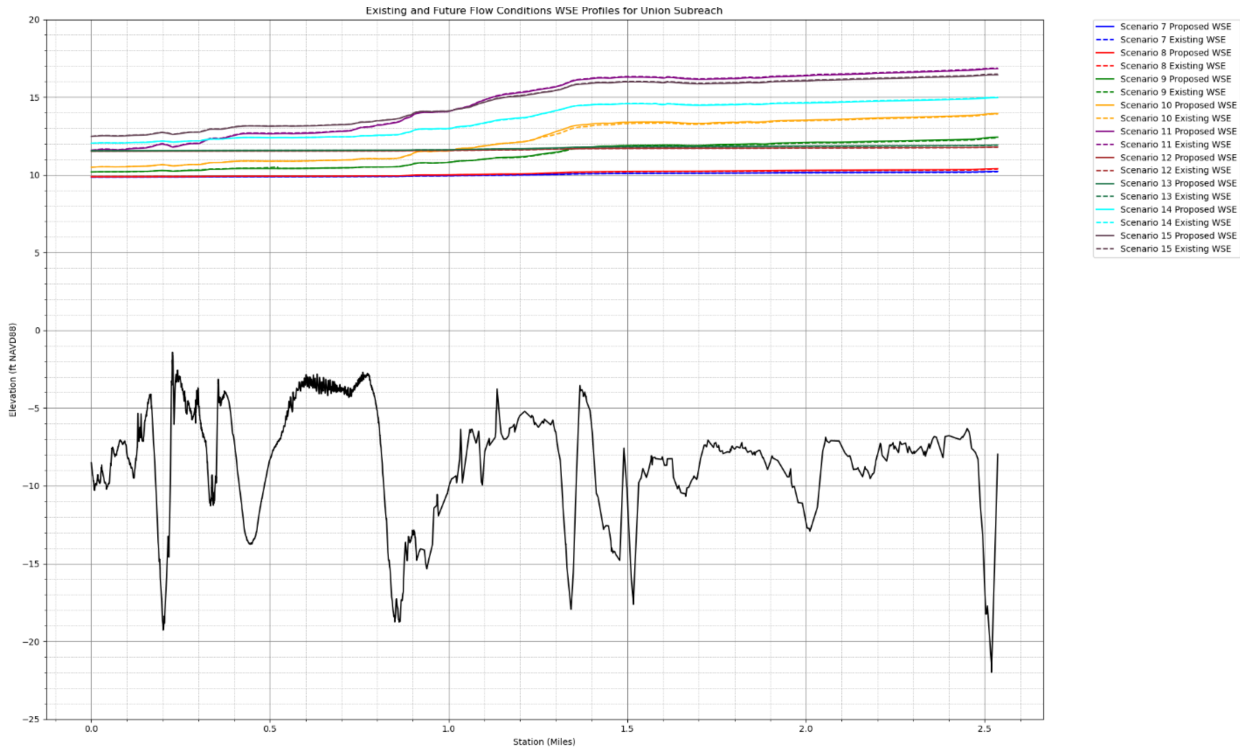


Figure 49. Union Slough water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

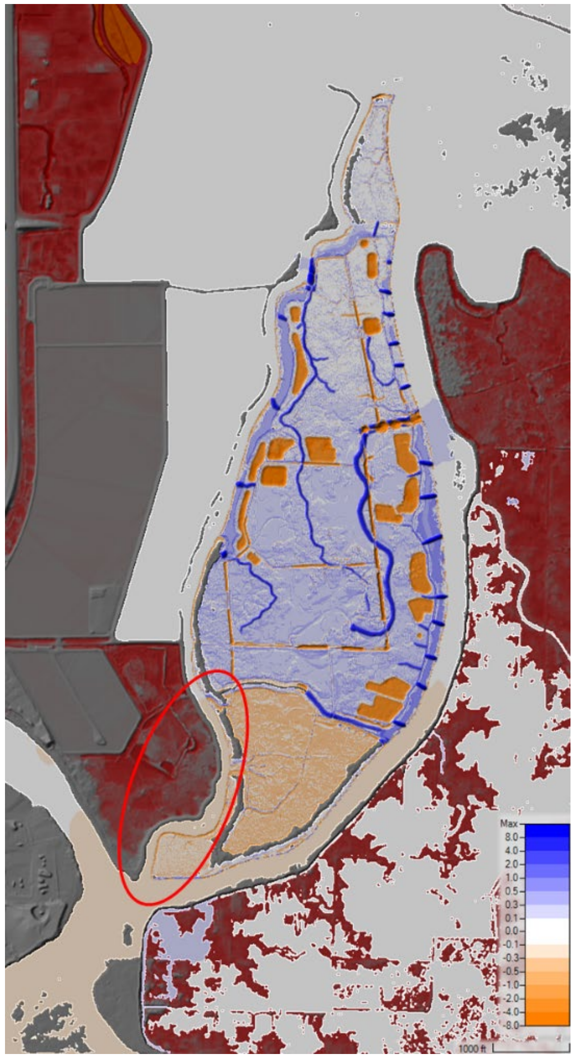


Figure 50. Inundation depth difference map for Scenario 8. Red circle marks decrease in WSE in Union Slough.

Increases in water surface elevations occur around river miles 1.25-1.75. The increases occur for Scenarios 9, 10, 11, 14, and 15 and is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Figure 51 plots the existing vs proposed conditions for scenario 10. This plot shows the most dramatic changes in water surface.

Discussions between NWS and NWD planning and engineering and OC led to several refinements of the grading plans and models to minimize any increases in flood elevation, as they are likely to result in increased overtopping of adjacent levees along Union Slough just west of Spencer Island. Several revisions to the project grading plans were tested. It was found that the configuration that does not result in unacceptable impacts to the environment, project budget, or increases in flooding to developed properties, requires increasing floodplain conveyance through widening an existing levee breach along Union Slough just west of the project at an existing City of Everett owned wetland mitigation site. Models for scenarios 7, 8, 9, 10 and 11 (50%, 10%, 2%, 1% AEP, 0.2% AEP riverine floods) were updated to include a wider levee breach at Union Slough as these are the only scenarios where flood elevations were affected by the breach widening at Smith Island.

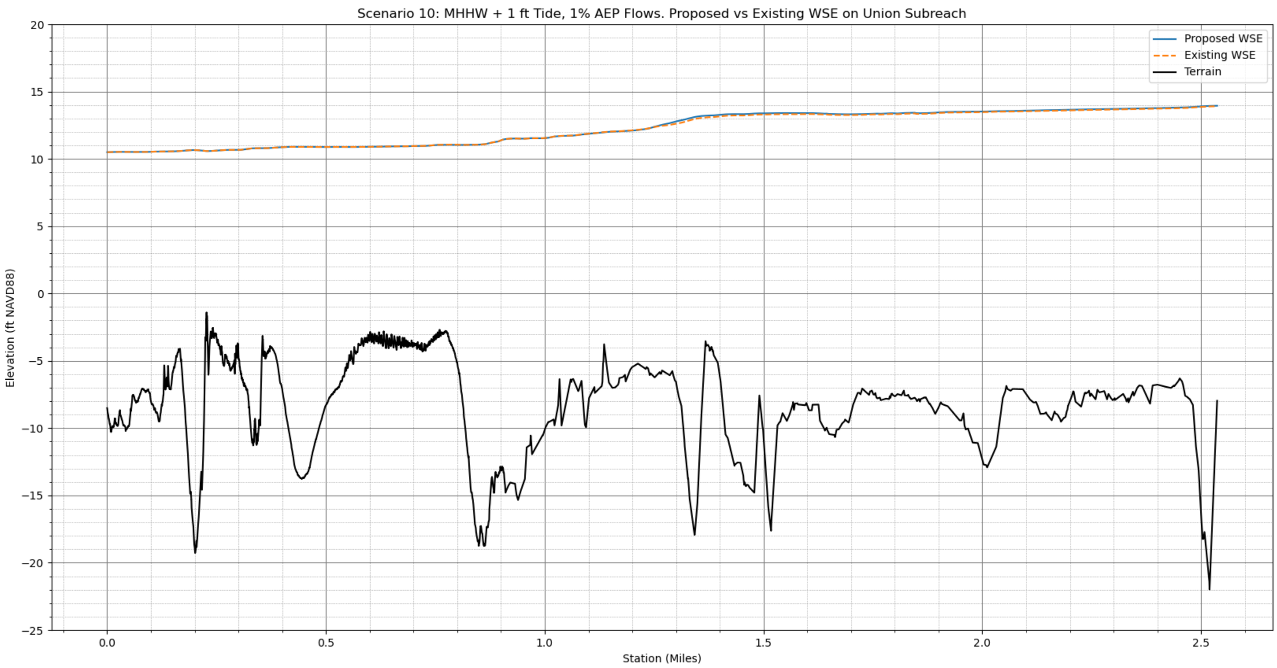


Figure 51. Proposed vs. Existing Conditions water surface profile at Union Slough sub reaches for the 1% AEP (historical) condition

With project and existing conditions velocities were compared for the 50% AEP (2-year), 10% AEP (10-year), and 1% AEP (100-year) existing conditions hydrology river flood flows. Within Spencer Island there are changes present in all 3 scenarios. For all scenarios, there appears to be an increase in velocities within the center part of the island. The upstream most part of Steamboat Slough shows an increase in velocity, and the more downstream parts show a decrease. Union Slough has a decrease in velocity at its upstream most portion. For the 100-year flows, Union Slough's velocity increases at the downstream end of the Island. There are also small differences in velocity inside Smith Island where overtopping occurs. Figure 52 shows the differences in velocity for the 100-year flow event (scenario 10). Refer to Annex D2 for more plots. Because existing conditions velocities are low, the small increases are not considered significant.

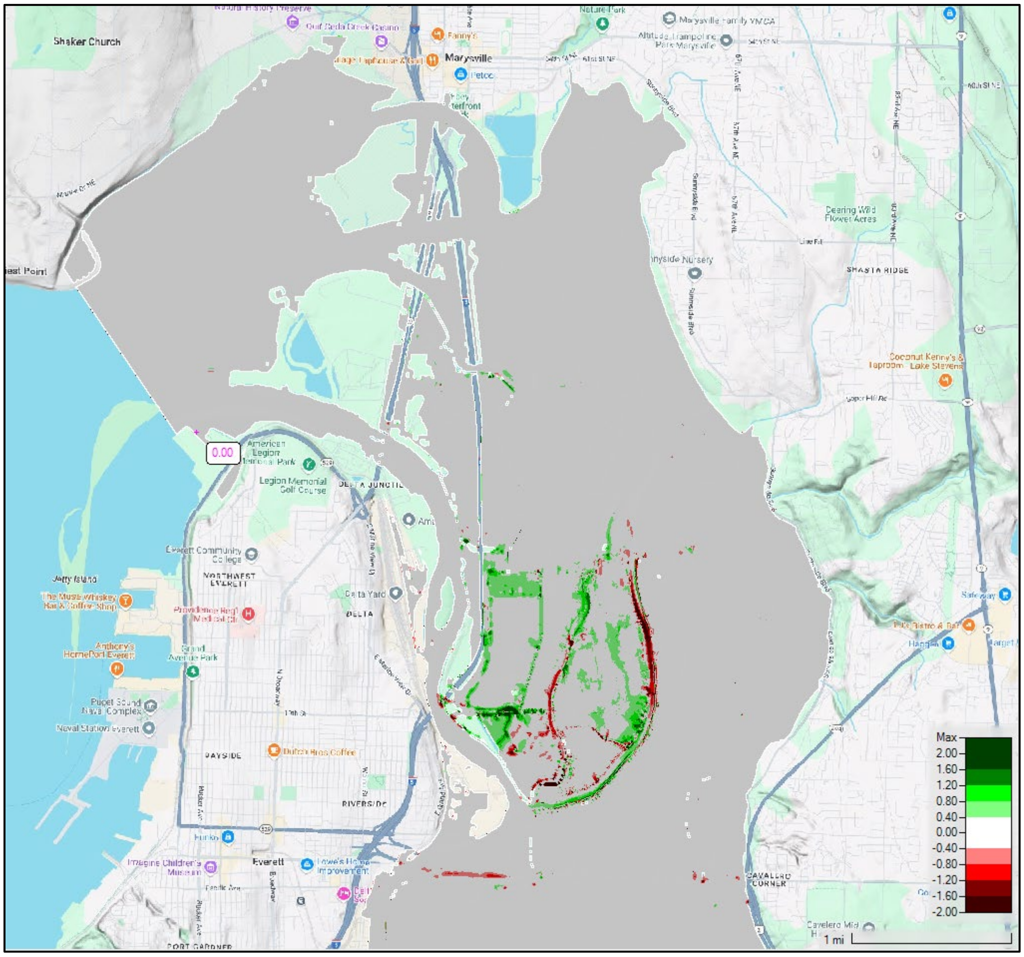


Figure 52. Velocity differences for 100-year (historical) flows

6.2. Riverine water surface elevation comparisons between USACE 2D model and effective FEMA FIS model

The 2D simulation maximum modeled water surface elevations within and around Spencer Island were extracted for the 0.99 through 0.002 AEP events. Stages for the 0.99 AEP event are essentially flat (elev. 9.3 feet). Note that this model presumes a steady downstream tide, and that the equivalent 0.99 AEP high tide event is higher by 0.8 to 1.65 feet depending on which method is used to compute annual maximum total water level exceedance statistics. Modeled stages that are lower than the coastal 0.002 AEP event (12.66 feet) are highlighted in blue in the tables below. These locations and events would be more influenced by coastal flooding than riverine flooding. All locations near Spencer Island are controlled by riverine flooding for the largest events. Higher fluvial flows result in a progressive increase in the down-valley slope in the water surface profiles (due to the effects of overbank roughness and dikes). Figure 53 shows the locations where water surface elevation data was extracted from the model. The cross sections are from the original FEMA UNET model.

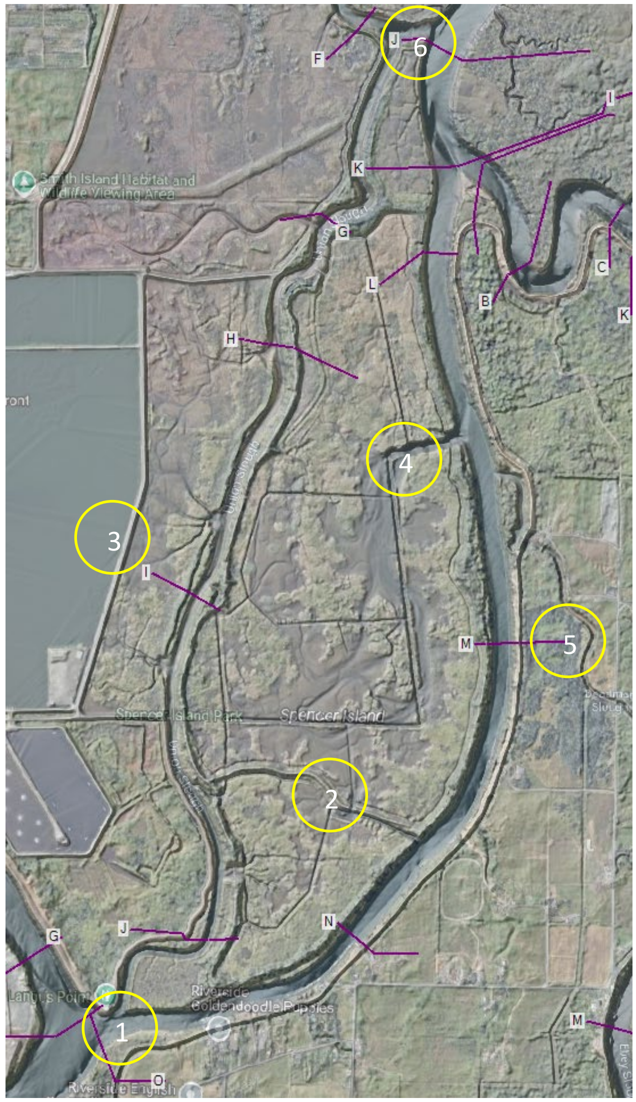


Figure 53. Output locations for WSE data

Table 19. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D ***model for existing, historical (observed)*** *conditions*

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	11.74	10.93	10.63	10.51	10.68	10.31
0.1	10	12.39	11.33	10.95	10.80	11.02	10.51
0.02	50	15.51	14.14	13.85	13.93	14.88	12.95
0.01	100	16.86	15.74	15.10	15.51	15.96	14.49
0.002	500	19.48	18.39	17.77	18.07	18.39	17.22

Table 20. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for 35% design, historical (observed) conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	11.65	10.72	10.65	10.63	10.70	10.34
0.1	10	12.29	11.07	10.98	10.95	11.05	10.55
0.02	50	15.44	14.20	14.03	13.99	14.83	12.95
0.01	100	16.76	15.62	15.44	15.35	15.81	14.43
0.002	500	19.43	18.31	17.98	17.93	18.27	17.14

Table 21. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for existing, 2080 flow conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	13.09	12.27	12.09	12.03	12.15	11.85
0.1	10	13.60	12.52	12.34	12.27	12.42	12.02
0.01	100	17.24	16.26	15.64	16.07	16.41	15.34
0.002	500	18.82	17.81	17.2	17.54	17.85	16.79

Table 22. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for 35% design, 2080 flow conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	13.03	12.18	12.13	12.11	12.16	11.87
0.1	10	13.51	12.44	12.38	12.35	12.42	12.04
0.01	100	17.18	16.22	16.03	15.96	16.30	15.28
0.002	500	18.76	17.23	17.46	17.41	17.72	16.71

Differences between the FEMA UNET 1D model and the USACE HEC RAS 2D model with respect to the FEMA base flood elevation (0.01 AEP) are shown in Table 26. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE existing conditions 2D 1% AEP flood stages near Spencer Island and Table 27 for the cross sections along Union and Steamboat Slough and the storage area that represents Spencer Island. For existing conditions, differences between the modeled stages range from 0.2 feet on the upstream end of Steamboat Slough to 1.3 feet on the downstream end of Union Slough. The FEMA WSE values are uniformly higher than the USACE 2D values. If the FEMA high tide of elevation 10.0 feet was used in the USACE 2D model stages would be higher reducing the magnitude of these differences.

Until the USACE 2D model is re-run with the FEMA model tide stage it is premature to say that the FEMA model over-predicts flood stages relative to the USACE 2D model.

Table 23. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE existing conditions 2D 1% AEP flood stages near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	FEMA regulatory WSE (ft)	FEMA BFE (NAVD88, ft)	USACE 2D 1%AEP Exist. WSE (ft)	FEMA regulatory minus USACE 2D (ft)	FEMA BFE minus USACE 2D (ft)
Snohomish River	G	3.68	15.4	16.1	14.7	0.7	1.4
Steamboat Slough	O	6.23	16.7	17.2	16.5	0.2	0.7
Steamboat Slough	N	5.7	16.7	17.2	16.4	0.3	0.8
Steamboat Slough	M	4.96	16.7	17.2	15.8	0.9	1.4
Steamboat Slough	L	4.2	16	16.6	15.1	0.9	1.5
Steamboat Slough	K	4.04	15.5	16.1	14.7	0.8	1.4
Steamboat Slough	J	3.76	15.3	15.9	14.3	1.0	1.6
Union Slough	J	4.5	15.7	16.3	15	0.7	1.3
Union Slough	I	3.79	15.5	16.1	15.1	0.4	1.0
Union Slough	H	3.24	15.5	16.1	15.2	0.3	0.9
Union Slough	G	2.91	15.5	16.1	14.3	1.2	1.8
Union Slough	F	2.49	15.2	15.7	13.9	1.3	1.8
All Cross Section Average			15.8	16.4	15.1	0.7	1.3
Spencer Island	SA#11		Not published	16.0	15.6	NA	0.4

Table 24. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE 35% Design conditions 2D 1% AEP flood stages near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	FEMA regulatory WSE	FEMA BFE (NAVD88, ft)	USACE 2D 1%AEP 35% WSE (ft)	FEMA regulatory minus USACE 2D (ft)	FEMA BFE minus USACE 2D (ft)
Snohomish River	G	3.68	15.4	16.1	14.8	0.6	1.3
Steamboat Slough	O	6.23	16.7	17.2	16.4	0.3	0.8
Steamboat Slough	N	5.7	16.7	17.2	16.3	0.4	0.9
Steamboat Slough	M	4.96	16.7	17.2	15.7	1.0	1.5
Steamboat Slough	L	4.2	16	16.6	15	1.0	1.6
Steamboat Slough	K	4.04	15.5	16.1	14.6	0.9	1.5
Steamboat Slough	J	3.76	15.3	15.9	14.3	1.0	1.6
Union Slough	J	4.5	15.7	16.3	15.3	0.4	1.0
Union Slough	I	3.79	15.5	16.1	15.3	0.2	0.8

Union Slough	H	3.24	15.5	16.1	15.1	0.4	1
Union Slough	G	2.91	15.5	16.1	14.4	1.1	1.7
Union Slough	F	2.49	15.2	15.7	14	1.2	1.7
All Cross Section Average			15.8	16.4	15.1	0.7	1.3
Spencer Island	SA#11		Not published	16.0	15.4	NA	0.6

Table 25. Comparison of USACE 35% Design conditions 2D 1% AEP flood stages to USACE Existing conditions near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	USACE 2D 1%AEP 35% WSE (ft) (w/o Smith Island Conveyance)	USACE 2D 1%AEP Exist. WSE (ft)	35% minus Existing (ft) (w/o Smith Island Conveyance)
Snohomish River	G	3.68	14.8	14.7	0.1
Steamboat Slough	O	6.23	16.4	16.5	-0.1
Steamboat Slough	N	5.7	16.3	16.4	-0.1
Steamboat Slough	M	4.96	15.7	15.8	-0.1
Steamboat Slough	L	4.2	15	15.1	-0.1
Steamboat Slough	K	4.04	14.6	14.7	-0.1
Steamboat Slough	J	3.76	14.3	14.3	0.0
Union Slough	J	4.5	15.3	15	0.3
Union Slough	I	3.79	15.3	15.1	0.2
Union Slough	H	3.24	15.1	15.2	-0.1
Union Slough	G	2.91	14.4	14.3	0.1
Union Slough	F	2.49	14	13.9	0.1
All Cross Section Average			15.1	15.1	0.0
Spencer Island	SA#11		15.6	15.6	0.2

6.3. Peak flow changes near Spencer Island and differences

The routed unsteady peak flows at each distributary channel were compared to the upstream inflow at Monroe near Spencer Island for the FEMA UNET model, the WSE 2D model, and the USACE 2D model. Table 19 compares flows for the 10% through 0.2% AEP events at Monroe and at the head of all distributary channels near Spencer Island. Total system flow appears to decrease with increasing discharge in these models, presumably because overbank attenuation is occurring. However, when comparing to the WSE and USACE 2D models, which show far less attenuation, it is possible the modeled loss of flow is a result of UNET model limitations (unsteady flow computation methods or underlying survey data).

It is notable that the total flow in the WSE 2D model near Spencer Island (Table 20) for the 0.01 AEP (100-year) event (173,200 cfs) is about 40,000 cfs more than the UNET model total system flow, and 101% of the gaged inflow at Monroe. The USACE 2D model (Table 21), which uses the same boundary conditions as the UNET model and similar 2D mesh as the WSE model, results in a peak flow through the I-5 corridor near Spencer Island of 206,750 cfs (98% of gaged inflow at Monroe). The WSE model includes several local inflows that the FEMA and USACE model do not, which add to the peak flow rates modeled by WSE. For consistency with the FEMA model these local inflows are not included in USACE modeling.

Flows in the distributary channels near the I5 bridges were summarized and compared in the USACE 2D Model in Table 21 to see if the project impacts flood flows at the bridges. At the Snohomish mainstem peak flows decrease for the 50% through 1% AEP events from 2.1% to 0.9%. At Union Slough flows increase form 4.1% for the 10% AEP event to 2.5% for the 1% AEP event. Flows in Ebey Slough at I-5 decrease 0.1% for the 1% AEP event and increase 3.2% for the 10% AEP event. Flows in Steamboat Slough at I-5 increase 0.1% for the 1% AEP event and increase 3.1% for the 10% AEP event. Flows in the mainstem range from 59% for the 50% to 10% AEP events when flows remain within dikes but decrease to 45% for the 1% AEP when widespread dike overtopping is occurring. In general, the changes in flow are low, as expected, given that the dikes are already breached at Spencer Island. The detectable changes in flow in the model indicate that the dikes are interfering with conveyance in large floods and removing them will help restore more natural floodplain connectivity.

Modeled flows at Spencer Island are a result of the combined influences of: upstream inflow hydrographs (timing, peak and volume); downstream tidal boundary assumptions; geometry for the channel, dikes, and overbanks; floodplain storage effects; and local runoff assumptions.

Table 26. FEMA UNET model total system flow near Spencer Island vs. Monroe

	RM/AEP	Q10 peak (cfs)	Q50 peak (cfs)	Q100 peak (cfs)	Q500 peak (cfs)
AEP		0.1	0.02	0.01	0.002
Reach 1 mainstem US	20.5	113,998	172,933	203,998	294,500
Reach 3 mainstem US	3.8	51,604	78,866	89,110	108,567
Total system flow Spencer	S 3, US 4, SS 5, ES 8	89,787	116,825	133,180	163,589
Total system / Monroe		79%	68%	65%	56%

Table 27. WSE 2D model total system flow near Spencer Island vs. Monroe

Flood Event recurrence interval	1.01	2	5	10	25	50	100	500
Location AEP	0.99	0.5	0.2	0.1	0.04	0.02	0.01	0.002
Mainstem near Spencer Island	14,400	34,900	47,200	49,600	56,500	74,100	84,800	98,700
Spencer Island west half + Union + floodplain	500	1,300	1,800	1,900	2,200	4,600	7,800	17,400
Spencer Island east half + Steamboat + Ebey + floodplain	8,200	20,400	27,300	30,200	35,500	62,900	80,600	113,800
Total system flow near Spencer Island	23,100	56,600	76,300	81,700	94,200	141,600	173,200	229,900
Monroe gage modeled peak	22,200	58,300	82,500	104,100	130,600	150,600	171,100	225,400
Total system / Monroe	104%	97%	92%	78%	72%	94%	101%	102%

Table 28. USACE 2D model total system flow near Spencer Island at I-5 Corridor vs. Monroe

Scenario	50% AEP			10% AEP			1% AEP		
Reach/Area	Prop.	Exist.	% Diff.	Prop.	Exist.	% Diff.	Prop.	Exist.	% Diff.
Snohomish Mainstem @ I-5	42,440	43,370	-2.1%	50,160	51,150	-1.9%	92,740	93,590	-0.9%
Highway overtopping @ I-5	-	-	N/A	-	-	N/A	620	420	47.6%
Union Slough @ I-5	5,260	5,060	4.0%	6,310	6,060	4.1%	23,450	22,870	2.5%
Steamboat Slough @ I-5	20,960	20,340	3.0%	24,910	24,150	3.1%	72,520	72,440	0.1%
Ebey Slough @ I-5	4,350	4,230	2.8%	5,220	5,060	3.2%	17,420	17,430	-0.1%
Total Flow @ I-5	73,010	73,000	0.0%	86,600	86,420	0.2%	206,750	206,750	0.0%
Snohomish @ Monroe	77,560	77,560		129,600	129,600		210,100	210,100	
Mainstem @ I-5 / Total @I-5	58%	59%	-2.2%	58%	59%	-2.1%	44.9%	45.3%	-0.9%
Total @I-5 / Monroe	94%	94%	0.0%	67%	67%	0.2%	98%	98%	0.0%

6.4. Floodplain management implications

The average change in the FEMA cross sections near Spencer Island is 0.0 feet, and the USACE computed water surface elevations (WSE) are on average 0.7 feet lower than published regulatory WSEs. Small rises in the 1% AEP WSE are possible along Union Slough at cross sections F, G, I and J and within Spencer Island (0.2 feet). To address this potential impact a portion of the existing Smith Island restoration project levee will be lowered adjacent to an existing constructed levee breach. Expansion of this breach diverts water north into restored tidal wetlands, increasing stages and flows in locations intended for that purpose. This mitigation approach was developed through several iterations of modeling and is the most practical solution the team could find that is still feasible within the constraints of the authorization. The floodmaps shown in Annex D-2 reflect this condition for the 10, 50, 100, and 500 year runs. See section 6.5 for more discussion of this configuration and potential effects on restored tidal wetlands.

For context it should be noted that the CLOMR modeling report (Otak, 2015) / no-rise analysis for the nearby Smith Island restoration project constructed by Snohomish County indicated potential rises of more than 0.5 feet at the outlet of the primary tidal channel near I-5. The effects of Spencer Island are considerably less because the dikes are already breached and the reconnected marsh area is much less than at Smith Island.

Note that the USACE 2D models described above are set up very differently than the effective FEMA Flood Insurance Study model, which uses the HEC-UNET code (now RAS 1D) to route an unsteady flow hydrograph through a branching river network (represented by 1D cross sections) where the channel is connected to storage areas with lateral weirs at the locations of dikes. This model was used to map the floodplain and floodway and uses a steady high tide for all simulations. Overflows of dikes treat the entire structure as a weir, use a constant discharge coefficient. Flows enter and leave a storage area instantaneously based only on available storage volume and elevation difference between the channel and storage area. Conveyance in storage areas resulting in a spatially varied water surface elevation (evident in the 2D modeling) is not computed or accounted for.

The combined effect of the 1D unsteady model limitations is a simplification of complex hydrodynamic processes and is likely contributing to the elevation differences between the models. As a practical engineering tool, the 1D unsteady model is outdated and unreliable for predicting the response to project configurations through a no-rise analysis, however the model is still effective and for compliance with the National Flood Insurance Program it needs to be updated to include the proposed modifications. Because all the proposed modifications will seek to balance cut and fill, no change to the elevation volume (storage area) curve is anticipated (See Annex D-3 for more information). Because of existing and new dike breaches, the storage area connections will need to be modified. These will allow water to enter storage areas earlier in the flood event, reducing available storage during the peak. It is possible this will result in a numerical rise of the BFE that could be physically unrealistic.

Running UNET is not possible given the age of the software, the model needs to be migrated into HEC-RAS unsteady for a no-rise analysis. Work completed previously by Otak consultants at Smith Island and work currently underway (Snohomish River FPMS study) can provide a working RAS model to aid in this work. A no-rise analysis will be completed in PED. Coordination with Snohomish County and FEMA will be necessary to scope this work. The effective model is outdated, and USACE will likely need to request acceptance of a model based on that used for this study, or the pending updates to the model being developed as part of a separate Floodplain Management Services project, which USACE is undertaking to update the hydrology and hydraulic modeling used for mapping the Special Flood Hazard Area of the Snohomish River.

Discussions with Snohomish County (Kit Crump, personal communication) indicate that the County strongly supports utilizing recent 2D and 1D/2D models developed by USACE in their restoration work on Ebey Slough and in future improvements to the FEMA floodplain models and maps. Proposed floodway modeling changes to include the effects of levee lowering/breaching and marsh/floodplain restoration are shown in Figure 54 below. This model update could result in a situation where the effective floodplain model used for no-rise analysis includes the grading plans for completed and funded restoration projects (and thus ensure a no-rise condition). Any update to the regulatory floodway boundaries needs to be approved by the County before it will be incorporated into updated modeling. The timeline for this is uncertain at present.

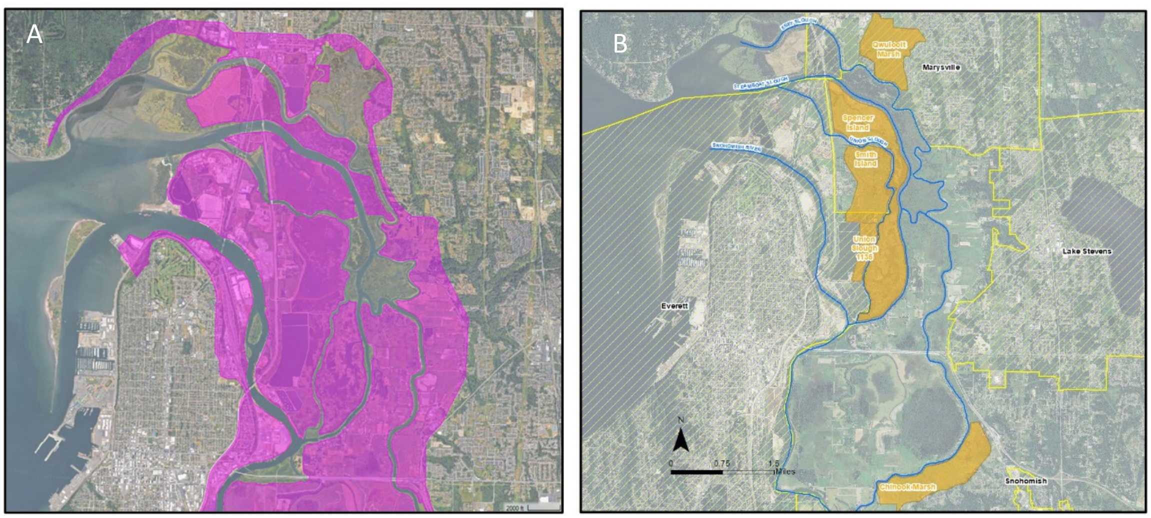


Figure 54. A) Snohomish River FEMA floodplain model density fringe (magenta areas) and B) recently completed or pending large scale restoration projects. The areas along channels not shaded magenta shown in A are mapped as floodway presently. The proposed change would convert the retsoraton areas shown in orange to floodway.

Once the hydrology and hydraulic model updates are complete, it is expected that the new maps will have lower flood elevations and inundation limits than are presently indicated. Dike lowering and floodway expansion associated with several restoration projects has increased conveyance in the lower valley. Based on preliminary model runs, expansion of the floodway as indicated, and use of updated models and terrain data would significantly reduce regulatory BFEs (greater than a foot in several locations). Updates to the hydrology are also underway to improve flood frequency estimates at the Monroe gage. The hydrology updates are likely to decrease the estimated 1% AEP peak discharge. The combined effect of changing the hydrology, expanding the floodway, and improvements in the modeling are likely to reduce regulatory flood elevations, however, these potential reductions would eventually be offset by climate affected hydrology (higher annual peaks, sea level rise) and need to be considered in that context.

The December 2025 was a near historical flood for the Snohomish. High water marks and levee failure data should be reviewed to help refine the model. Existing dikes and levees that frequently breach may need to be removed from the model (natural valley condition) if that better represents recently observed flooding. Unmaintained dikes on Spencer Island that frequently overtop and have a history of failure during high flow events are not expected to be repaired after future breach events as there is no longer an active diking district. This means that simulations that assume high ground depicted in in the lidar data will effectively contain water are likely conservative from the standpoint of estimating water levels in the channel, but non-conservative for depicting flooding on the landward side of levees.

6.5. Hydrologic evaluation of potential effects on City of Everett and Snohomish County restoration projects

At the request of the City of Everett the 2D hydraulic models for existing conditions and proposed conditions were used to assess the hydrologic changes that could result at the City of Everett Smith Island Union Slough ecosystem restoration and mitigation projects and the joint City and County Smith Island Estuary Restoration Project (Figure 55), which includes the Smith Island Advanced Mitigation site. The month of December 2022 which included the king tide of record was used as representative for the period of analysis. Model output locations used in the analysis are shown in Figure 56.

City of Everett Advance Mitigation Site and Smith Island Ecosystem Restoration Project

As shown in Figure 57 tidal flows through the main breach increase significantly because of restoration. Positive flows reflect flows from Union Slough into the mitigation site. Overall tidal flows into the site increase by about 120 cfs on average, or about 44%. Most of this increase is because of levee lowering and breaching on Spencer Island, increasing flux on the distributary channels, and due to widening of the existing breach. The maximum flow into the site increases by 500 cfs, or about 19%. The minimum flow (ebb tide discharge) decreases by about 30 cfs, or 3%.

One of the bigger differences observed is the influence of water draining from Spencer during the high tides into Union Slough (see star), which fills up the 1135 wetland, and causes the flow leaving the City advance mitigation site on Smith Island (under existing conditions) to reverse to the north, since Union Slough will primarily be fed by flows from Spencer on a high tide. Note that at this stage water freely flows into the adjacent wetland to the north. At lower low tides total outflow from the wetland is essentially unchanged.

If increasing tidal inflows to the wetland is associated with habitat improvements, then we would expect this site to benefit from restoration actions on Spencer Island, and thus the County owned portion of the site as well.

As shown in Figure 58, in the main channel near well 1, tides (MLLW, MHHW, mean) are not significantly altered by the Spencer Island Restoration or conveyance (additional levee lowering near well 1, despite increased flows into the site at high tide. No effects to the wetland plant community would be expected from these small changes in stage.

In the main channel near well 3, located at the west end of the site, tides (e.g. MLLW, MHHW, MTL) are not significantly altered by the Spencer Island Restoration or conveyance (additional levee lowering near well 1, despite increased flows into the site at high tide. No effects to the wetland plant community would be expected from these small changes in stage. See Figure 59.

Water surface elevation hydrographs along the Smith Island setback levee show no significant changes compared to existing conditions for day-to-day tidal conditions, effects insignificant (see Figure 60, Figure 61).

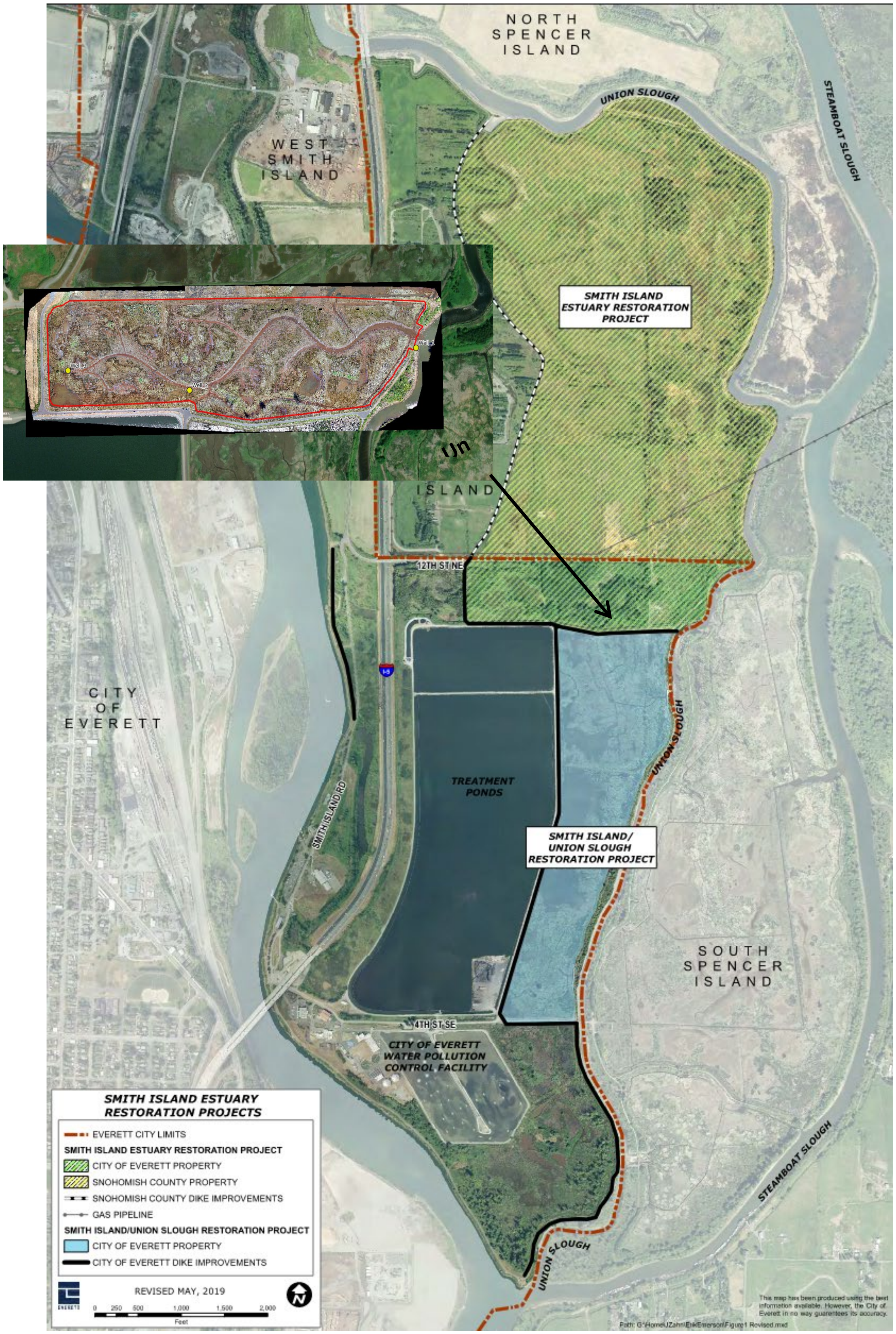


Figure 55. Constructed/restored tidal wetlands in the vicinity of Spencer Island

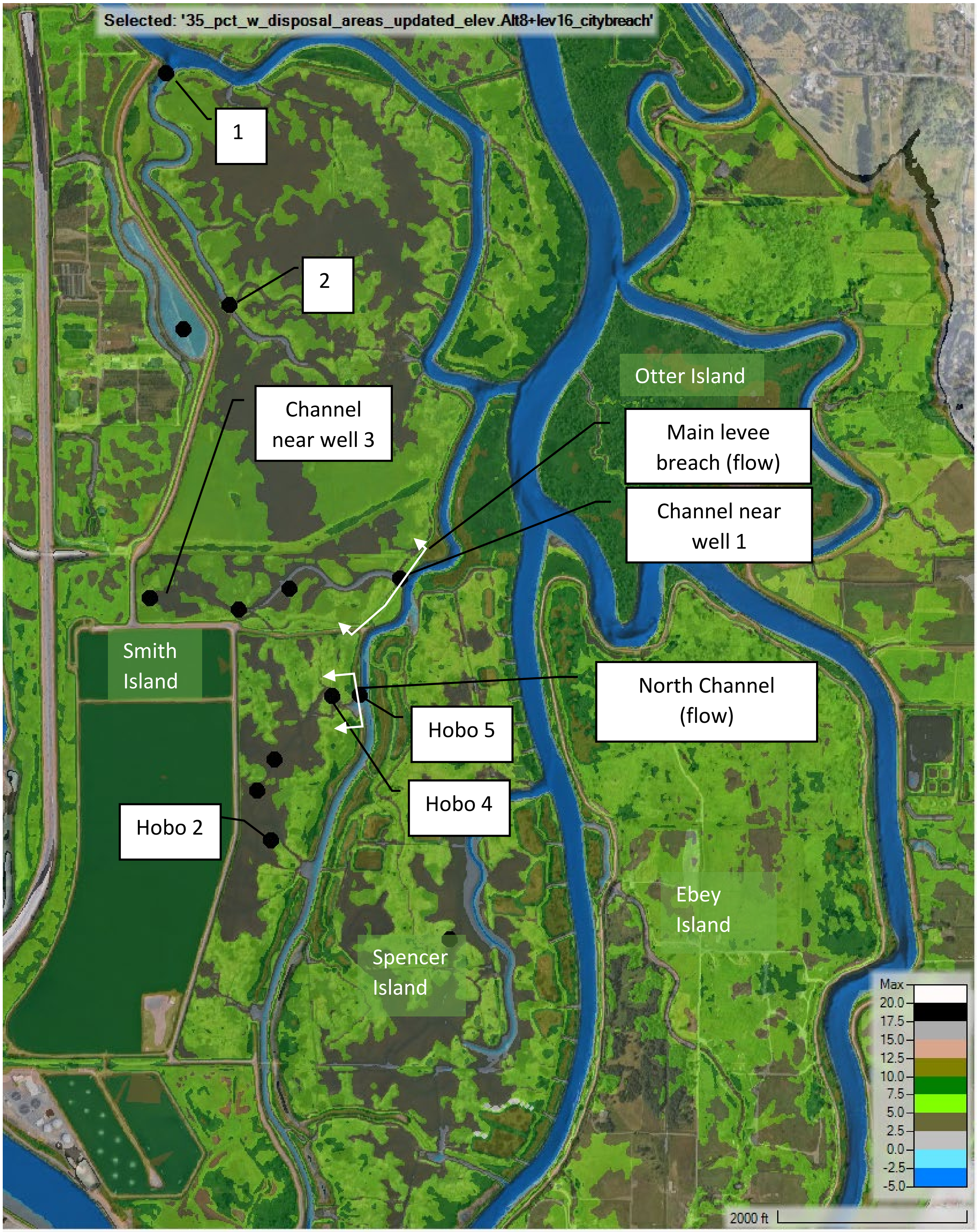
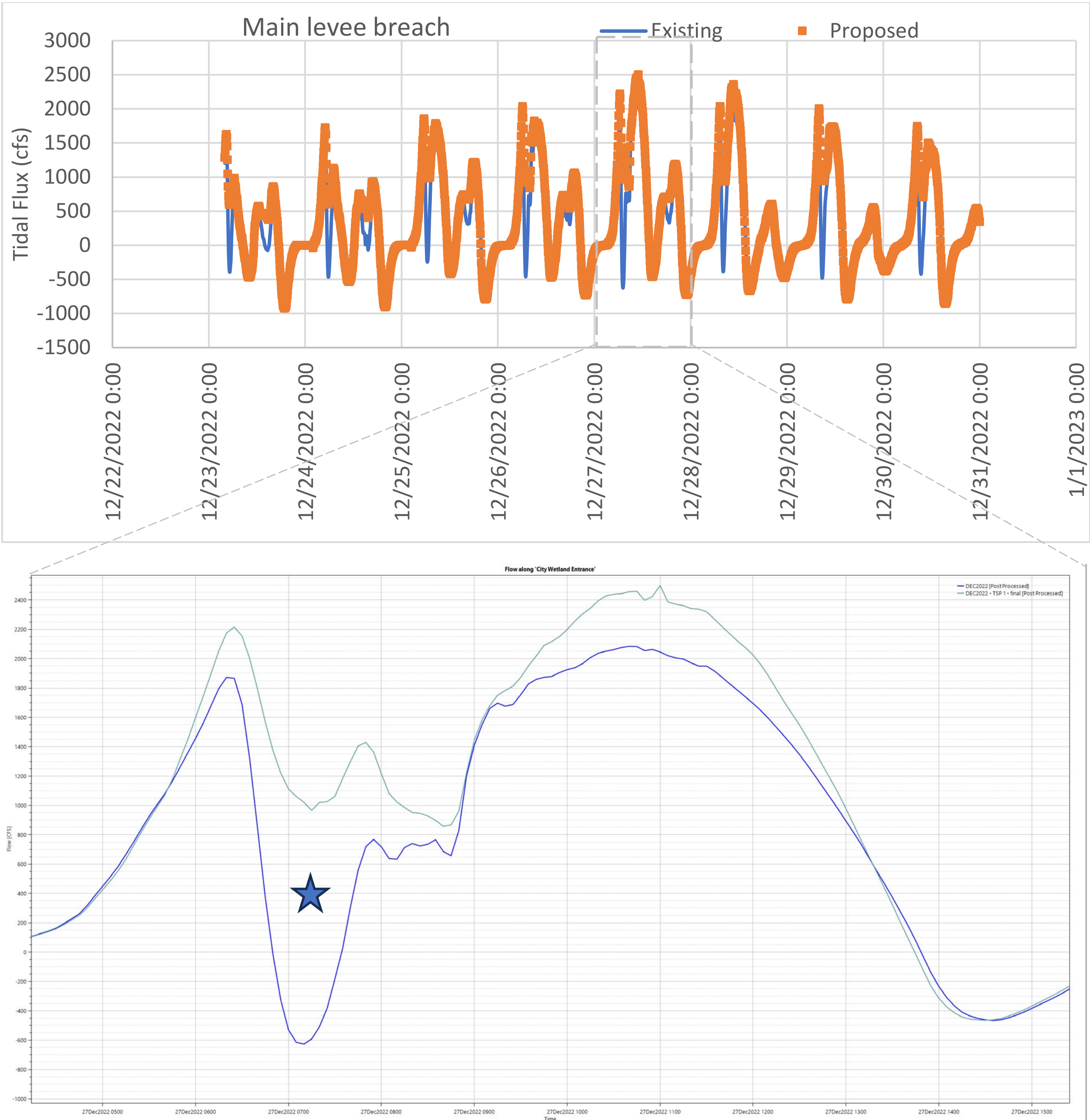
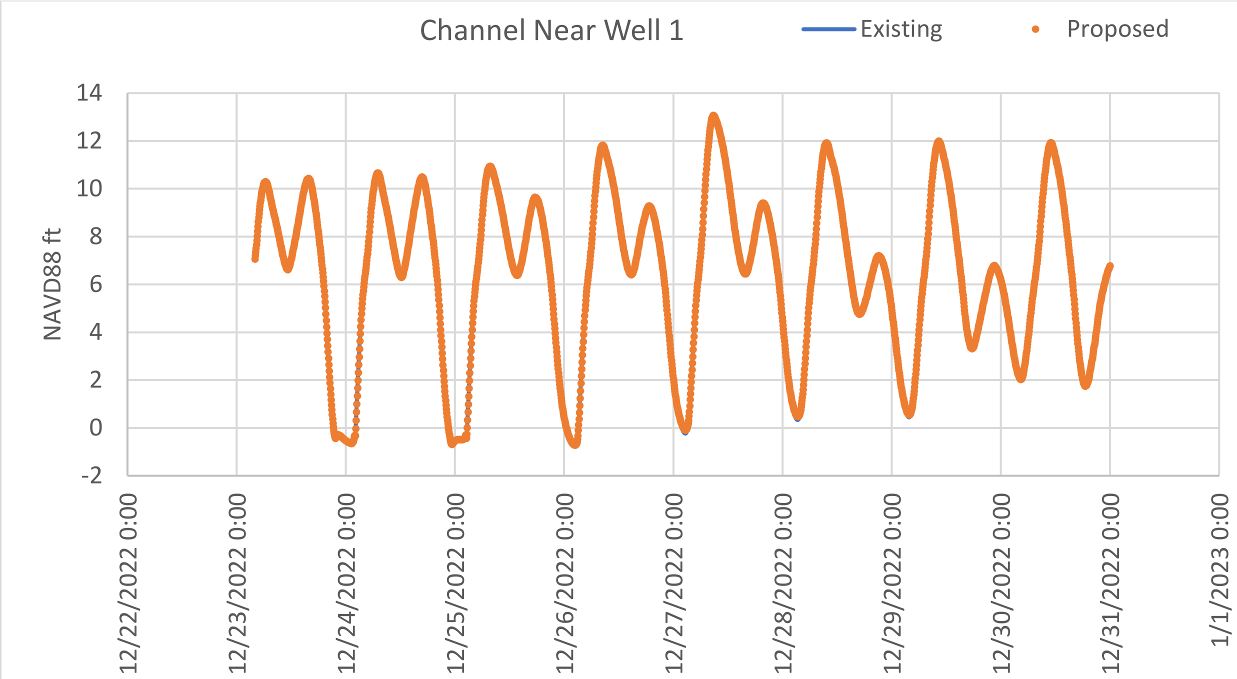


Figure 56. WSE and flow comparison points for December 2022 simulation, showing existing terrain and proposed grading plan



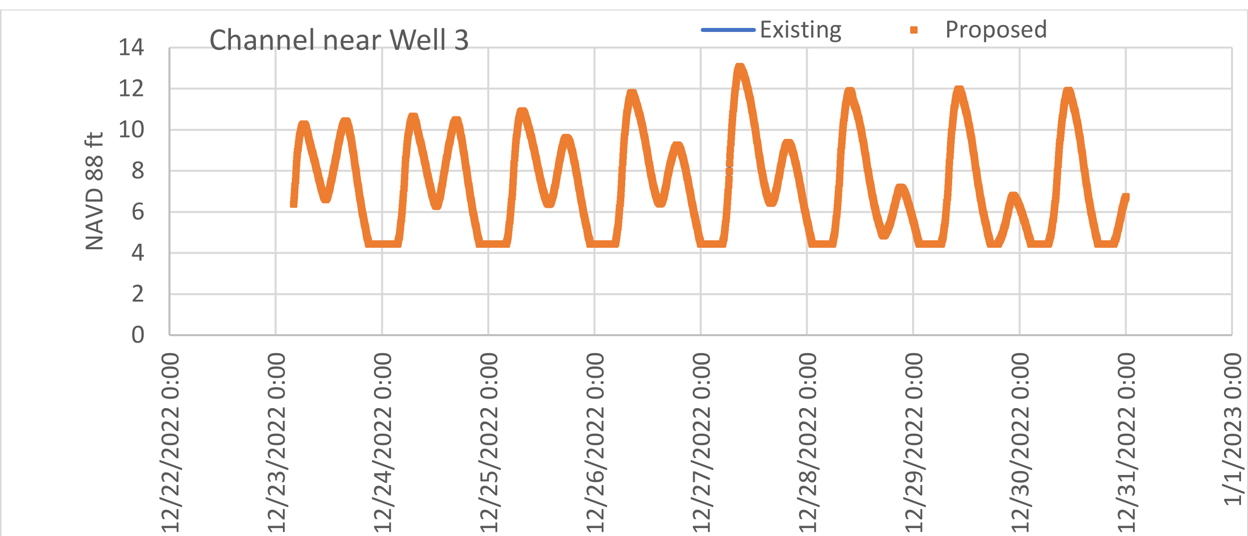
Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-960.264	-926.412	2084.43	2498.881	267.6407	389.9591

Figure 57. Tidal flux through main breach, with and without grading of existing levee breach



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-0.776	-0.72	13.067	13.072	6.40522	6.435574

Figure 58. Tidal channel near Well 1 at City advance mitigation site



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
4.446	4.446	13.065	13.069	7.173679	7.198134

Figure 59. Tidal channel near Well 3 at City advance mitigation site

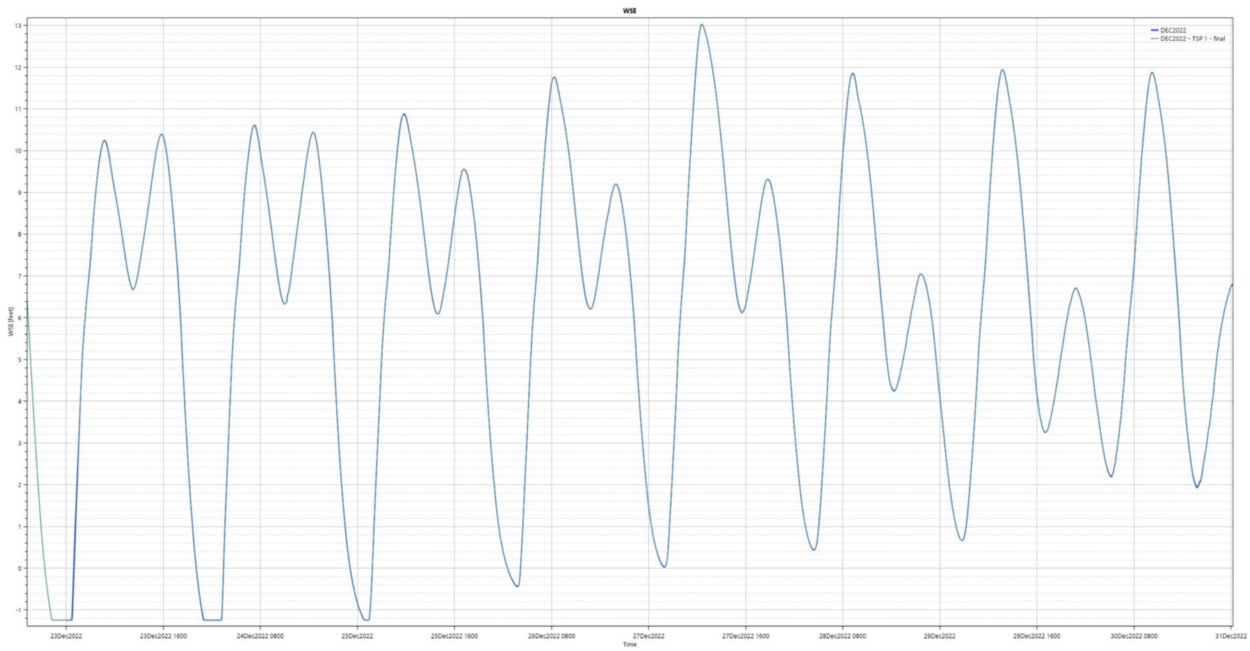


Figure 60. Stage at north end connection with Union Slough (point 1) – no detectable difference between existing and proposed conditions

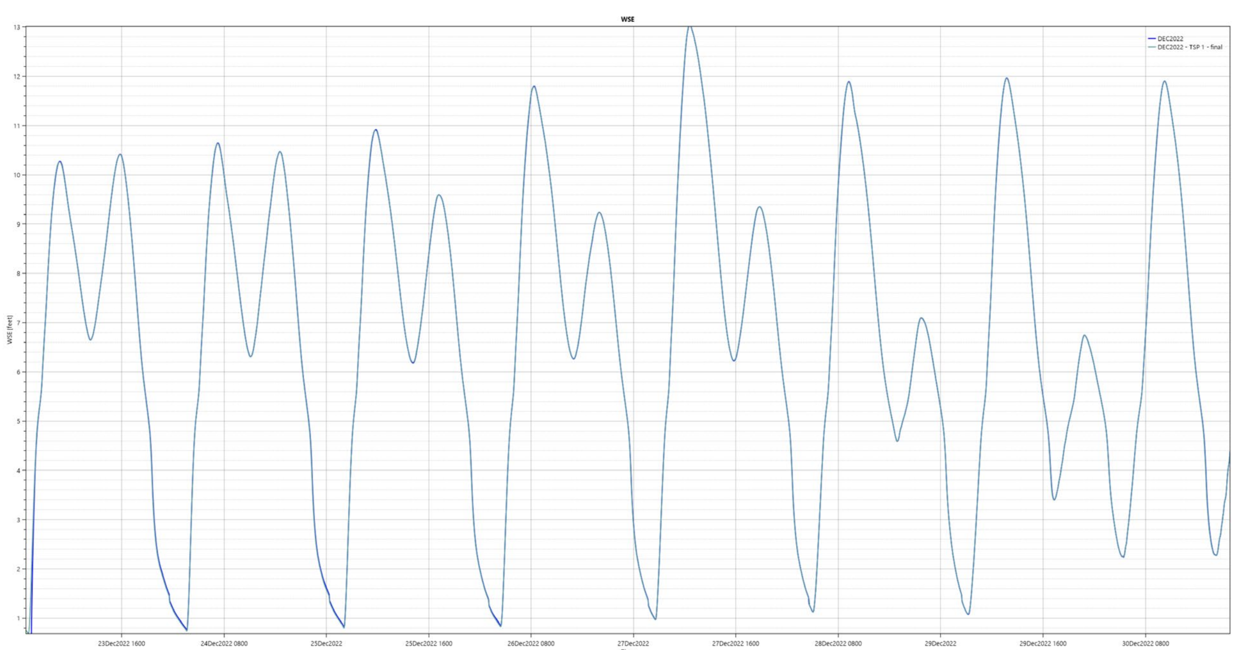


Figure 61. Stage hydrograph near dogleg point of setback levee (point 2) - no detectable difference between existing and proposed conditions

City of Everett Smith Island Union Slough Mitigation Site and Section 1135 Ecosystem Restoration Project

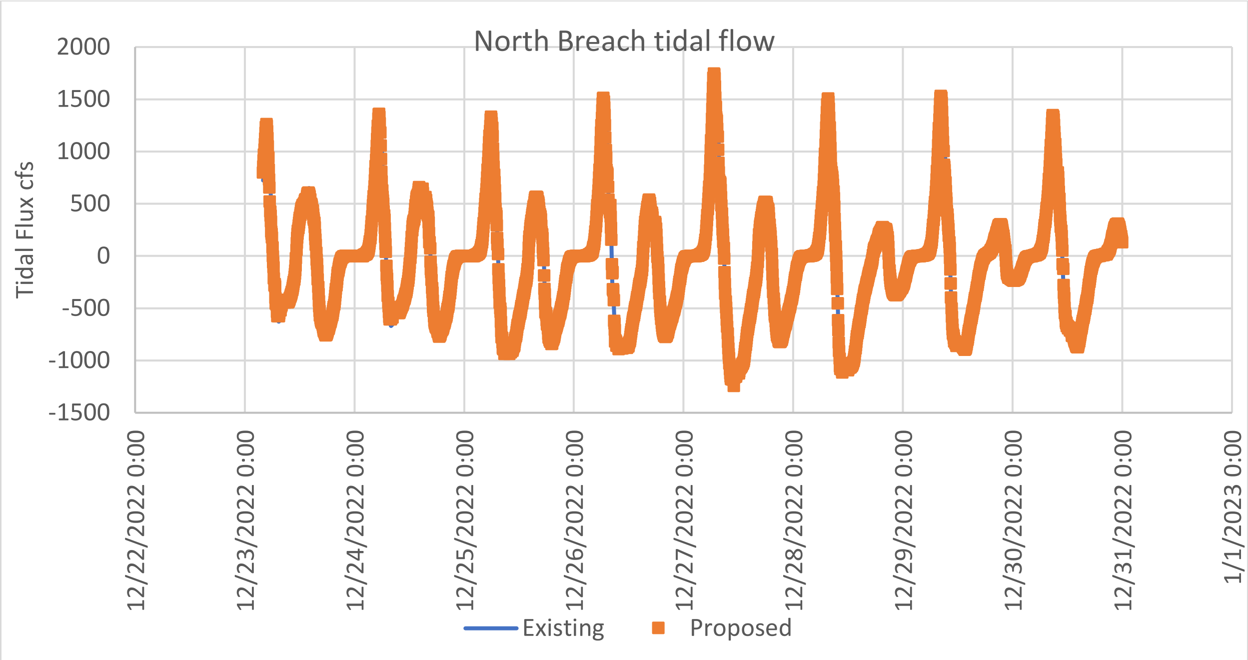
As shown in Figure 62 tidal flow into the north channel of the Union Slough advance mitigation site does not significantly change. Note that negative flows are flows out of the site, and positive flows are flows into the site. Outflows from the site appear to increase slightly, this is most likely due to water that is passing through Spencer and into the middle and south breaches into this wetland complex flowing north with the outgoing tides and exiting back to Union Slough here. The minimum flow increases by -130 cfs, which is roughly 10%. The maximum inflow decreases slightly, by 40 cfs, or about 2%. The average flow (-90 cfs) is essentially unchanged. The average reflects the typical condition for this location (flows returning from the wetland to Union Slough).

At the HOBO 5 monitoring station in Union Slough the with-project tidal range increases, with a lower low tide elevation (decrease of 0.6 ft), due to restoration. The mean tide decreases about 0.1 feet. This is likely due to increases in connectivity to Union Slough and Steamboat Slough, allowing for more efficient drainage of Union Slough, and also due to increased outflow from adjacent marshes which will aid in further tidal channel development. The high tide elevation remains unchanged. See Figure 63.

At the HOBO 4 monitoring station which is located within the mitigation site upstream of the Union Slough connection, the with-project tidal range increases, with a significantly lower (~1 ft) MLLW tide elevation, because of the Spencer Island restoration project. The mean tide decreases about 0.2 feet. This decrease is presumably due to increases in connectivity to Union Slough and Steamboat Slough, allowing for more efficient drainage of Union Slough, and also due to increased outflow from adjacent marshes which will aid in tidal channel development and vegetation establishment. The high tide elevation remains unchanged. See Figure 64.

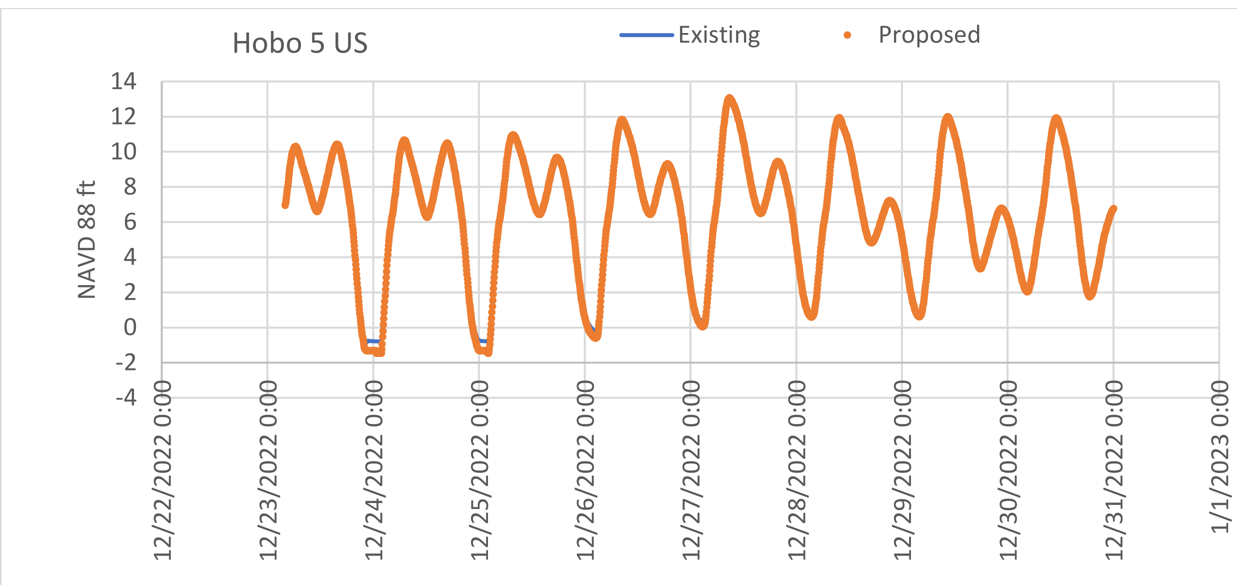
At the HOBO 2 monitoring station which is located within the mitigation site near the setback levee, the with-project tidal range does not change significantly because of the Spencer Island restoration project. The mean tide does not change, and the changes to the high tide and mean tide are too small to be meaningful. The lack of change is likely due to the persistence of hindered drainage from the wetland (ponding) near the most deeply subsided portion of the site. The increase in tidal range and the decrease in the MLLW at station 4 suggest channel erosion from the outlet back into the marsh could increase, which would be beneficial from the standpoint of draining ponded areas in the distal portions of the marsh. See Figure 65.

The overall assessment of the potential effects to the city mitigation sites are as follows: no significant change in the MHHW or MTL elevation are likely, but a modest decrease in the MLLW elevation is possible, with the magnitude inversely related to distance from the north outlet channel connection to Union Slough. The decrease in the MLLW elevation will result in an increase in the effective tidal range and the duration that water drains from the site daily. This increase in drainage could beneficially deepen existing channels through erosion, and if this erosion extends far enough into the marsh, some ponded areas could experience improved drainage and water quality. No change to wetland plant conditions is expected since the average and high tide elevations will remain unchanged. It should be noted that the proposed breaches and levee lowering on Spencer Island significantly increase the exchange of water in a normal tide cycle and during floods. This allows fish to more easily swim between Otter Island, Smith Island, and Spencer Island improving connectivity, a primary restoration objective.



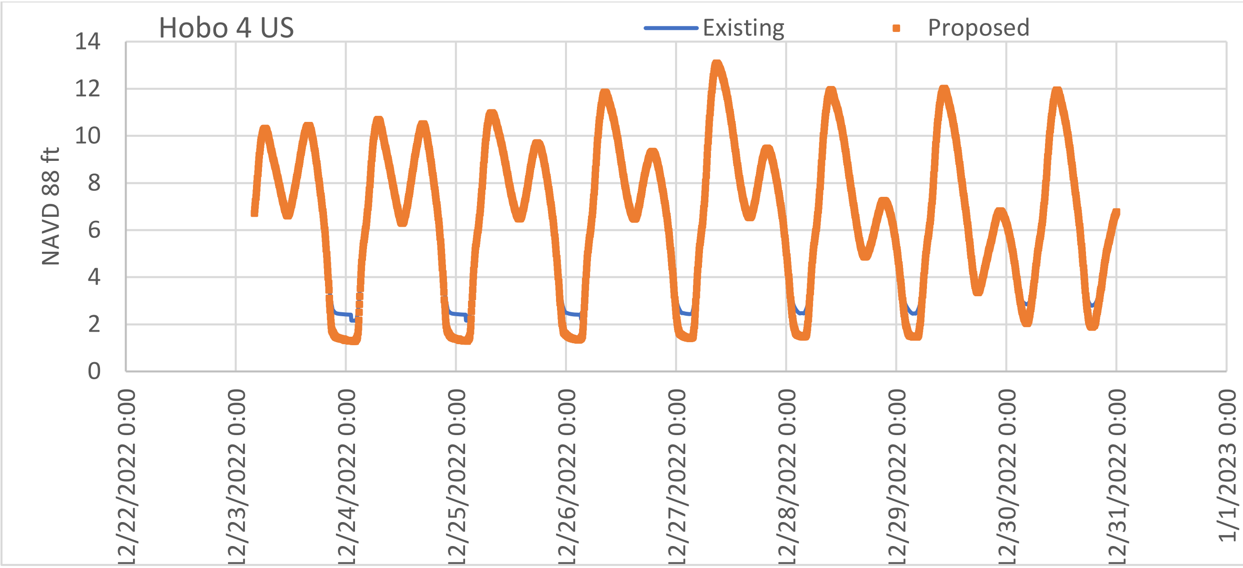
Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-1107.18	-1245.18	1785.035	1745.242	-91.562	-92.6128

Figure 62. Tidal flux (flow) at North Breach (Smith Island/Union Slough Restoration Project)



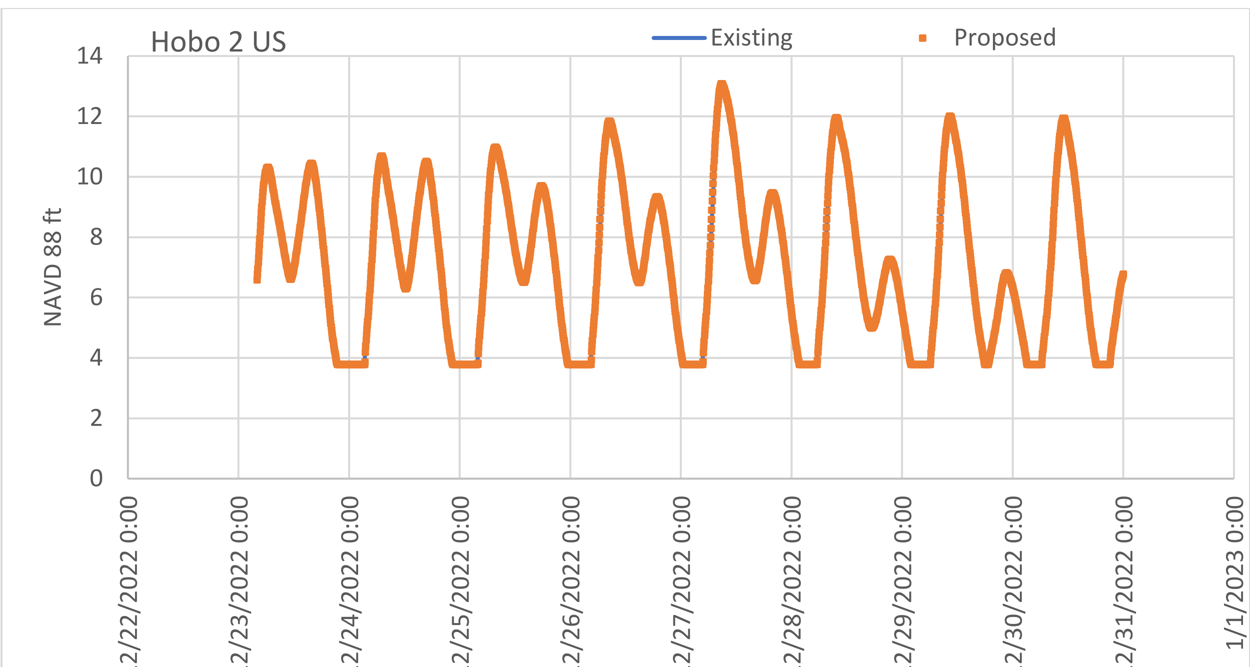
Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-0.843	-1.447	13.08	13.081	6.507352	6.446531

Figure 63. WSE at HOBO logger #5 (Smith Island/Union Slough Restoration Project)



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
2.154	1.285	13.081	13.081	6.836635	6.669405

Figure 64. WSE at HOBO logger #4 (Smith Island/Union Slough Restoration Project)



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
3.785	3.785	13.082	13.084	7.08278	7.100881

Figure 65. WSE at HOBO logger #2 (Smith Island/Union Slough Restoration Project)

7. Summary and Conclusions

The following summarize main findings from this analysis:

1. No updates to hydrology were made as part of this study. It has been used without adjustment. Review of available data suggest revision of the effective model hydrology is warranted given that two decades have elapsed since the last analysis was conducted.
2. Use of the FEMA effective 1D model for design of the tidal marsh restoration project is insufficient to confidently size and orient tidal channels and locate dike breaches or determine effects of the project on nearby reaches. For this reason, the Snohomish County 2D model prepared by WSE was utilized subject to the modifications described herein.
3. The modified 2D model reproduced observed flood elevations at Ebey Slough and the Snohomish Mainstem. Peak stages matched between 0.01 and 0.43 feet for the December 2022 event, and between -0.09 and 0.13 feet for the December 2023 event. Peak flows at Snohomish were reproduced within -8.7% and -4.6% for the December 2022 and 2023 validation events respectively.
4. The USACE 2D existing conditions model shows less water surface elevation values than the FEMA FIS study. On average, the 1% flows show 0.7 feet less on the USACE 2D existing model compared to the FEMA regulatory water surface elevation, and 1.3 feet compared to the FEMA BFE water surface elevation.
5. Coastal (tidal) flood elevations exceed riverine flood elevations within Spencer Island for all floods events with 99% to 10% AEP. Riverine flood elevations are higher than coastal flood elevations for less frequent floods (<10% AEP). Restoration actions (levee lowering, breaching) will not influence tidal flooding in the vicinity of Spencer Island, however these actions will influence flood elevations in large fluvial flood events.
6. Small changes in WSE are possible within and around Spencer Island for fluvial flooding. Changes are generally less than 0.1 feet. Flood elevations generally decrease within Steamboat Slough, Ebey Island, and south of Spencer Island. Flood elevations are expected to increase slightly in Union Slough west of Spencer Island, and more so in the City/County mitigation wetland immediately northwest of Spencer Island. With inclusion of mitigation for induced flooding as part of the restoration project (consisting of expansion of the existing levee breach on Smith Island), the potential increase in inundation (induced flooding) on developed portions of Smith Island can be avoided. This will induce flooding instead on tidal wetlands that were purposefully restored to allow flooding to occur.
7. Evaluation of the effects of the Smith Island conveyance improvement were completed at the request of the City of Everett. Widening of the existing breach into the city of Everett mitigation site will normalize (improve) tidal hydrology for the City and County wetlands and increase conveyance of floodwaters across the city mitigation site and into the Snohomish County Smith Island tidal marsh restoration project. This will locally increase inundation in these restored wetlands, while reducing flood elevations (and potential levee overtopping) upstream along the Union Slough 1135 levee. USACE anticipates purchase of flowage easements in the tidal wetlands to accommodate these changes, and affected parties have been coordinated with in advance.
8. The project repositions fill within an existing density fringe area, increasing conveyance. While the changes in WSE due to proposed grading at Spencer Island are small, the FEMA flood

insurance rate maps likely require a Conditional Letter of Map Revision once the 60% plans are ready.

8. Recommendations for PED Phase

Isolated geometry changes were made to the model geometries to improve the accuracy of the high flow runs where dike overtopping is widespread. Due to time constraints, these geometry updates were not included in plans where dike overtopping is not occurring. The geometry changes were mainly made to tighten breaklines and cell perimeters around dikes and highpoints. For PED phase, all existing conditions and with project plans should be synced to use the same respective geometry and terrain data sets.

Surveys of levees on Ebey Island and Spencer Island are needed to ensure levee overtopping near Spencer Island is accurately estimated. Partial topographic survey of the levees was completed in September 2025 by the NFS, after completion of modeling. Review of this survey data indicates the levees in the lidar DEM are higher by about 2 feet than actual surveyed elevations, which means that existing conditions elevations along dikes in the hydraulic models are artificially high by the same amount. The existing topo survey will be combined with additional topo and bathymetric survey of the remainder of the levees and ditches in March 2026. The survey data will be used to replace the topography for the levees being used in the civil grading plans and hydraulic modeling. Once the model is updated with lower topographic elevations for the existing levees the modeled overflows from the sloughs into Spencer Island will increase. This will reduce the differences between FWP and FWOP inundation and reduce the need for the Smith Island conveyance improvement.

The model should be migrated to RAS 2025 due to superior meshing tools and computational efficiency. Mesh faces along channels and levees should be refined. Recalibration can be considered if the run times can be significantly reduced. Near historic flooding occurred in December 2025. High water marks should be acquired to improve the calibration.

Discussions with Snohomish County regarding status of unaccredited levees in the model and assumptions regarding levee breaching are necessary to complete the no-rise analysis. This work will be done using a separate FEMA flood map and model update underway as part of ongoing FPMS study in FY 26.

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Feasibility Report Engineering Appendix

Spencer Island Ecosystem Restoration HH&C Annex D1: Hydrology & Hydraulics for Feasibility Phase

Snohomish County, WA

20-Jan 2026 35% ATR

Prepared by

US Army Corps of Engineers®
Seattle District

Contents

Figures

Tables

1. Overview

This hydraulics, hydrology and coastal (HH&C) Annex compiles existing conditions hydrologic, hydraulic, coastal, topographic and geomorphic data at the Spencer Island project site. This annex also compiles preliminary hydraulic modeling performed to refine the design of the Tentatively Selected Plan. This annex also includes a GIS analysis of the Spencer Island marsh tidal channel network and topography relevant for ecosystem restoration project design. The same analysis was performed on nearby Snohomish River estuary reference sites including the north tip of south Spencer Island, Otter Island, Mid-Spencer, Smith Island (Figure 1) to differentiate sites that are higher functioning ecologically and to develop restoration metrics from that data.

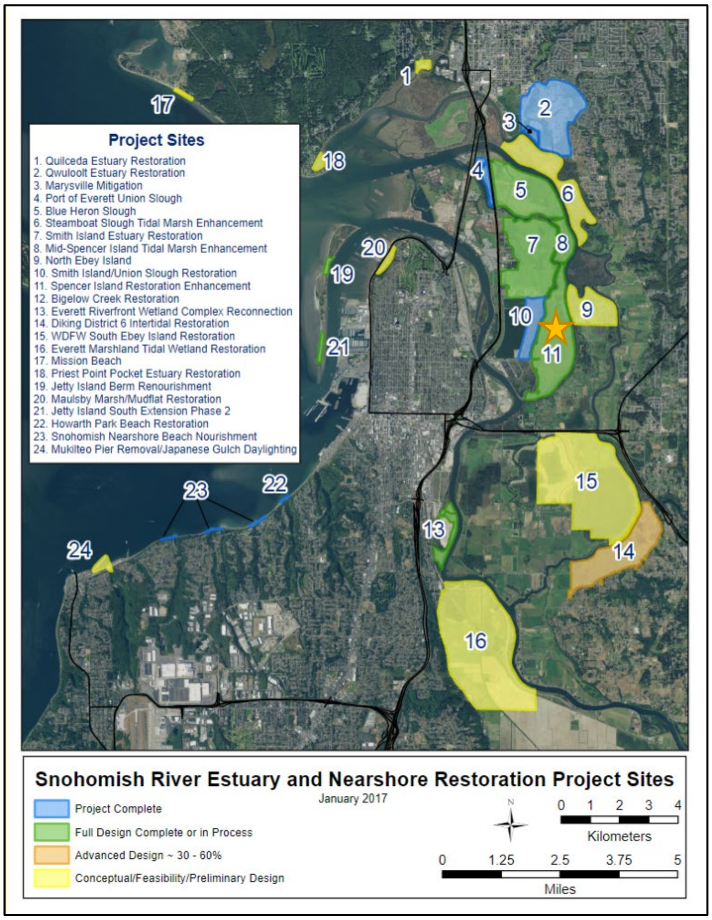


Figure 1. Spencer Island ecosystem restoration project in context with nearby completed and proposed projects. Spencer Island is starred (site 11).

2. Site Data

2.1. Project Area

The Spencer Island ecosystem restoration project (project) drains a combined 1,665 square miles of the Snohomish River basin (Figure 2). The project area (Figure 3) is bounded by the City of Everett wastewater treatment plant and Union Slough ecosystem restoration project to the west, the north tip of Ebey Island and southern half of Otter Island to the east, Ebey Island and US Highway 2 to the south and west, and the Buse Cut and Mid-Spencer Island to the north. The entire island is part of unincorporated Snohomish County. Land ownership is divided roughly equally in terms of area between Snohomish County and the State of Washington (WDFW). The municipal boundary between the City of Everett and State and County land is the centerline of Union Slough. The County has zoned the island and surrounding area as density fringe (Figure 4), which strictly limits development, due to the importance of the island for conveying floodwaters.

According to Table 2 of the WDFW Desktop Review (WDFW, 2023), several easements are present on the site. Easements have been granted to the WA DNR, Northwest Pipeline Corp., Puget Sound Energy, Dike District #5, Snohomish County PUD, and the RCO.

Location data:

PLSS: Township 29N, Range 5, Portions of sections 10, 15, 16, 21, 22

City: Unincorporated

County: Snohomish County

State: Washington

Basin: Snohomish

River: Snohomish River, Union Slough, Steamboat Slough

Tributary drainage area: 1,665 square miles

River Mileage: Steamboat Slough: 3.65 to 5.95; Union Slough: 2.86 to 5.03.

Land Ownership: State of Washington, Snohomish County

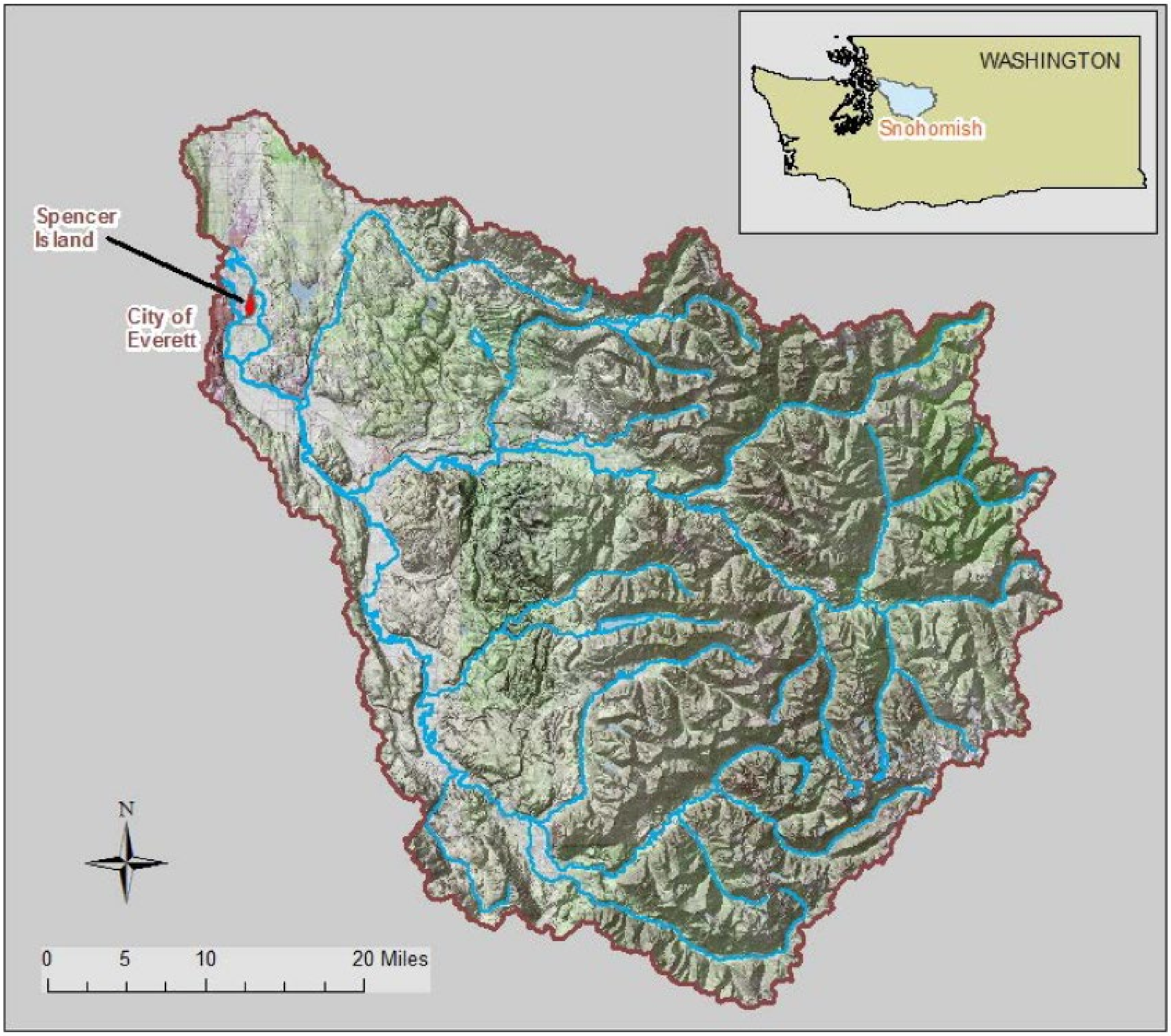


Figure 2. Spencer Island and Snohomish River watershed

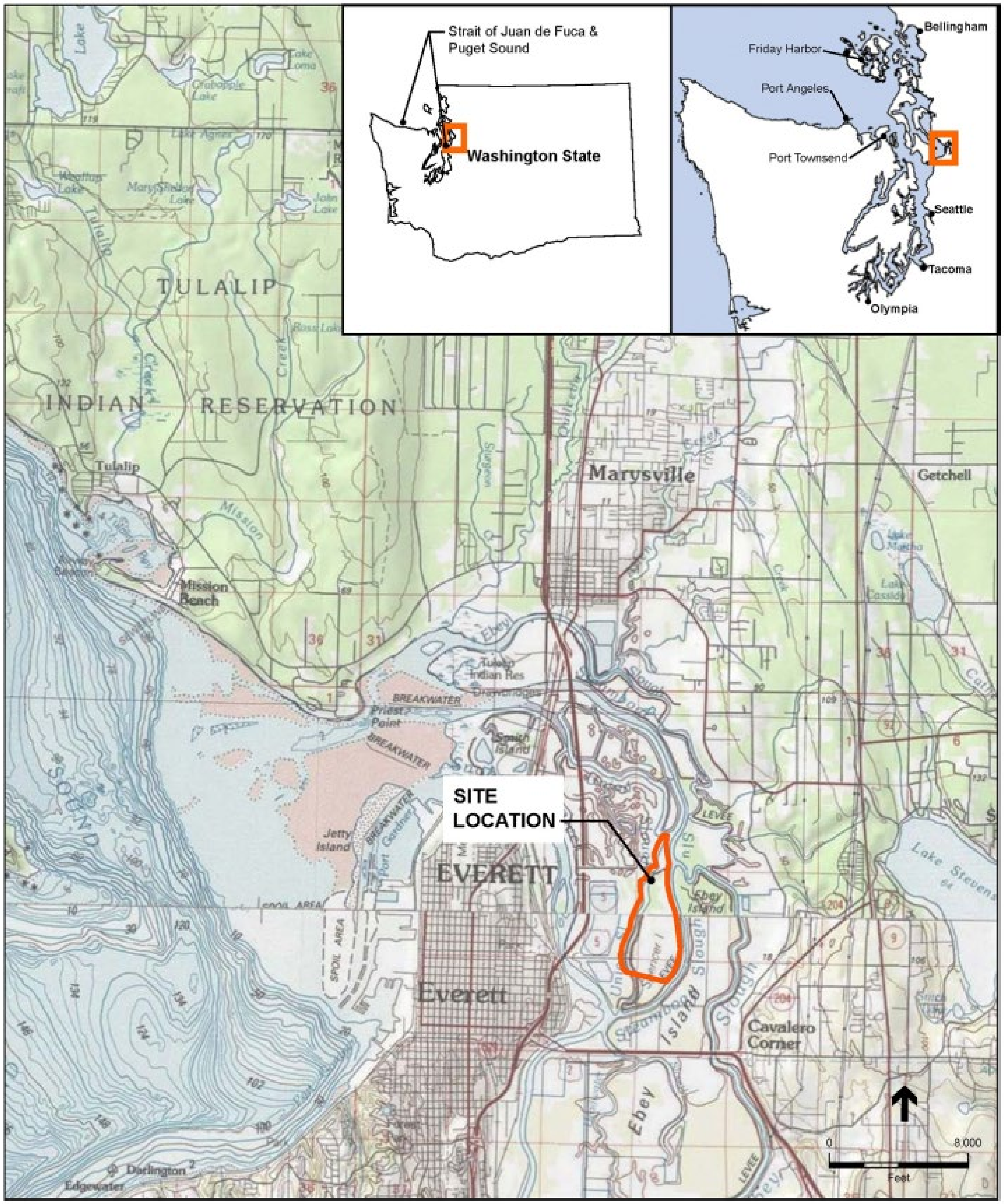


Figure 3. Spencer Island and Vicinity

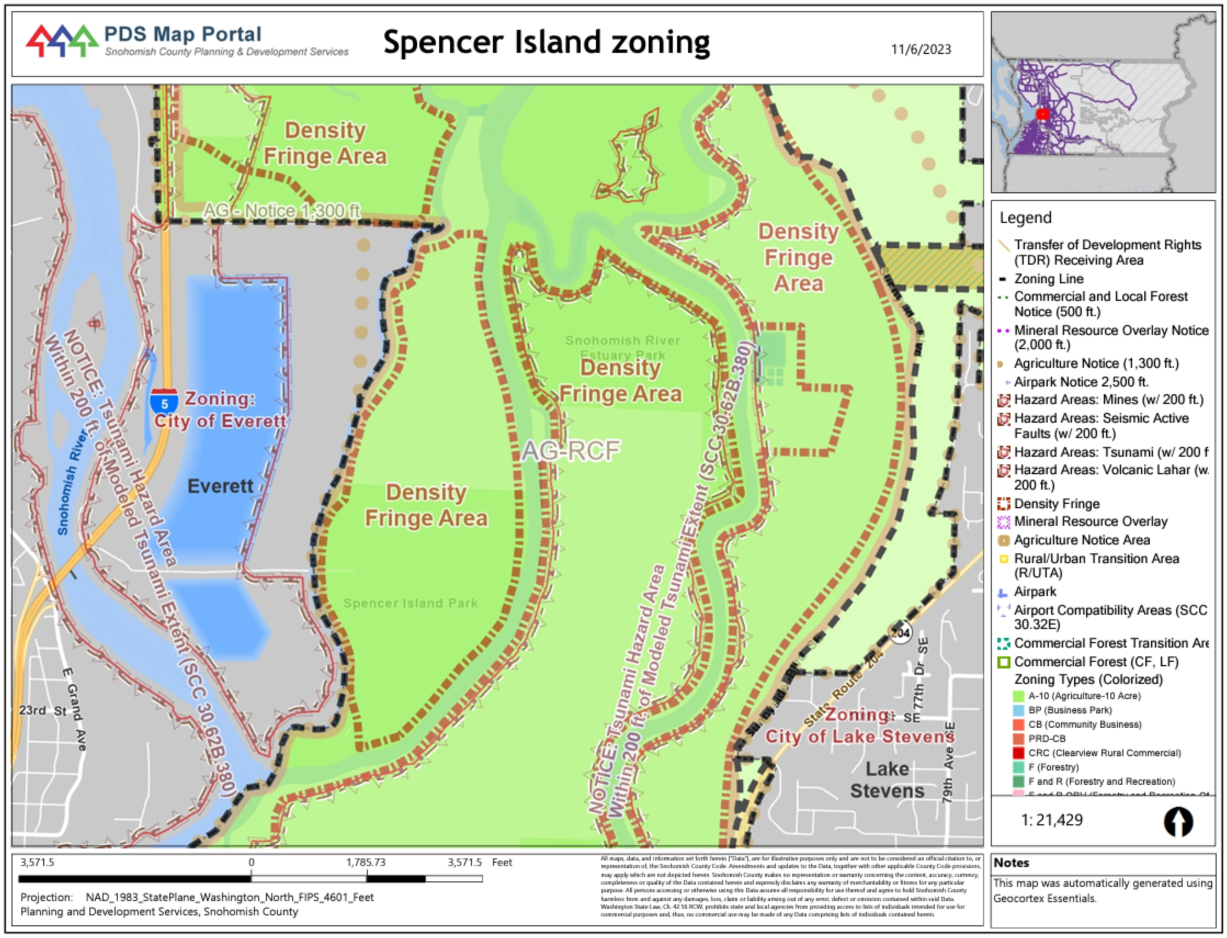


Figure 4. Snohomish County zoning in the vicinity of Spencer Island

2.2. General Site conditions

Per Salish Sea Wiki:

> *The Snohomish is one of the largest river delta sites in Puget Sound. Recovery of historical wetland area is a target of Salmon Recovery in the Snohomish Watershed. Portions of the Estuary are in the City of Everett but most are in Snohomish County. It is in usual and accustomed harvest areas of the Tulalip Tribes of Washington with portions within the tribal reservation. The lower delta is being modified under a series of large scale restoration projects including Qwuloolt Restoration, Smith Island Restoration, and Blue Heron Mitigation Bank among others. These projects are reestablishing a large area of tidal inundation in the saline mixing zone, and when complete will be the largest estuary restoration by area in Puget Sound. Upstream, freshwater tidal lands are in agricultural production, divided into diking districts such as Marshlands and Ebey Island, and depend on diking and pumping to lower water tables. There is controversy over the loss of agricultural lands as Snohomish County works to increase Snohomish Agricultural Resilience. Sea Level Rise effects may be important to long term planning. The Estuary is a study area of the Snohomish Sustainable Lands Strategy.*

3. Hydrology

Spencer Island is located between two Snohomish River distributary channels (Union Slough to the west, Steamboat Slough to the east). Union Slough reportedly forms the natural boundary between fresh water tidal wetland zone and the brackish tidal wetland zone (Collins 2002). The site and connected slough channels experience daily tidal fluxes from Puget Sound. Due to the difference in channel length and size between the mainstem and distributary channels, high and low tides occur at slightly different times. This results in dynamic conditions where upstream and downstream tidal fluxes can occur simultaneously in the mainstem and slough channels on incoming and outgoing tides depending on the location and phase of the tide cycle.

3.1. Tides

For feasibility level analysis and design tidal datums for the site are based on Seattle. Tidal hydrology is summarized below in Table 1 and Table 2. Note that the influence of backwater in the Sloughs likely results in a vertical shift upwards in these datum planes as well as a phasing lag for tides. Stage recorders can be installed in the site to provide a local to Seattle correlation to transfer the datum planes with more reliability.

Modeling work completed by USACE for the nearby Qwulloolt project indicates that the Seattle tide station best captures the tidal amplitude at the site, although the phasing can differ by up to an hour. Conversations with Watershed Science and Engineering, Inc who developed a fully 2D HEC-RAS model for the valley (WSE 2021) confirmed the validity of this observation.

Table 1. Seattle Tidal datums used for project site

Datum	Value	Description
MHHW	9.02	Mean Higher-High Water
MHW	8.15	Mean High Water
MTL	4.32	Mean Tide Level
MSL	4.3	Mean Sea Level
DTL	3.34	Mean Diurnal Tide Level
MLW	0.49	Mean Low Water
MLLW	-2.34	Mean Lower-Low Water
NAVD88	0	North American Vertical Datum of 1988

Table 2. Seattle tide station extremes

Max Tide	12.77	Highest Observed Tide
Max Tide Date & Time	12/27/22 8:36	Highest Observed Tide Date & Time
Min Tide	-7.38	Lowest Observed Tide
Min Tide Date & Time	1/4/1916 0:00	Lowest Observed Tide Date & Time

Tidal extreme water level frequency data are shown below for the Seattle gage using the peak over threshold method (Table 3, Figure 5). The latest total water level flood frequency estimates include the December 2023 flood of record. That event exceeds the largest previously observed event by more than 0.5 feet and is higher than the previous 500-year tide estimate. The flood was a combination of annual king tides and a storm that had one of the lowest atmospheric pressures on record.

Table 3. ***Seattle (NOAA #9447130) extreme water level frequency curve, Peak over threshold method***

% annual exceedance	Return period (year)	Total Water Level (feet, MLLW)	Total Water Level (feet, NAVD88)	±95% Confidence Interval (feet)
99	1.01	13.34	11.0	0.0354
50	2	13.6	11.26	0.0638
10	10	14.05	11.71	0.0954
2	50	14.54	12.2	0.1204
1	100	14.77	12.43	0.1307
0.2	500	15.37	13.03	0.1542

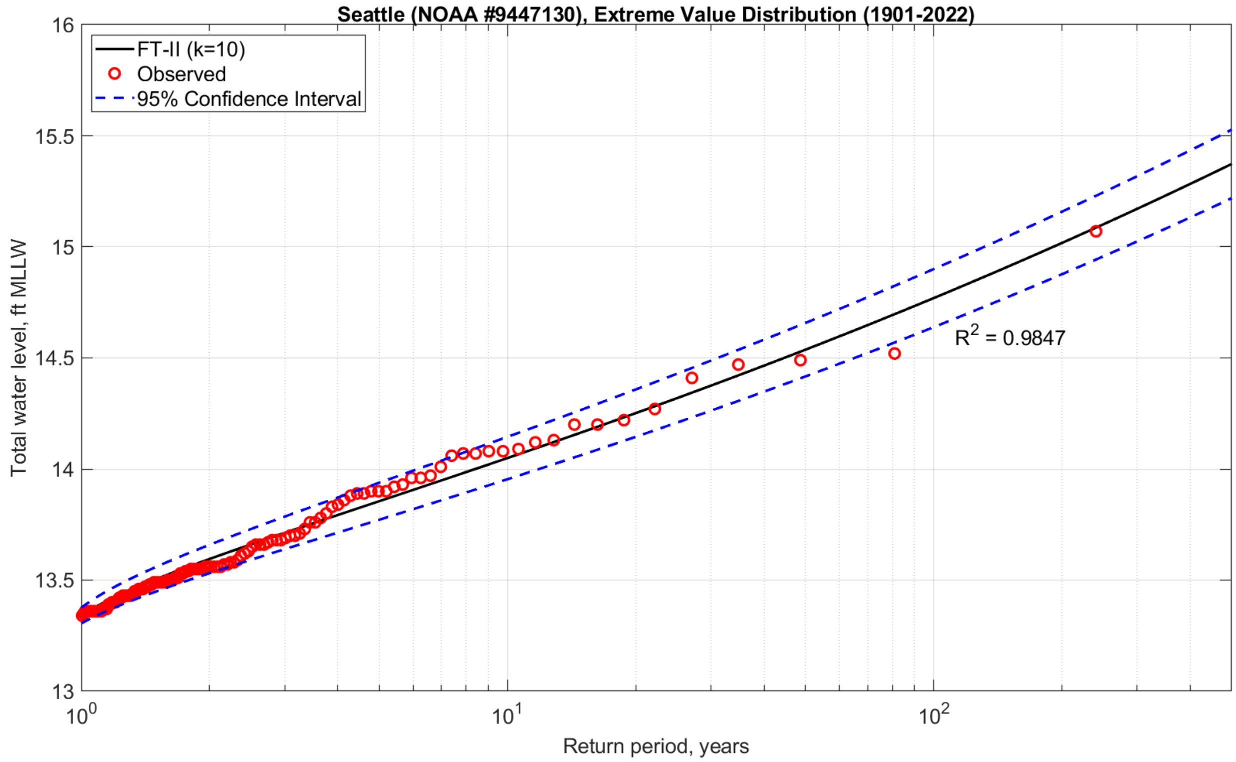


Figure 5. ***Extreme water level frequency curve following the Weibull distribution using peak over thresholds method (period of record = 116 years; N = 194)***

3.2. Snohomish River Basin

Spencer Island is also subject to frequent fluvial flooding from the Snohomish River basin, which drains the combined flows of the Snoqualmie, Skykomish, Tolt, Sultan and Pilchuck Rivers (Figure 2). Real time stages and streamflows are measured at Monroe (RM 20, DA 1,536 sq. mi.), upstream of the tidal backwater zone and on the Pilchuck River near Snohomish (DA 129 sq. mi.). The total drainage area of the gaged proportion of the watershed tributary to the mainstem at the split to Union Slough and Steamboat Slough is 95% (1,665 sq. mi. of 1,749 sq. mi.). Tidal backwater extends upvalley past the City of Snohomish (river mile (RM) 13). The USGS gage at Snohomish was stage only until 2022. Now the gage measures both streamflow and stage. The streamflow period of record at the Pilchuck, Snohomish at Snohomish and Snohomish at Monroe gages are shown below in Figure 6 and Figure 7.

Note that flood stage data go back to 1906 at Snohomish. Flow and stage were measured in the 1940s through 1960s at Snohomish, however flow measurement at this site is difficult because of the influence of tides (flow reversals) and upstream levee overtopping that diverts flow through the floodplain (unmeasured at gage) . The 1906 flood is reported to have had a stage of 35 feet which would likely qualify as a historical event (exceeding a 1% annual chance of exceedance). If the available gaged stage and flow data pairs from the 1940s through 1960s are used to derive a flow-stage rating curve at Snohomish, the peak discharge for the 1906 flood ranges from 130,000 to 180,000 cfs (Figure 8). The switch to the Monroe site for gaging in the 1960s makes sense given the wide variation in flood discharge for a given stage at Snohomish. Note the small to negligible increase in flood discharge at

Snohomish relative to Monroe for the four years of overlapping record (1966-1968, 2023). Between October 2022 and April 2024 USGS measured streamflows at Snohomish in addition to Monroe, and this data is used for stage-flow calibration of the larger HEC-RAS model (Figure 9).

Damaging floods recorded by the Monroe occurred in water year 1991, 2009, 1996, 2007, and 1976. The Snohomish gage was operational prior to the Monroe gage and recorded two large floods of comparable magnitude in 1951 and 1960. USGS published peak flood stages (without flows) for very large floods that occurred in 1905, 1916, 1920, 1932. As part of the FEMA FIS historical floods for 1898, 1907, and 1918 were estimated by regression to build out the historical record which was then used to compute annual peak flow frequency statistics. There is considerable uncertainty in the methods and data used in the FIS, and 24 years have elapsed since that analysis was completed.

For the time being, the best estimates for peak flood discharge should be derived from either the WSE 2D HEC-RAS model or the FEMA UNET model. The WSE model has the advantage of including the effects of potential increased streamflow resulting from climate change, and accounts for valley storage effects.

Future revisions of peak flow frequency estimates (for PED phase) should focus on analyzing spring and fall/winter flood events separately (mixed population), investigate the validity of the 1906 data, and combine all valid records for the Snohomish and Monroe gages to maximize the period of record and improve the Bulletin 17C analysis and the balanced hydrographs used in the FEMA unsteady flow UNET model.

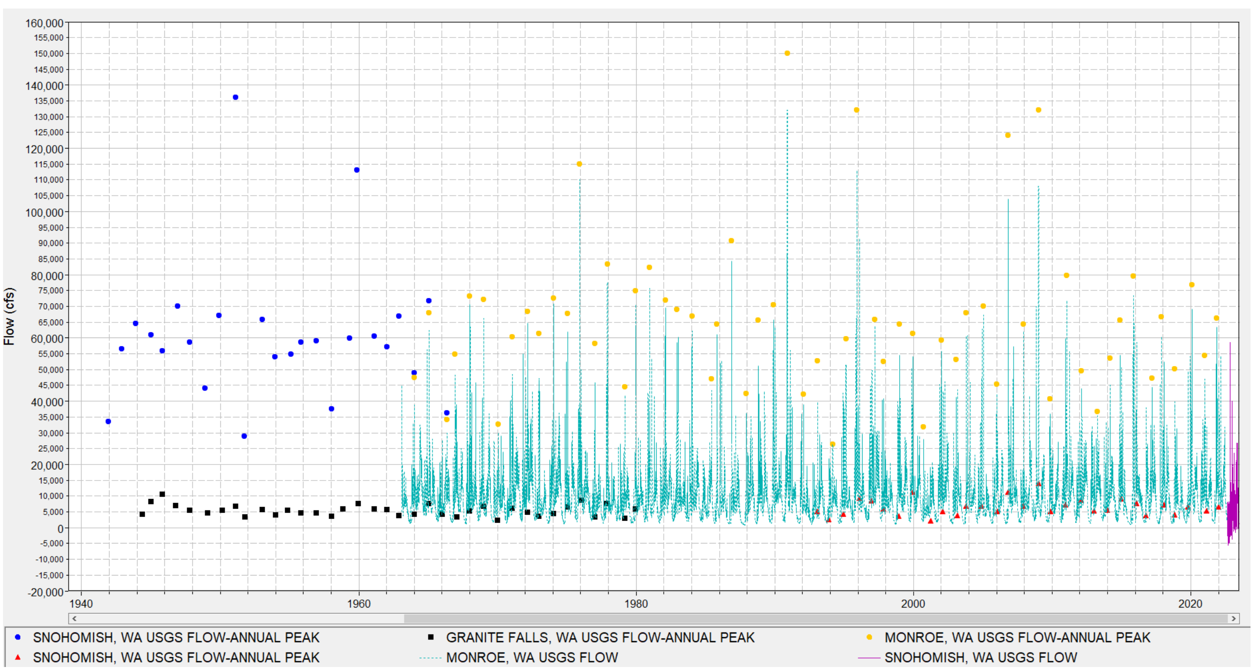


Figure 6. Systematic period of record streamgage data for the Snohomish River at Monroe (orange circles, turquoise dashed line) Snohomish River at Snohomish (blue circles, purple line), and Pilchuck River at Granite Falls (black squares) and near Snohomish (red triangles), 1941-2023

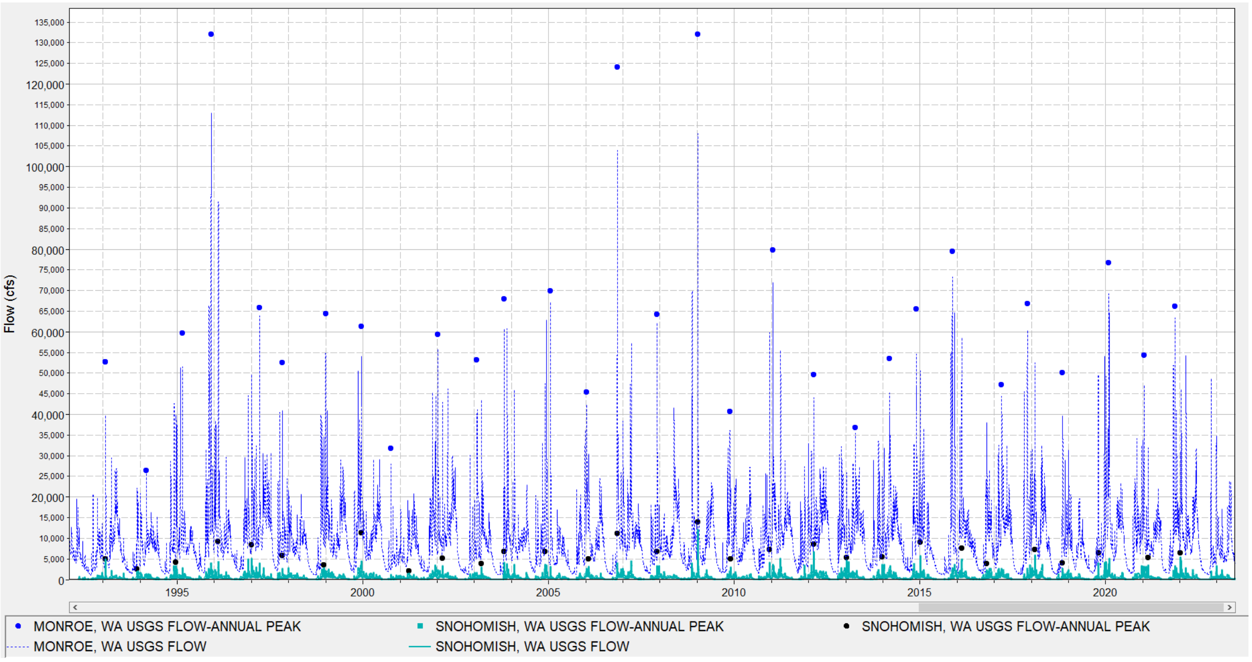


Figure 7. Period of record of Pilchuck River near Snohomish compared with Snohomish at Monroe indicating weak correlation of timing of Pilchuck River annual peaks with mainstem Snohomish River annual peaks (peak discharges often occur months apart)

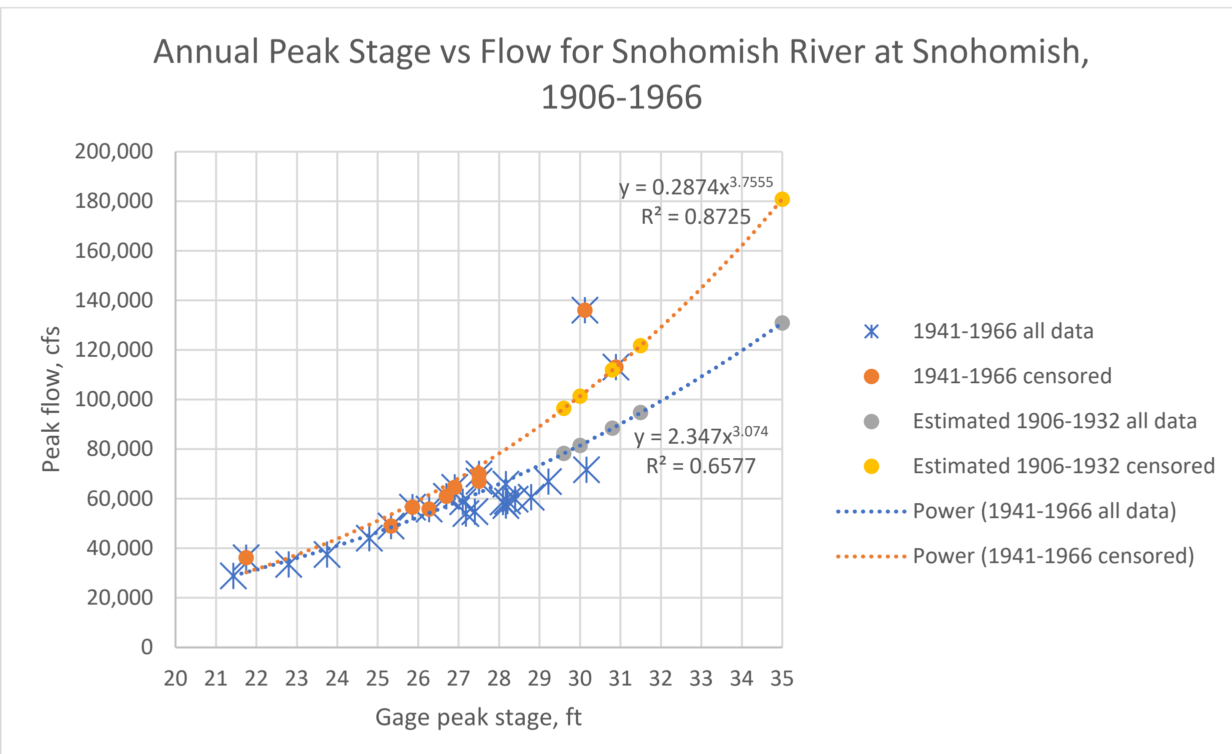


Figure 8. Snohomish River at Snohomish historical flows, 1906-1966

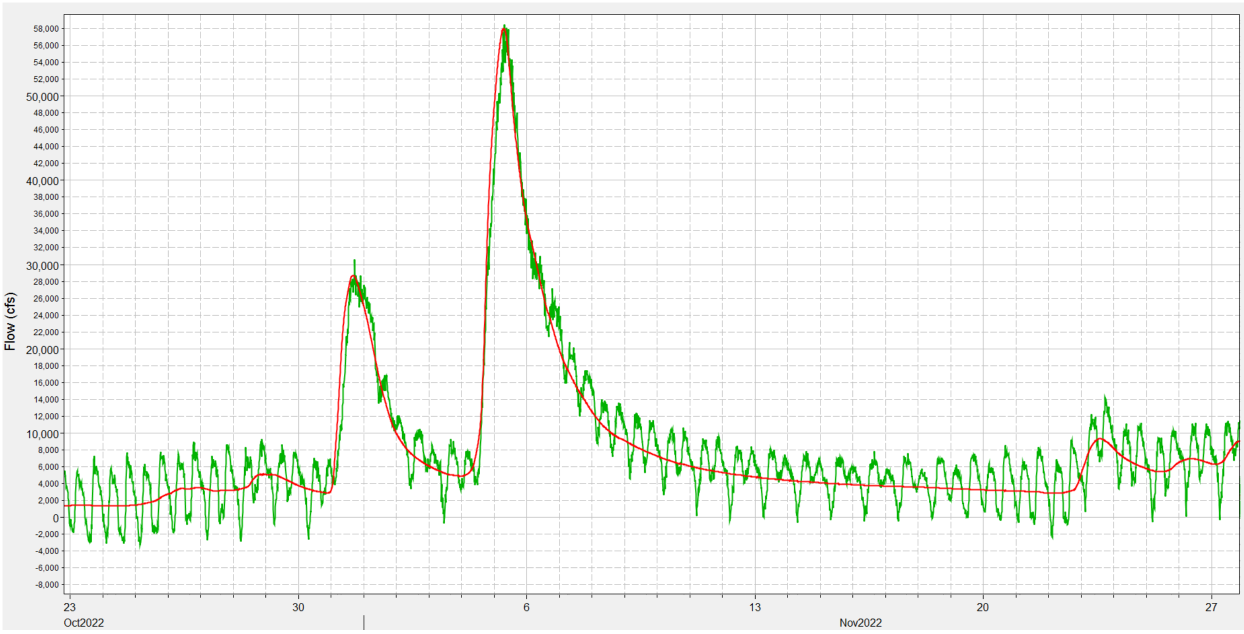


Figure 9. Comparison of real time flows on the Snohomish River at Snohomish (RM 13) and Monroe (RM 20) for October-November 2022 showing very close agreement with peak discharge and effects of daily tides, resulting in upstream flow reversal

3.2.1. Annual peak flow frequencies

Flood flow frequencies (or annual exceedance probabilities) at Spencer Island are not easy to estimate without modeling as they depend on the flow distribution between the mainstem, Ebey Slough and Steamboat/Union Sloughs,largely uncorrelated effects from tidal elevation and phasing, as well as antecedent flooding/dike conditions and local runoff. Previous modeling for the FEMA FIS indicates that flood discharges in the Sloughs are most strongly influenced by the magnitude and volume of the flood hydrograph at the gages and the amount of floodplain storage/attenuation that occurs as the flood wave progresses downstream. Tides can influence attenuation by increasing stages and dike overtopping. If dikes overtop and floodplain areas fill prior to arrival of the flood peak from upstream, attenuation is lessened, and peaks remain higher than they would if the floodplain areas are dry and begin to fill up during the progression of the main flood wave. Similarly, if dikes fail in a previous but remain unrepaired, downstream flood attenuation can be enhanced in the next flood. If dikes fail prior to floodwater reaching the dike crest, downstream attenuation would also be higher than modeled. The complexities and uncertainties of these effects and conditions result in a need for simplification and use of statistical approaches to define probabilistic flood risk.

For purposes of Feasibility Study H&H analyses, no new hydrologic analyses were performed. Existing studies, data and models are leveraged for purposes of this study. Relevant information is provided below. Shortcomings and limitations of the data and approaches that may warrant updates as part of 35% to 65% PED work are highlighted.

Table 4. WSE estimated peak flood flow statistics for the Snohomish River + Pilchuck River based on historical data as compared with effective FEMA FIS estimates and USGS regression equation estimates for the mainstem Snohomish upstream of Spencer Island

Flood Event		Snohomish River at Monroe (DA 1,536 sq. mi.)		Pilchuck River near Snohomish (DA 129 sq. mi.)		Snohomish + Pilchuck (DA 1,665 sq. mi.) (1)(2)		Snohomish mainstem upstream of Spencer Island (DA 1,749 sq. mi.) (1)(3)	
Return Period (Years)	Annual Exceed. Probability (%)	WSE (cfs)	FEMA (cfs)	WSE (cfs)	FEMA (cfs)	WSE (cfs)	FEMA (cfs)	USGS Drain. Area ratio (cfs)	USGS Ungaged regres. (cfs)
1	99%					*49,865*	*54,759*	*50,862*	*47,853*
2	50%	62200		5970		68,170	*77,561*	69,900	71,300
10	10%	101,700	120,700	10,300	8,900	112,000	129,600	117,000	130,000
50	2%	139,200	174,400	13,900	12,100	153,100	186,500	160,000	183,000
100	1%	156,100	196,800	15,400	13,300	171,500	210,100	180,000	208,000
500	0.2%	197,700	242,900	18,900	17,200	216,600	260,100	227,000	266,000

Notes:

1. Estimated by linear regression of peak flow frequency estimates to fill data gaps.

2. FEMA and WSE peak flows near Spencer (Snoh + Pilchuck) are not routed from gages to site and do not include local runoff or attenuation.

3. USGS regression-based estimates do not include drainage area tributary to Ebey Slough/Ebey Island

Flood frequency statistics as reported by WSE (2021) are provided below for the Monroe and Pilchuck gages. Total storm runoff volume, valley floor flood storage capacity and tides influence the ultimate peak discharge at the project site. Model runs that include observed tidal fluctuations preserve valley floor flood storage capacity and have smaller flood peak discharges than models that maintain a constant downstream tidal elevation. A steady tide assumption is reasonably conservative to estimate peak flood stages as it recognizes the probabilistic coincidence of peak tides and peak river flows, but it creates a physically unrealistic water surface elevations in some locations and does not provide reasonable estimates of velocity or tidal flux in the tidal zone. Note that the peak flood flows estimated by WSE are about 20% lower than the FEMA FIS peak flows for the same recurrence interval event (Table 4). It should be noted that the FEMA hydrologic period of record noted in the Technical Support Data Notebook (WEST 2001, Figure 2-3) combines Monroe gage data from 1964-1999 with historic flood estimates (developed by USACE) for 1898, 1907, 1918 and 1922.

Note that the WSE model combines balanced inflow hydrographs for the Skykomish River near Gold Bar, Snoqualmie River near Carnation, N. Fork Tolt River near Carnation, Sultan River below Power Plant, and Pilchuck River near Snohomish plus local runoff scaled by drainage area to the upstream inflow hydrographs, based on the November 2006 storm pattern. Thus, flows at the Monroe gage in the model are not based on estimates from the gage record, but from hydraulic routing.

Table 5. WSE estimated flood flow statistics for the Snohomish River based on historical data

Snohomish River near Monroe

Return Period	Instantaneous Peaks	1 hour Dur.	3 hour Dur.	6 hour Dur.	12 hour Dur.	1 day Dur.	3 day Dur.	7 day Dur.
2	62,200	62,100	61,900	61,200	59,900	56,500	47,800	35,900
5	85,500	85,400	85,300	84,500	82,800	77,700	64,800	47,100
10	101,700	101,600	101,500	100,400	98,500	91,800	75,900	53,900
25	122,800	122,600	122,600	121,300	119,100	109,900	89,600	62,100
50	139,200	138,900	138,800	137,300	135,000	123,400	99,700	67,800
100	156,100	155,500	155,500	153,800	151,300	137,100	109,600	73,200
500	197,700	196,600	196,500	194,300	191,600	169,800	132,600	85,300

Table 6. WSE estimated flood flow statistics for the Pilchuck River based on historical data

Pilchuck River near Snohomish

Return Period	Instantaneous Peaks	1 hour Dur.	3 hour Dur.	6 hour Dur.	12 hour Dur.	1 day Dur.	3 day Dur.	7 day Dur.
2	5,970	5,890	5,780	5,540	5,080	4,090	2,900	2,140
5	8,560	8,390	8,220	7,960	7,370	5,850	4,160	2,940
10	10,300	10,000	9,810	9,560	8,900	7,060	5,020	3,460
25	12,400	12,000	11,800	11,600	10,800	8,640	6,140	4,120
50	13,900	13,500	13,200	13,000	12,300	9,860	7,000	4,600
100	15,400	14,900	14,600	14,500	13,700	11,100	7,870	5,080
500	18,900	18,200	17,800	17,700	17,000	14,100	9,990	6,210

3.3. Future conditions hydrology

USACE guidance (ER 110-2-8162, and ECB 2018-14, Rev. 3) provide policy and guidance for consideration of sea level change and climate change effects on inland hydrology for studies and civil works projects. Policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance resilience of communities. Climate change has been considered in H&H evaluations both quantitatively and qualitatively. This Annex is focused on quantitative evaluations. Refer to Section 6 of this Annex and Annex D3 for qualitative discussion of potential effects of future with and without project conditions.

3.3.1. Annual peak flow frequencies

Snohomish County (WSE 2020) updated historical flood frequency curves based on hydrologic modeling work completed by the UW Climate Impacts Group (CIG). As reported by WSE The CIG forecasted increase in peak runoff by mid-century for the Snohomish gage near Monroe is 14.5% and the increase by late century of 24.4%. The mid-century predictions end in 2069 which is less than a decade from the end of the 50-year planning period (2075) and are a reasonable first approximation for purposes of feasibility level analysis.

Table 7 and Table 8 provide flood frequency statistics for the Monroe and Pilchuck gages accounting for mid-century increases in streamflows caused by climate change. Resulting water surface profiles for the mid-century scenario are shown in Figure 47. For reference at the RM 4 split from the mainstem Snohomish River into Steamboat Slough (upstream end of Spencer Island) 1% AEP (100-year) flood levels are forecasted to increase by about 2 feet by mid-century even though modeled sea levels are 1-ft higher. This indicates about half of the increase in future inundation could be attributable to sea level rise and the other half to increases in basin runoff. Refer to Annex H-2 for detailed inundation maps of the project site for future conditions.

Table 7. WSE estimated flood flow statistics for the Snohomish River based on historical data scaled based on climate change impact projections for mid-century

Snohomish River near Monroe								
Return Period	Instantaneous Peaks	1 hour Duration	3 hour Duration	6 hour Duration	12 hour Duration	1 day Duration	3 day Duration	7 day Duration
2	71,200	71,100	70,600	70,300	69,300	68,900	58,800	44,800
5	97,900	97,800	97,200	97,100	95,800	94,700	79,800	58,800
10	116,400	116,300	115,700	115,400	113,900	111,900	93,400	67,300
25	140,600	140,400	139,800	139,400	137,800	134,000	110,300	77,500
50	159,400	159,000	158,200	157,800	156,200	150,400	122,700	84,600
100	178,700	178,000	177,300	176,800	175,000	167,100	134,900	91,400
500	226,400	225,100	224,000	223,300	221,600	207,000	163,200	106,500

Table 8. WSE estimated flood flow statistics for the Pilchuck River based on historical data scaled based on climate change impact projections for mid-century

Pilchuck River near Snohomish								
Return Period	Instantaneous Peaks	1 hour Duration	3 hour Duration	6 hour Duration	12 hour Duration	1 day Duration	3 day Duration	7 day Duration
2	6,540	6,460	6,360	6,140	5,700	4,710	3,600	2,530
5	9,380	9,200	9,050	8,820	8,270	6,730	5,160	3,480
10	11,300	11,000	10,800	10,600	10,000	8,130	6,230	4,090
25	13,600	13,200	13,000	12,900	12,100	9,940	7,620	4,870
50	15,200	14,800	14,500	14,400	13,800	11,300	8,690	5,440
100	16,900	16,300	16,100	16,100	15,400	12,800	9,770	6,000
500	20,700	19,900	19,600	19,600	19,100	16,200	12,400	7,340

3.3.2. Relative Sea level change

This project incorporates considerations of analysis of sea level rise in accordance with ER 1100-2-8162. USACE estimated sea level change based on low (historical), and medium and high emissions scenarios are shown below in Figure 10. Presuming the project is constructed in 2027 sea levels/ tidal datums at the site could increase by!0.8 to 3.6 feet by 2080 and steadily increase thereafter. Forecasted sea levels based on low, intermediate, and high emissions scenarios are shown below in Figure 8. By 2063 the mean tide level could inundate the average island elevation daily (under high emission scenario) and by 2117 under the intermediate emission scenario. The proposed dike lowering elevation could be exceeded by the MHHW by 2045 under the high emissions scenario and 2081 by the intermediate emissions scenario. Expected sedimentation within and along the island will extend the forecasted time for intersection between these reference elevations and datums, resulting in a project that is expected to provided intended benefits for the duration of the 50-year planning period.

The NOAA Sea Level Rise Viewer tool was used to see how the changes in mean sea level could manifest near Spencer Island by 2080. From inspection of Figure 11 through Figure 14 daily tidal inundation for nearly all conditions appears to result in inundation patters resembling very large floods on the Snohomish River. It is unclear if landowners will adapt by increasing the height of dikes or abandon the low-lying floodplain areas allowing them to convert back to tidal marsh or tide flats.

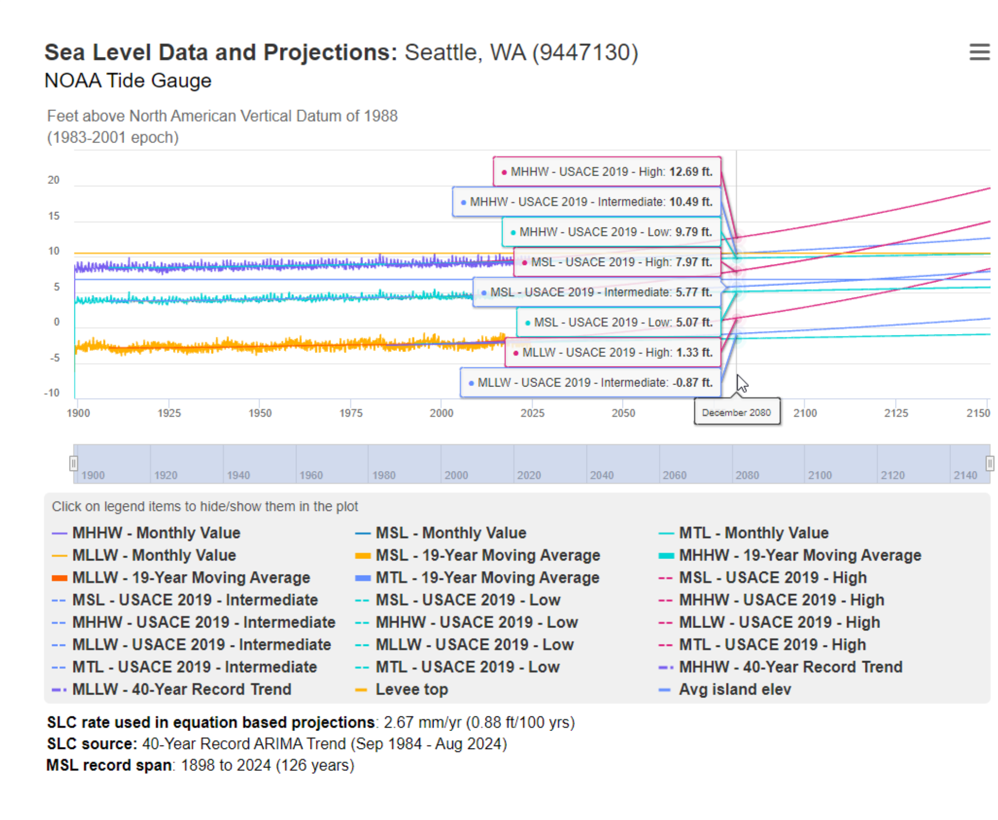


Figure 10. ***USACE low, intermediate, and high sea level change prediction for Seattle, WA (source: https://climate.sec.usace.army.mil/slat/)***

Table 9. Water Levels (FT, NAVD88) based on Seattle Tide Gauge Annual Exceedance probability water levels including projected Sea Level Change from 2020 to 2120

Return Period, Years	Annual Exceedance Probability (AEP)	water levels in year 2020	water levels + low SLC in year 2120	water levels + intermediate SLC in year 2120	water levels + high SLC in year 2120
100	1%	12.40	13.27	14.72	19.34
10	10%	12.00	12.87	14.32	18.94
2	50%	11.50	12.37	13.82	18.44
1	99%	10.70	11.57	13.02	17.64

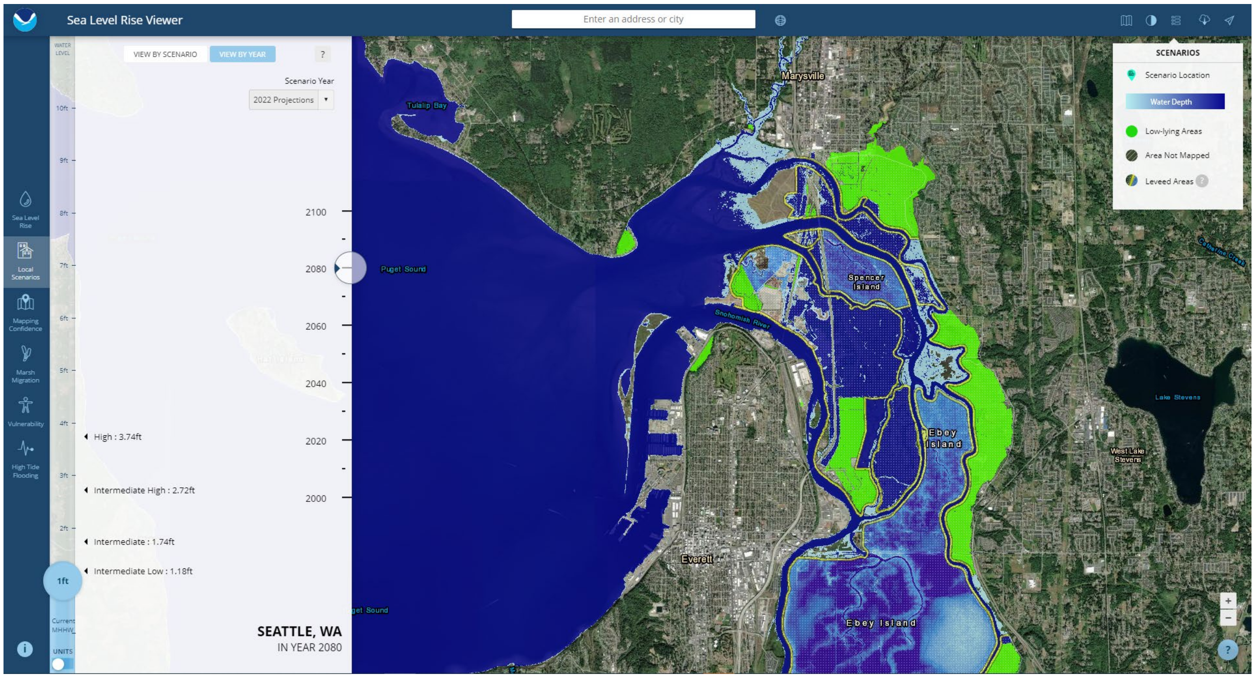


Figure 11. MHHW + 1' (~2080 intermediate low)

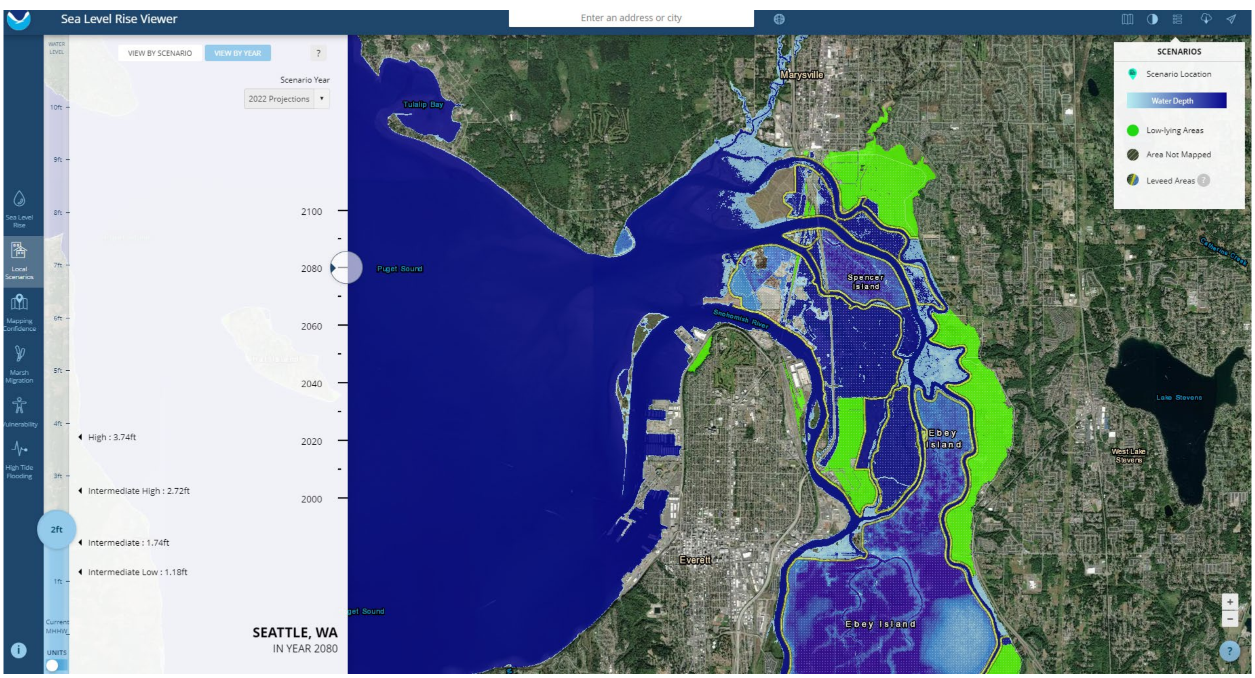


Figure 12. MHHW + 2' (~2080 intermediate)

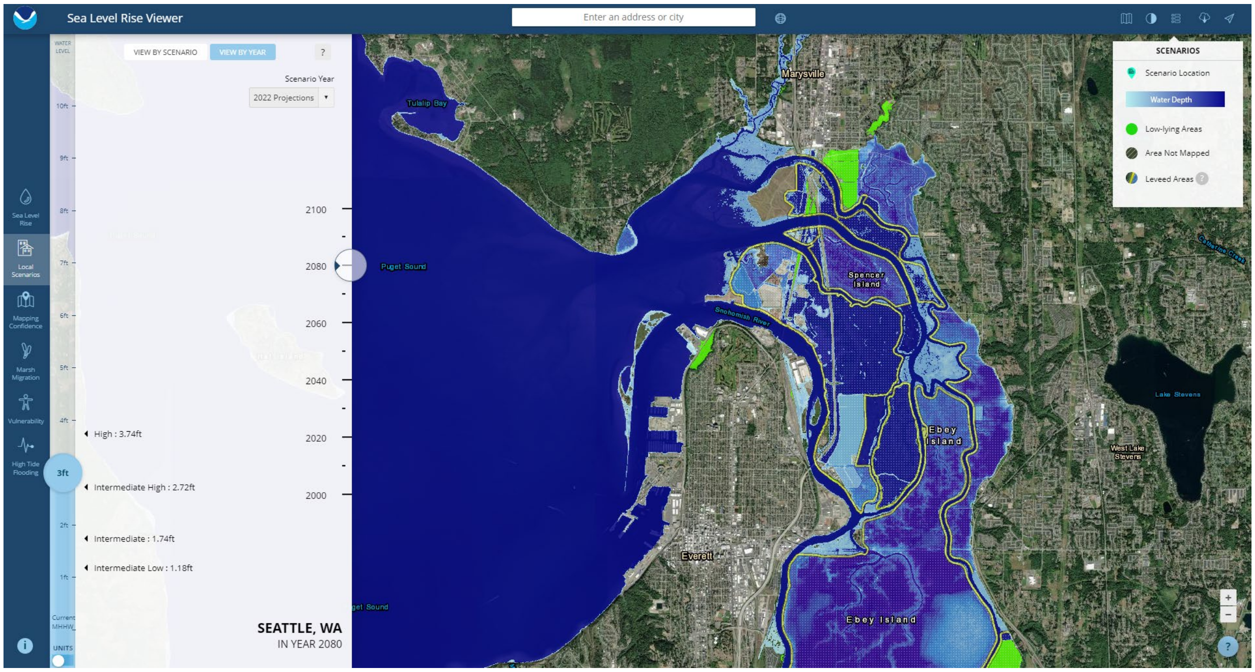


Figure 13. MHHW + 3' (~2080 intermediate high)

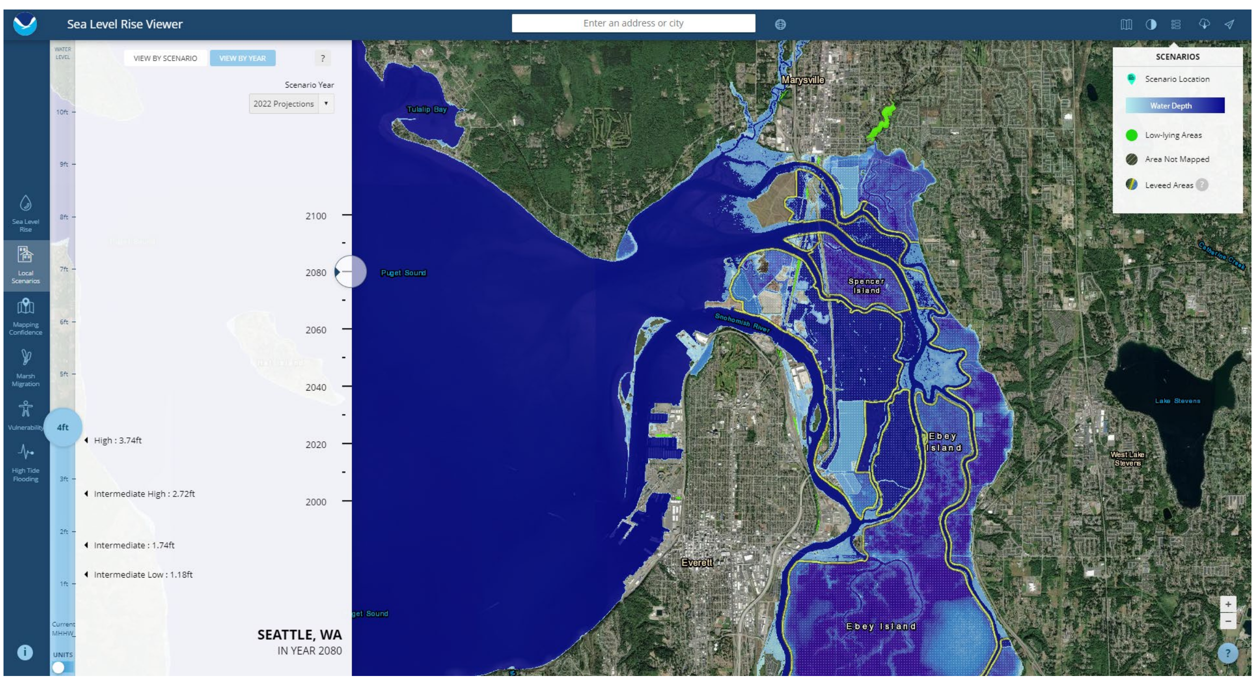


Figure 14. MHHW + 4' (~2080 high)

3.4. Ordinary High-Water Mark

Ordinary high water mark estimation procedures published by Ecology (2016) were employed at Spencer Island using available mapping, topographic, hydrologic, hydraulic and field geomorphic indicators. Site information indicates the OHWM varies across the site due the complex hydrology and hydraulics present. To aid HTRW surveys (where soil (upland) must be distinguished from sediment) a single representative OHW elevation of 11.0 ft NAVD88 was selected to apply to the entire island, which corresponds to the elevations surveyed along Steamboat Slough, the measured monthly high water level averages, and modeled monthly high water level averages, as well as first-order methods (assuming OHWM occurs at an elevation above MHHW).

Ordinary high water (OHW) surveys by USACE, WDFW, and WA Dept. of Ecology were conducted in August 2024 in the south portion of the project are plotted in Figure 15 (overlaid with existing lidar 1-foot contours and the 50% AEP (2-year) river flow inundation) and summarized in Table 10.

The average OHW elevation of the data collected in the south end of Spencer Island is 9.1 feet, with a minimum of 7.73 feet and a maximum of 11.54 feet. Spatial trends in the data show that there is an east-to-west and south-to-north gradient in elevation within the sampling zones caused by existing dikes. The locations of surveyed OHW points track very closely with inundation boundary for the 1-year tidal flood and 2-year river flood scenario (approx. elev. 10 to 11 feet NAVD88).

From inspection of the surveyed elevations by location, there is as much as 1.9 feet of elevation difference between the OHW line along the outboard dike face at Steamboat and Union Slough dikes and about a half foot of fall between the south and north side of the South Cross Dike and the inboard to outboard side of the Union Slough dike. This suggests that dike removal will lower the OHW line along Steamboat Slough and increase it along Union Slough as water will be able to move freely between the sloughs and equilibrate.

The target dike lowering elevation of 10.5 feet used for feasibility level design is based on the average of the daily high tides measured at the Union Slough breach and Snohomish County cross dike bridge tide gages (described in next section). This elevation is higher than the average surveyed OHW but less than the representative OHWM that factors in hydrologic and hydraulic data. Further survey and discussion with the TAG could be conducted to refine this elevation in the design phase.

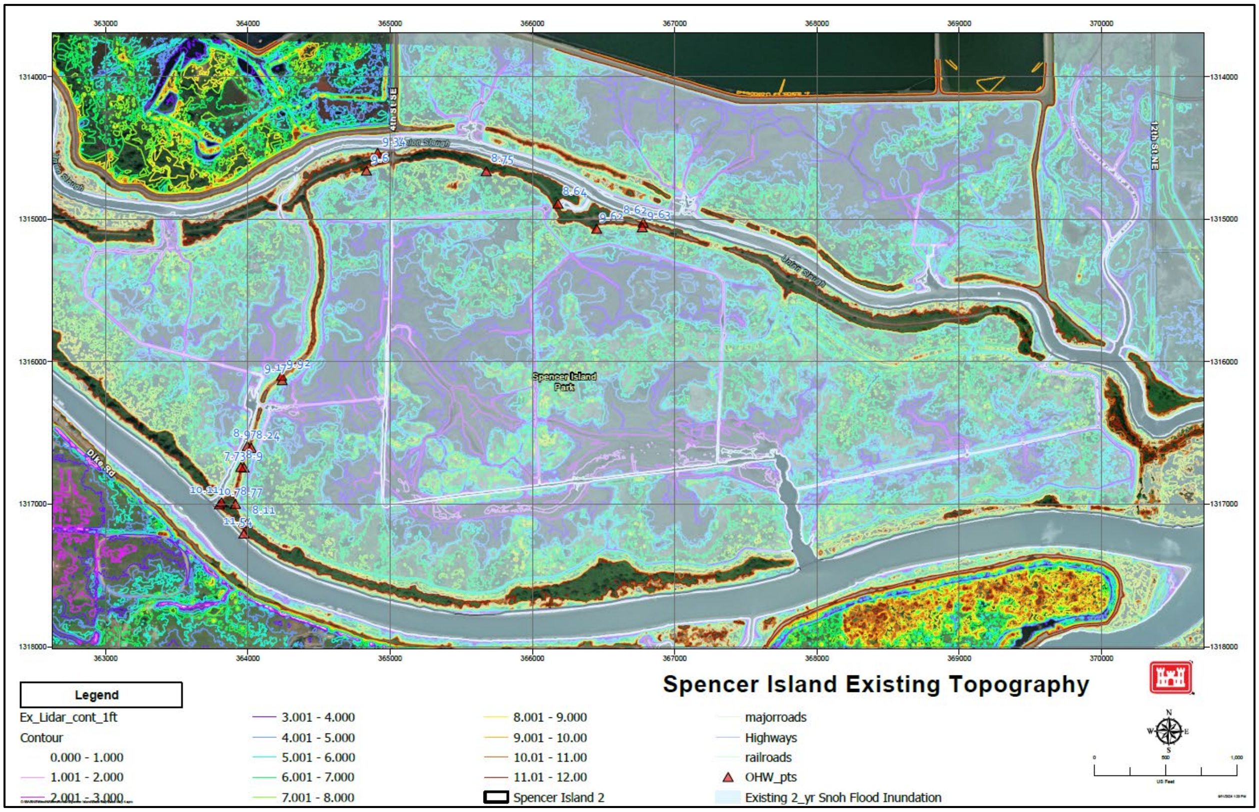


Figure 15. August 2024 OHW data at south end of Spencer Island overlaid with existing lidar and Snohomish River 2-year river flow inundation

Table 10. Statistics for OHW by sampling zone

Statistics by location (elev. feet, NAVD88)	Inboard of Union Slough Dike	Outboard of Union Slough Dike	South of South Cross Dike	North of South Cross Dike	Inboard of Steamboat Slough Dike	Outboard of Steamboat Slough Dike
Min	8.8	8.6	8.9	7.7	8.1	10.1
Max	9.6	9.3	9.2	9.9	8.8	11.5
Avg	9.4	8.9	9.0	8.6	8.4	10.8

3.5. Snohomish Estuary and Water level monitoring

WDFW deployed 6 sensors in and around Spencer Island beginning in March and April 2023 to assist with model calibration and baseline monitoring (Figure 16). The loggers are programed to collect samples every 15 minutes. A barometric pressure sensor is also deployed on the SC bridge south monitoring station. Data collected from March through July are presented in Figure 17 below. This period includes the annual snowmelt freshet and annual June King tides and represents seasonal average high-water conditions (ordinary high water).

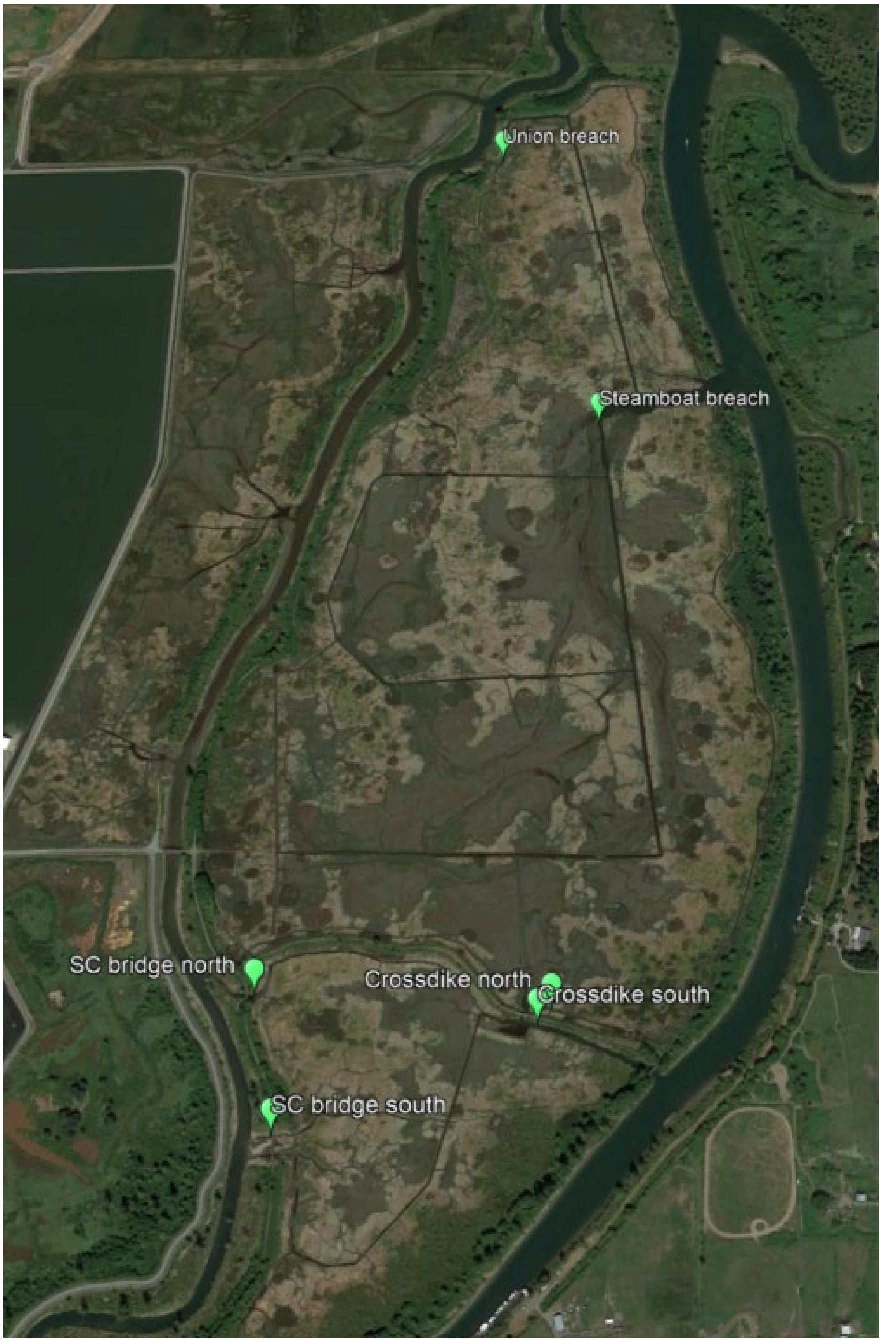


Figure 16. Continuous water sensors deployed on Spencer Island by WDFW

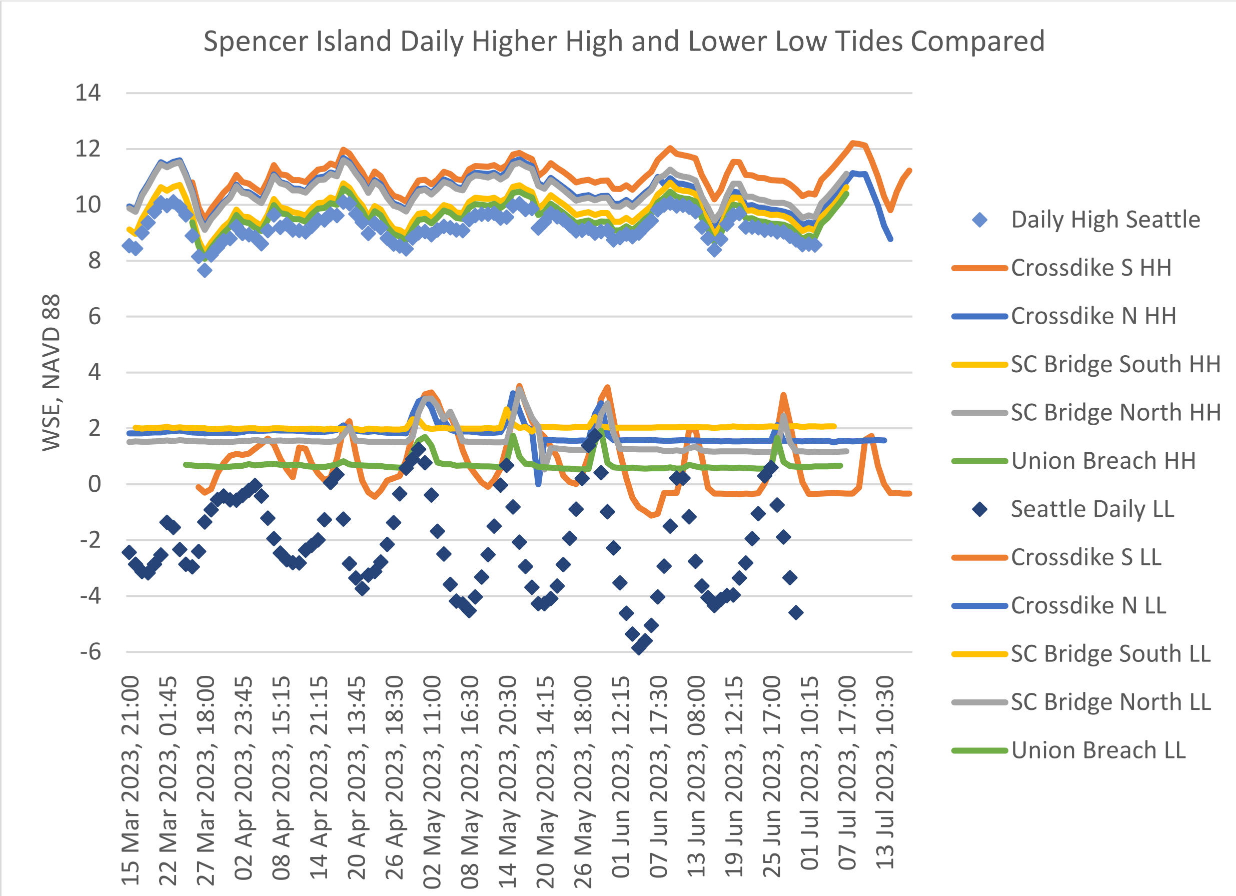


Figure 17. Continuous water sensors deployed on Spencer Island by WDFW

Mean daily higher high tides (MHHW) in the March through June time period at the south end of the site at the south cross dike station (representative of Steamboat Slough) averaged 11.03 feet. At the north end of Spencer Island MHHW averaged 10.6 feet in the same period. MHHW at the site are about 0.2 to 0.5 ft higher at Union Slough and 1.5 to 2 feet higher at the South end of the island at the south cross dike (which is directly connected to Steamboat Slough). Mean daily lower low water (MLLW) elevations recorded by the gages are higher than at Seattle by as much as 5 feet due to fresh water in the sloughs that maintains a higher base level at the site. At Union Slough the gage was not less than 0.5-ft NAVD 88. These averages are in the range of surveyed OHW indicators on the south end of the island. Tides at Seattle during this period were close to long term means (MHHW = 9.2 feet, MLLW = -2.1 feet). Note that anomalies were present in the Steamboat slough breach channel gage, so those data were excluded from the above plot. Sensor drift issues with data after July (after sensors were pulled for download and reinstalled) confound some of the datum calculations so these were excluded.

The City of Everett and their contractor collected 6-minute water level data at three locations along the primary tidal channel constructed at the Smith Island advanced mitigation site, that is located directly west of the north end of Spencer Island and immediately south of the County Smith Island project (Figure 18). Data provided were collected between 22 May and 6 July 2023. Data are shown in Figure 19.

Figure 18. Continuous water sensors deployed on Smith Island by City of Everett at the Advance Mitigation Site

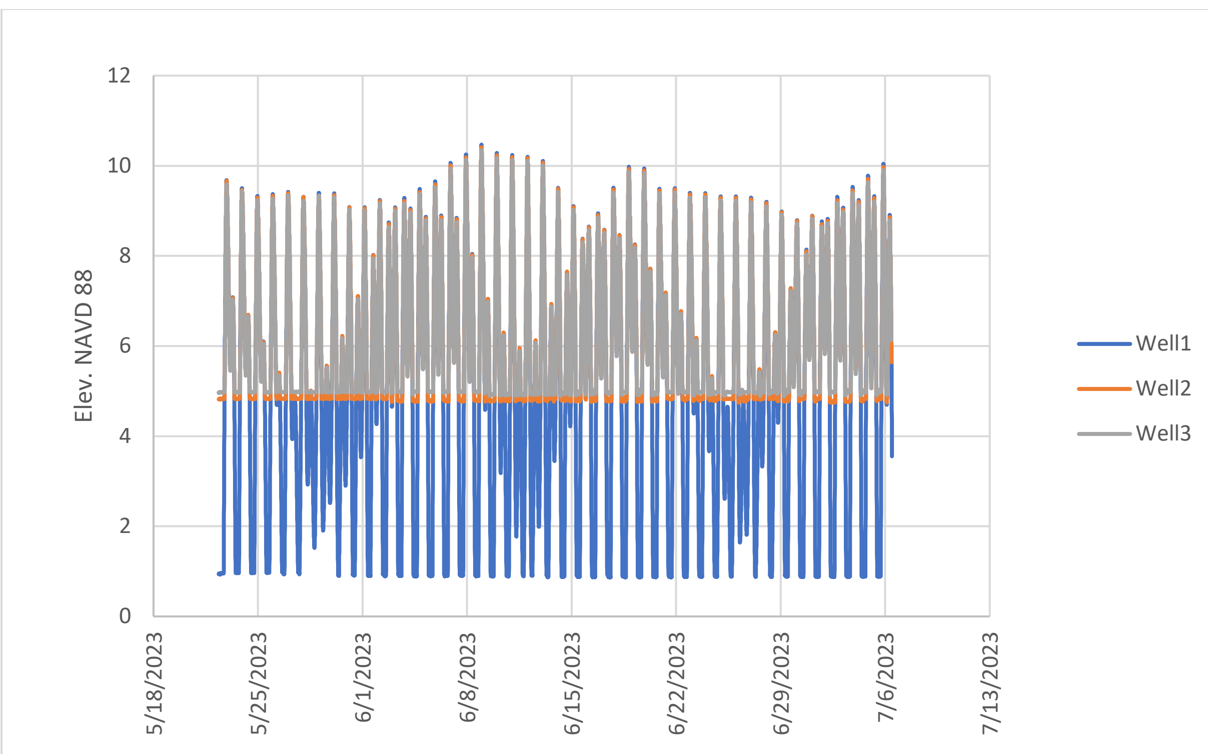


Figure 19. Union Slough Advance Mitigation Site tide measurements May through June 2023

For the period of data provided by the city to the Corps the highest tide recorded at the Advance Mitigation Site was located at the downstream tidal channel Well_1 and occurred on June 8, 2023. The tide reached a maximum of 10.46 feet which was nearly equal to the 10.47 feet recorded at the Union breach station across the river at Spencer Island established by WDFW for the same date. Tides at this site did not drop lower than elevation 0.9 feet, similar to the WDFW Union breach (bottoms out at 0.6 feet).

Since 2013 several water level (depth), conductivity, and temperature sensors (CTD) have been deployed throughout the Snohomish estuary to support monitoring and restoration efforts (Figure 21) by NOAA-NMFS and the Tulalip Tribes. Cramer Fish sciences compiled available data for 24 sites, which was provided to the Corps in July 2023. This data did not extend to the selected validation periods and was not used. WDFW set stage probes throughout the Spencer Island area, however problems with sedimentation inside the probes make it difficult to use for model validation. If this data is cleaned up, it can be applied to future validation.

Snohomish County manages two gages along the study area: Ebey Slough above Highway 2, and Snohomish River at French Slough. The USGS manages two more gages along the Snohomish: Snohomish River at Snohomish, and Snohomish River Near Monroe. These gages are updated in real time and data can be accessed on the internet. These sources were used for model validation (details in section 5.1). Figure 20 shows the gage locations of these four sites.

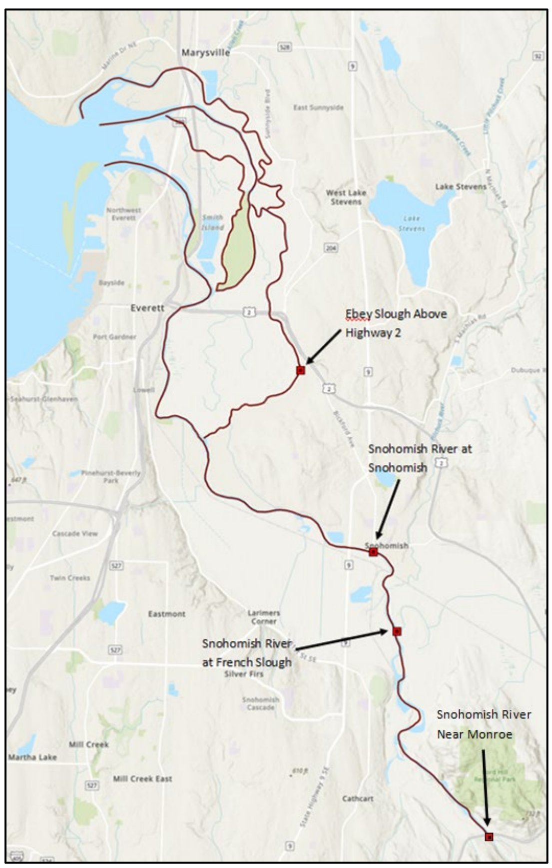


Figure 20. Snohomish County and USGS real time stream gages

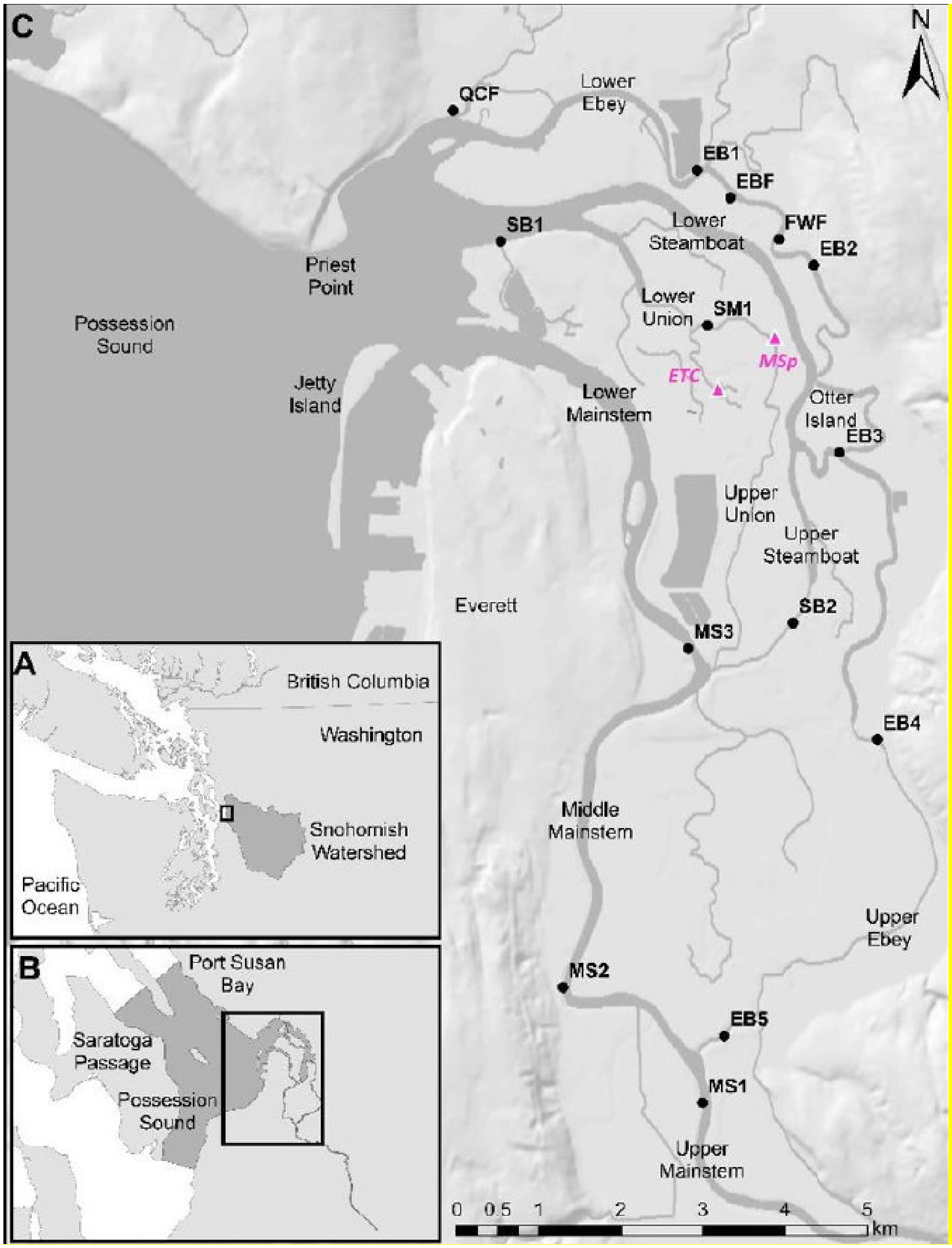


Figure 21. Continuous Water Sensors Network in the Snohomish Delta, Snohomish County sites are labeled ETC (East Tidal Chanel) and MSp(Union Slough at mid-Spencer)

4. Relevant Previous Investigations and Data

4.1. 2001 FEMA flood insurance study

The Corps and WEST Consultants refined previous flood frequency estimates for the mainstem Snohomish River in 1999-2001 as part of the Flood Insurance Study revision work for FEMA. The USACE UNET unsteady flow hydraulic modeling utilized flood frequency statistics for both the volumetric runoff and peak discharge (balanced hydrograph method). Table 11 below provides a summary of the upstream boundary conditions inflow data. Note that the peak flow statistics are strongly influenced by estimates for historical floods at Snohomish using data from upstream gages routed to the site using numerical methods as well as correlation with gages outside the basin. Refer to the Seattle District project files for details of the methods and estimates.

Table 11. Flood frequencies for peak, 1, 3, 5, and 7-day events.

Recurrence Interval (years)	10	20	50	100	500
Exceedance Probability (%)	10%	5%	2%	1%	0.2%
Peak Values for Period of Record (cfs)	100000	115000	135000	150000	189000
Peak Values with Historic Events (cfs)	114000	137000	173000	204000	293000
Scaling Ratio	1.14	1.19	1.28	1.36	1.55
1-Day Average Daily Flow (cfs)	92100	107000	128000	145000	190000
1-Day Average Daily Flow (Scaled) (cfs)	104994	127470	164030	197200	294500
3-Day Average Daily Flow (cfs)	78900	91600	109000	123000	158000
5-Day Average Daily Flow (cfs)	64700	74700	88300	99100	126000
7-Day Average Daily Flow (cfs)	55700	63500	73800	81700	101000

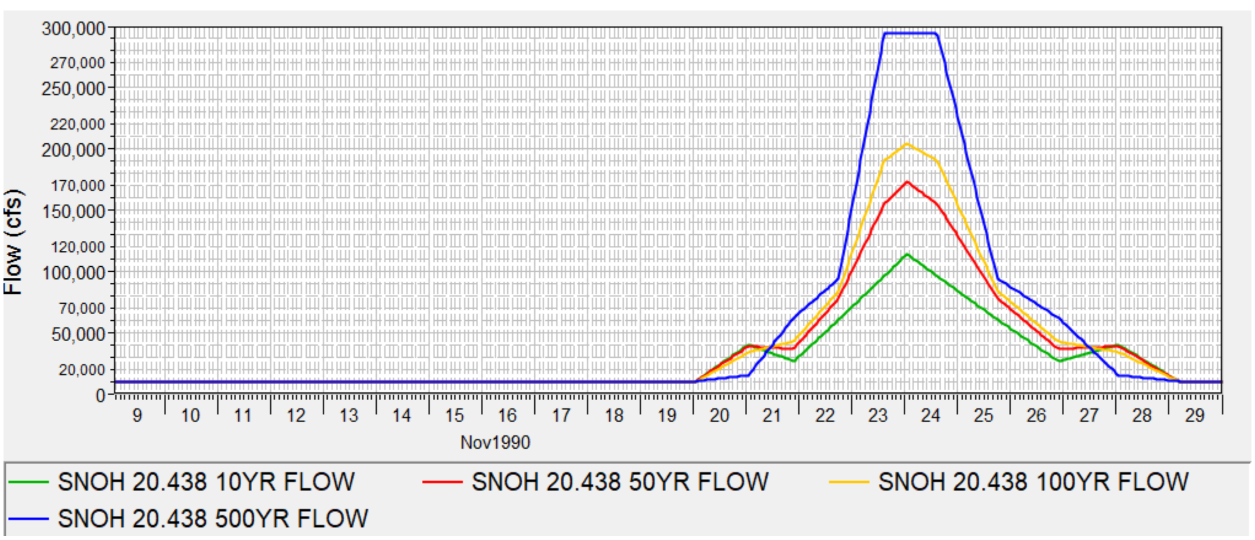


Figure 22. UNET model balanced inflow hydrographs at Monroe gage

The event hydrographs were routed through from the Monroe gage downstream along the approximately 20.5 mile long 1-dimensional reach. The model has lateral weirs along dikes connected to overbank floodplain areas to model flood wave attenuation. The model has interconnected 1-d reaches along all the distributary channels (sloughs) which are also connected to floodplain storage areas. The model includes a constant high tide equal to the MHHW elevation plus 1-foot. The model schematic is shown below in Figure 23.

The FEMA FIS UNET model DSS file was queried to show how event maximum discharge varies between the upstream and downstream ands of each reach. Peak flows are summarized below in Table X. From inspection, the dike system and extensive floodplain of the Snohomish have a significant influence on the peak discharge as flood waves travel downstream. The upstream end of the mainstem has a peak 1% AEP inflow of 204,000 cfs, however by the time the flood wave reaches Spencer Island, the total flow in the river measured at the midpoint of Spencer Island (mainstem and all sloughs) has dropped to 133,180 cfs. Note that the model predicts only 18,900 cfs would flow down Steamboat and Union Sloughs past the upstream (south) end of Spencer Island, however the flow in the sloughs more than doubles (to 40,300 cfs) at the north end of the Island due to floodwaters passing from the Ebey Island storage area into Steamboat Slough.

Spencer Island was modeled as a single 1-dimensional storage area (Figure X). In 1999 when the model was developed the project area was completely ringed with dikes. The crest of the dike controls the amount of overflow into and out of the storage area. Now that the dike is breached in at least two locations it is the storage area connection is outdated, and it is possible that the modeled stage hydrograph could be impacted, however the island has not experienced major changes to topography that are likely to alter the results. A project no-rise analysis will be conducted in PED to verify this assumption.

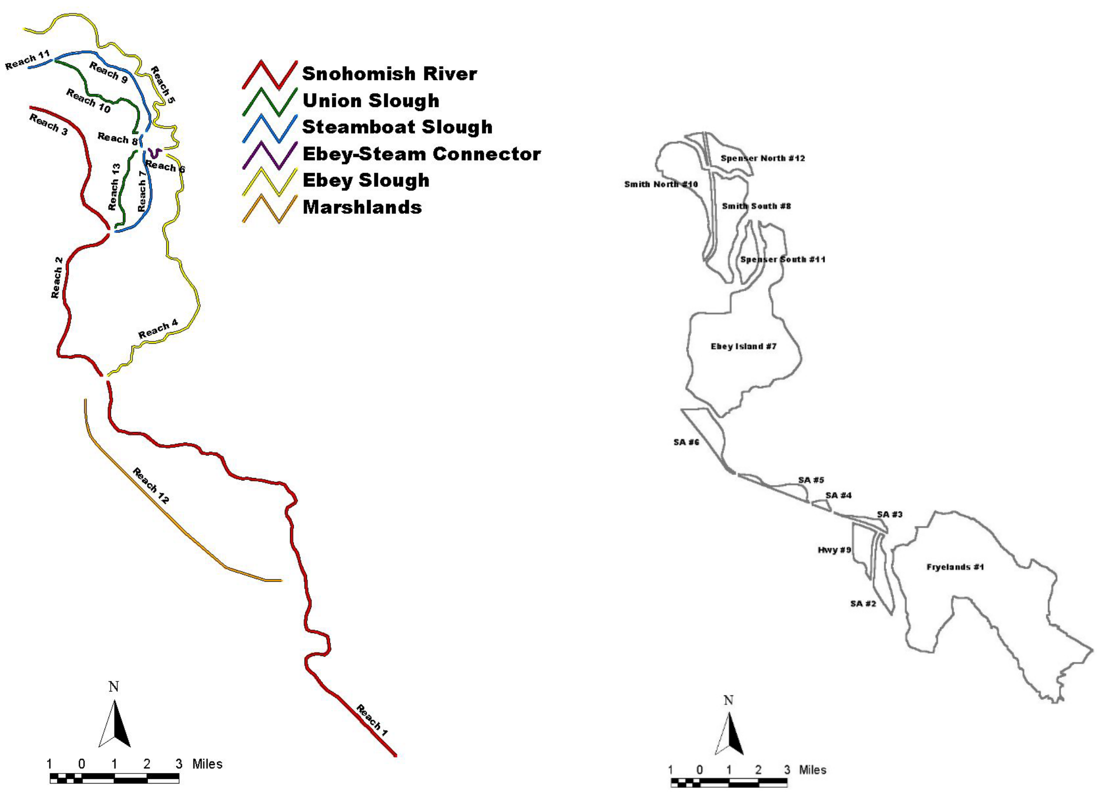


Figure 23. UNET model reaches and storage areas (WEST 2001)

Note that the 64-bit versions of Windows (Windows 10, etc.) are not able to run native UNET models and HEC no longer maintains support for UNET. HEC recommends migration of UNET models to HEC-RAS. FEMA still allows use of UNET but notes that it cannot be used for floodway determination and that it can result in large differences in computed stages relative to other software around bridges and culverts. UNET is not georeferenced and has no inundation mapping capability. As part of the Qwulloolt restoration project on Ebey Slough, USACE conducted a no-rise analysis with the UNET model to analyze the effects of a proposed dike setback. For practical reasons, a no-rise analysis for Spencer Island should plan to utilize a HEC-RAS model based on the effective UNET model. Work completed recently by WEST consultants for Snohomish County (see next section) will facilitate that analysis.

Table 12. 2001 FEMA FIS UNET model reach and Spencer Island peak flow summary for the 0.1, 0.02, 0.01 and 0.002 AEP events

Modeling reach	RM/AEP	Q10 peak (cfs)	Q50 peak (cfs)	Q100 peak (cfs)	Q500 peak (cfs)
		0.1	0.02	0.01	0.002
Reach 1 mainstem US	20.5	113,998	172,933	203,998	294,500
Reach 1 mainstem DS	8.2	107,048	127,869	153,178	224,588
Reach 2 mainstem US	8.2	67,517	79,633	68,711	90,434
Reach 2 mainstem DS	3.8	63,576	76,932	81,954	85,740
Reach 3 mainstem US	3.8	51,604	78,866	89,110	108,567
Reach 3 mainstem DS	0.5	50,441	74,241	89,109	119,784
Reach 4 Ebey Slough US	13.2	39,533	72,489	84,470	134,159
Reach 4 Ebey Slough DS	6.8	28,710	35,490	41,337	73,997
Reach 5 Ebey Slough US	6.8	7,055	14,512	23,814	49,311
Reach 5 Ebey Slough DS	0.5	6,100	10,734	13,704	27,823
Reach 7 Steamboat Slough US	6.25	8,823	9,270	12,819	13,020
Reach 7 Steamboat Slough DS	4.05	9,539	24,406	35,584	51,891
Reach 8 SS-US Connector US	4.04	35,474	55,442	74,875	106,264
Reach 8 SS-US Connector DS	3.76	34,657	52,559	65,500	82,395
Reach 9 Steamboat Slough US	3.75	27,796	44,393	49,690	54,068
Reach 9 Steamboat Slough DS	0.8	28,841	47,578	71,234	91,252
Reach 11 Steamboat Slough US	0.8	35,708	66,287	96,215	119,469
Reach 11 Steamboat Slough DS	0.17	36,404	74,835	101,343	158,220
Reach 13 Union Slough US	4.65	3,156	5,540	6,108	20,019
Reach 13 Union Slough DS	3	3,152	3,401	4,698	4,720
Reach 10 Union Slough US	2.7	6,865	10,526	15,902	28,348
Reach 10 Union Slough DS	0	6,867	18,721	24,983	28,849
Spencer Island US end	**SS 6.25, US 4.65**	**11,979**	**14,810**	**18,927**	**33,039**
Spencer Island DS end	**SS 4.05, US 3.0**	**12,691**	**27,807**	**40,282**	**56,611**
Total system flow Spencer	**S 3, US 4, SS 5, ES 8**	**89,787**	**116,825**	**133,180**	**163,589**

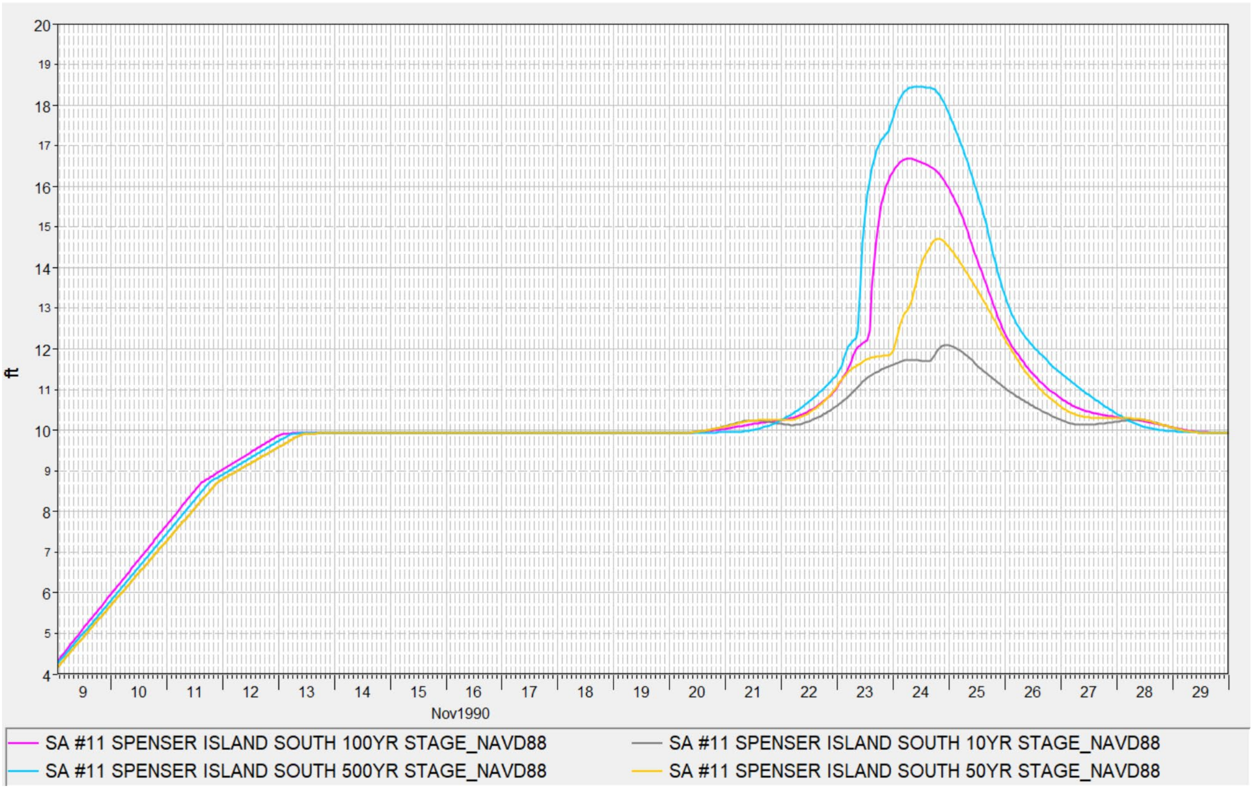


Figure 24. UNET computed stages (NAVD 88) for Spencer Island South storage area #11

4.2. 2012-2016 Smith Island Ecosystem Restoration Project

As part of the adjacent Smith Island ecosystem restoration project Snohomish County and WEST Consultants and Otak, Inc. migrated the UNET model to HEC-RAS unsteady to model the effects of the proposed dike setback and restoration project. This part of the floodplain is administered by the City of Everett. Note that the City of Everett Corporate Boundary extends to the centerline of Union Slough, but the southwest corner of the Smith Island project overlaps with City lands. The Corps and City of Everett constructed ecosystem restoration project at Union Slough adjacent to the Smith Island project and Spencer Island in the mid-2000s Both of these sites were modeled previously as a single storage area (#8). Cross dikes are present within this storage area that affect conveyance. WEST consultants completed the model revisions. A geo-referenced HEC-RAS unsteady flow model was built from the UNET model. This model was updated using new survey data (corrected effective). The final determination letter was received in 2016 from FEMA (FEMA, 2016). The restoration project was constructed by Snohomish County and completed by 2018. As shown below the model revisions resulted in lowering and increasing BFEs by 0.7 feet upstream of I-5.

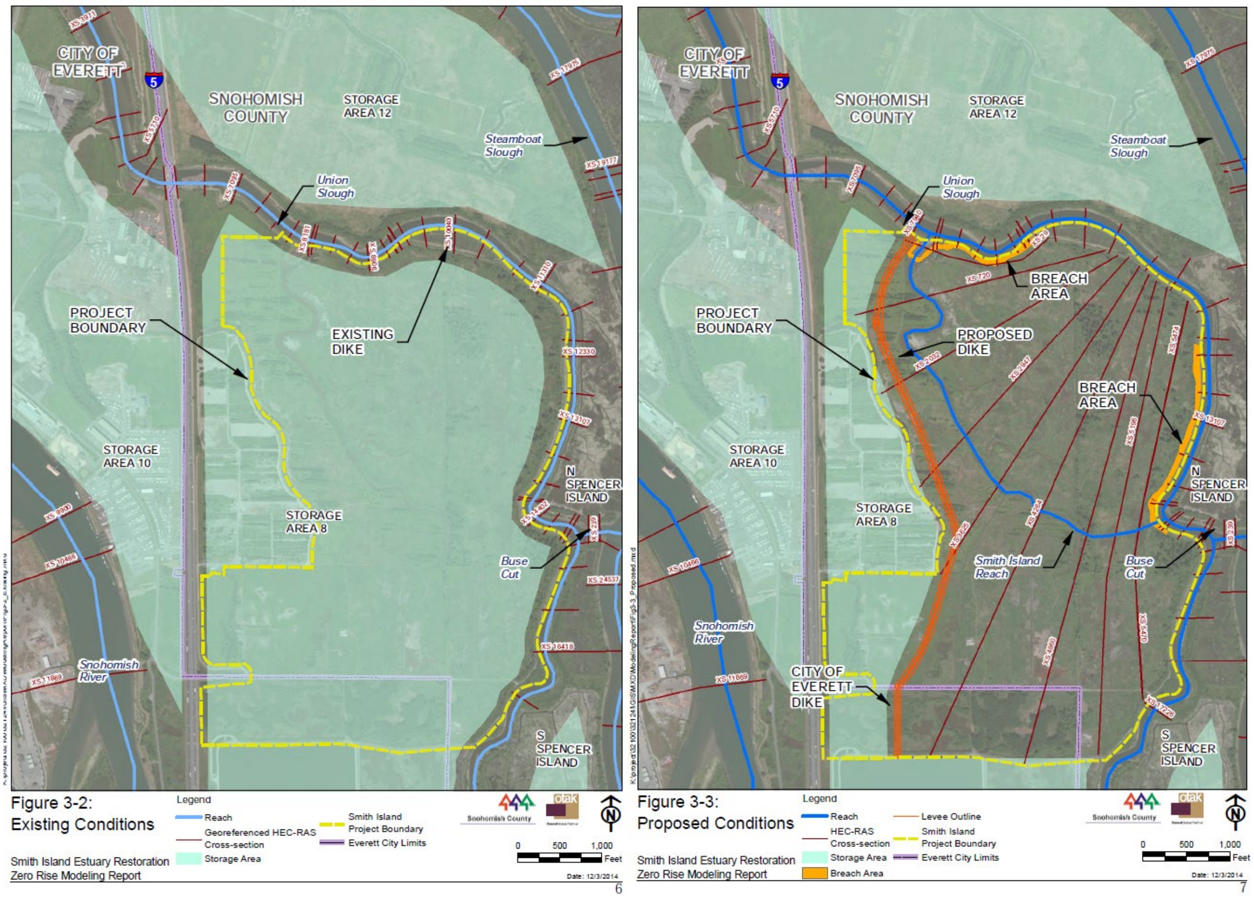


Figure 25. Smith Island restoration project CLOMR HEC-RAS model adjustments

Otak reports modeling result for changes from existing conditions resulting from the Smith Island project as follows:

> The project conditions' decreases in peak water-surface elevations over the upper portion of the reach adjacent to Smith Island are due to the dike breaches that allow more water to flow freely across Smith Island, thus effectively increasing the total conveyance capacity of the reach (Union Slough between overbank dikes and Smith Island). <u>The maximum decrease in water-surface elevation is about 0.5 feet with the decreases extending about 2,600 feet upstream of the Buse Cut located near the upstream end of Smith Island project boundary [emphasis added]</u>. Despite the increased flows across the island, peak water-surface elevations under the project conditions are reduced by about 0.4 to 0.5 feet (Figure 4-2) compared with that under the existing conditions. The breaches in the dike allow water to flow more freely across the area opened east of the dike setback with less backwater and ponding which used to be caused by the existing higher dike profile.
>
> The local increase in project conditions' water-surface elevation just upstream of the East Tidal Channel outlet is about 0.7 feet, with the increase extending about 1,300 feet upstream of the outlet. This local jump in the water-surface elevation appears to be the result of a jump in the discharge resulting from the return flow from the island. As noted above, the dike breaches allow significantly more water to flow freely across Smith Island, with a majority of this flow returning to Union Slough through the low notch created at the East

Tidal Channel outlet (see Figure 4-1). This large increase in flow along Union Slough, from just upstream to just downstream of the dike breach, results in a large value for the convective acceleration term in the momentum equation in the one-dimensional HEC-RAS numerical solution schemes that must be balanced by an increase in the water-surface and/or energy grade slope. The increase in water surface elevation is compensated by the loss of energy across the location of the return flow and caused the increase in the upstream water surface elevation. This is a localized result with the large increases only affecting water-surface elevations along Union Slough near the East Tidal Channel outlet; changes elsewhere are minor and less influenced by the proposed dike setback project in the Smith Island (see discussion below). In Figure 4-3, the water-surface elevations under existing and project condition are shown in comparison with the Base Flood Elevations (BFE) from the FEMA Digital Flood Insurance Rate Maps (DFIRM) near the East Tidal Channel outlet.

At all other locations in the modeled area changes in peak water-surface elevations are very minor. Along Ebey Slough changes range from zero to a 0.03 ft decrease under project conditions. Along the Snohomish River changes under project conditions are less than 0.01 ft., ranging from -0.007 ft. to +0.007 ft. Changes in maximum water-surface elevation are all negative along Steamboat Slough, ranging from -0.001 ft. to -0.046 ft. Changes in maximum water-surface elevations in the storage areas are all zero or negative except for SA12 that shows a small increase of 0.0069 ft. SA 12 [Spencer Island] represents the area between Union Slough and Steamboat Slough just north of Smith Island and the small increase here is related to the local increase along Union Slough at the East Channel outlet.

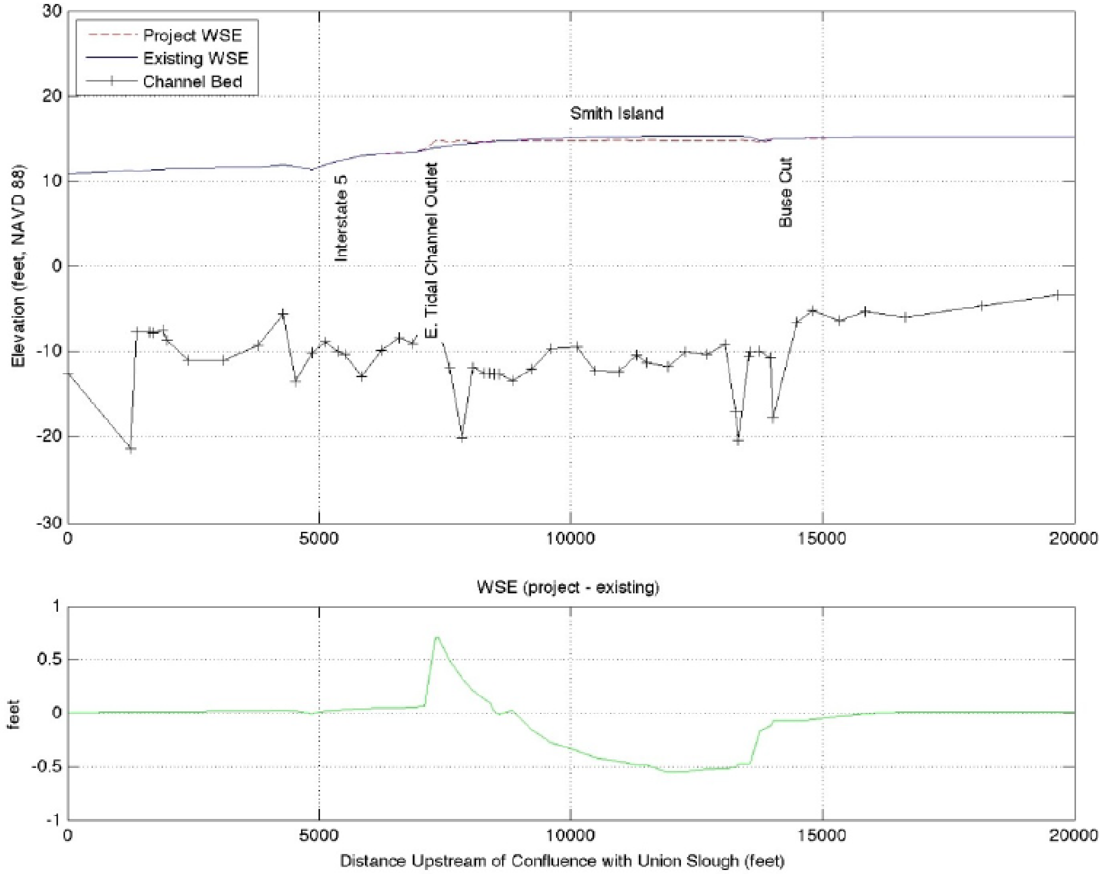


Figure 4-1. Comparison of existing and project conditions computed maximum water-surface profiles along Union Slough.

Figure 26. Modeled WSE changes at Union Slough from CLOMR study

Table 13. BFE comparison table from FEMA 2016 CLOMR

BFE Comparison Table			
Flooding Source: Union Slough		BFE Change (feet)	Location of Maximum Change
Existing vs. Effective	Maximum increase	0.0	N/A
	Maximum decrease	0.7	Approximately 860 feet upstream of Interstate 5
Proposed vs. Existing	Maximum increase	0.7	Approximately 1,990 feet upstream of Interstate 5
	Maximum decrease	0.0	N/A
Proposed vs. Effective	Maximum increase	0.7	Approximately 1,990 feet upstream of Interstate 5
	Maximum decrease	0.7	Approximately 1,220 feet upstream of Interstate 5

In the CLOMR M2 form (request to FEMA to modify the effective flood insurance rate maps), Snohomish County notes the following that are directly relevant to Spencer Island:

> Construction of the new setback dike (dike) will result in floodplain fill with a significant portion of this fill located in the Density Fringe. Development in the Density Fringe is governed by Snohomish County Code (SCC), Chapter 30.65 “Special Flood Hazard Areas”, in sections 30.65.240 through

> 30.65.285. It is managed by the Department of Planning & Development Services (PDS), which is the County Department that is responsible for requesting this CLOMR Application as part of their Flood Hazard permit conditions. The Density Fringe is managed to a 1-foot cumulative rise standard (SCC 30.65.240). SCC 30.65 is attached to this application. [emphasis added]
> The new setback dike is not intended to provide 100-year protection but rather is designed to U. S. Army Corps of Engineers (USACE) standards to provide 10-year protection, plus 2.0 feet of freeboard, and to qualify for the USACE PL84-99 maintenance program.

The above implies that any changes resulting from restoration at Spencer Island would be handled in the same manner as those resulting from the larger Smith Island project.

4.3. Effective FEMA Flood Insurance Study

The current effective FEMA flood insurance rate (FEMA, 2023) show that Spencer Island is located entirely within the FEMA AE flood zone, with a mapped floodway that spans the entirety of both Union Slough and Steamboat Slough (between the dikes). Base Flood Elevations for the 100-year flood event are shown on the map, as water surface profiles (Figure 28-Figure 30), and summarized in Table 14 and Table 15. The entirety of island landward of the existing dikes is mapped as a Density Fringe area. Density fringe areas are areas where not more than 2% of the land area can be developed in a manner that displaces floodwaters (Snohomish County Code (SCC) section 30.65.240) and the width of new construction cannot exceed more than 15% of the width of flow through the property or fringe area, whichever is less (SCC 30.65.255). WEST consultants noted in their model files that the 15% reduction was applied when computing the encroached water surface elevations shown in the FIS floodway tables.

Construction within the floodway is generally limited to only those actions that are necessary for public works, provided that the modifications do not worsen flooding (no-rise). In Snohomish County public works such as water dependent utilities and dikes shall not cause a cumulative increase in the base flood elevation of more than 1 foot (SCC 30.65.260). Restoration actions at Spencer will primarily remove fill from the existing dikes/dikes, increasing conveyance in the floodway. Some of these materials will be placed within the density fringe zone, but below an elevation that would restrict the passage of floodwaters. The work would likely be classified as a permitted use per SCC 30.65.280 (3) preserves and reservations, (4) parks and recreational activities, (7) water dependent utilities. SSC 30.65.285 (3) specifically mentions filling of marshlands as prohibited uses. Clarification may be necessary to determine if placement of spoils next to constructed channels is prohibited. Since this has been done at nearby restoration sites the presumption is that it is not prohibited.

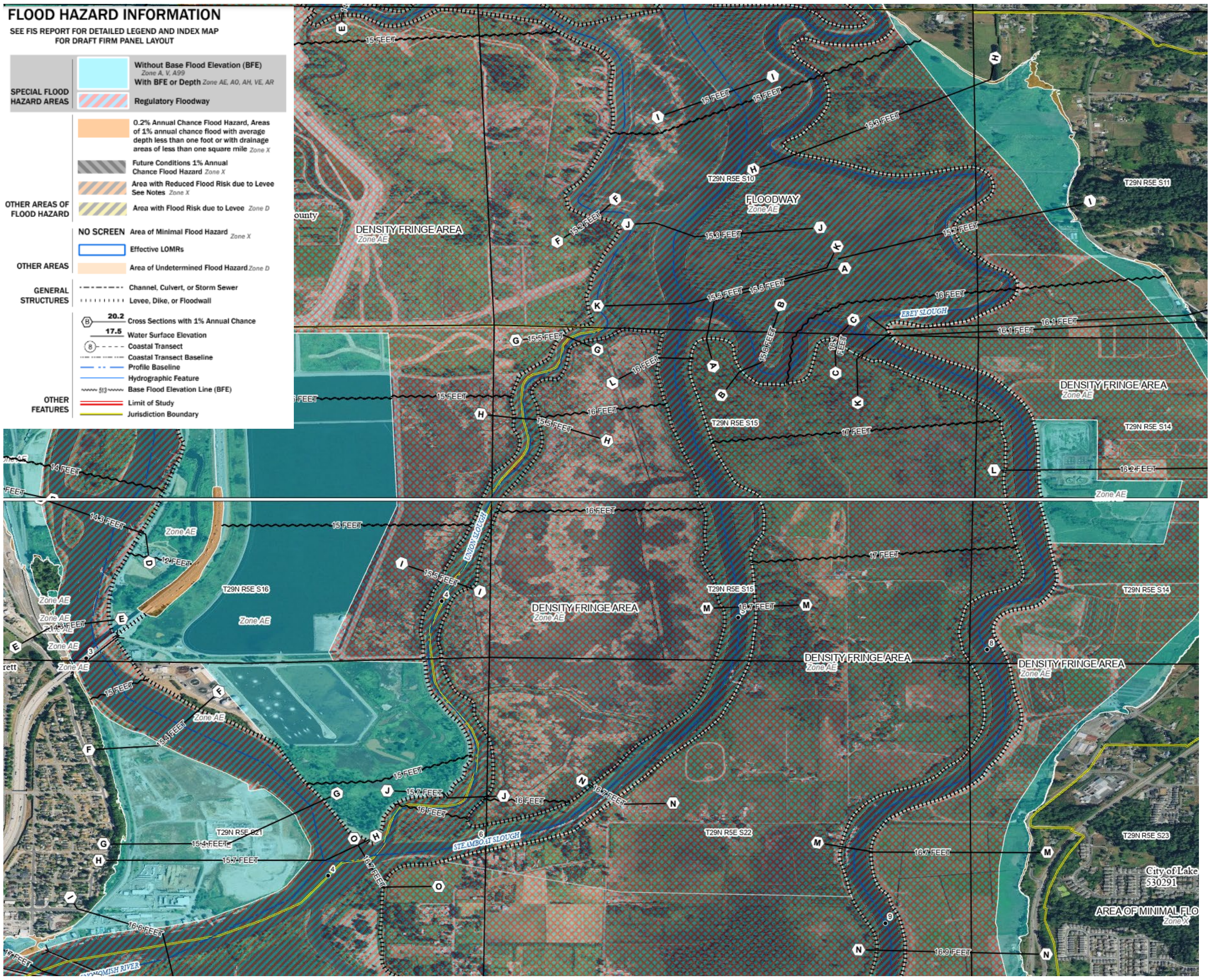


Figure 27. Effective FEMA Flood Insurance Rate Maps (FEMA Flood Hazard Viewer, 2023)

Note that the reported BFEs in the AE zone and on the cross section cut lines reflect the inclusion of a density fringe area (partially blocked storage area). Note in the floodway tables that the lower two miles of Steamboat Slough and lower mile of Union Slough are controlled by flooding from Puget Sound. The published flood elevations are higher along Steamboat Slough than Spencer Island, and higher in Spencer Island than Union Slough. There is about 1.5 feet of fall in the water surface profile along Steamboat Slough and about a half a foot along Union Slough. The FEMA UNET model, while outdated, appears to capture the macro scale differences is water levels between the various sloughs and islands. The BFE for Spencer Island is lower than the 2001 UNET computed WSE by about 0.7 feet, the reason for the discrepancy is not apparent, but could be related to updated hydrology or floodway assumptions.

The FEMA floodway tables show that there is an allowance for 0.5 to 0.6 feet of rise to account for the floodway fringe becoming fully developed subject to the density fringe requirements. In this analysis 15% of the area outside of the floodway boundary is assumed to become developed (block flowing water). Given that two large scale restoration projects have been completed along Union Slough, and Spencer Island is forthcoming, the density fringe areas and floodways could arguably be reanalyzed since new development will be prohibited in these areas in perpetuity (they could be converted to floodway or the development potential / conveyance / storage reduction reduced to 0%). This would have the effect of lowering the published base flood elevations along Union Slough, Steamboat Slough and possibly along the mainstem and Ebey Island.

Discussion and coordination with Snohomish County and FEMA (and likely the city of Everett) will need to be factored into the project schedules especially if map revisions are requested.

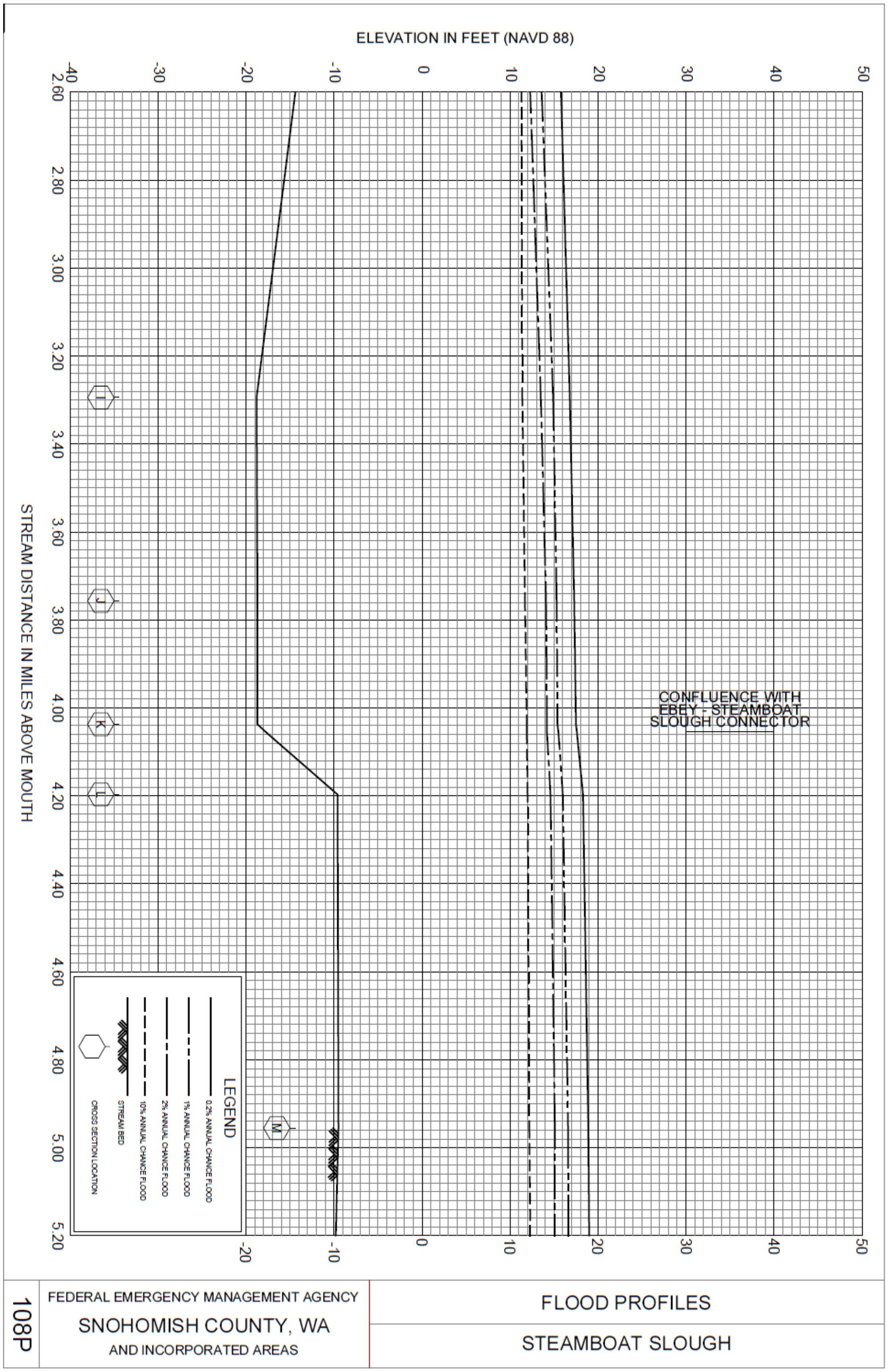


Figure 28. Steamboat Slough flood profiles from effective FEMA FIS (1 of 2)

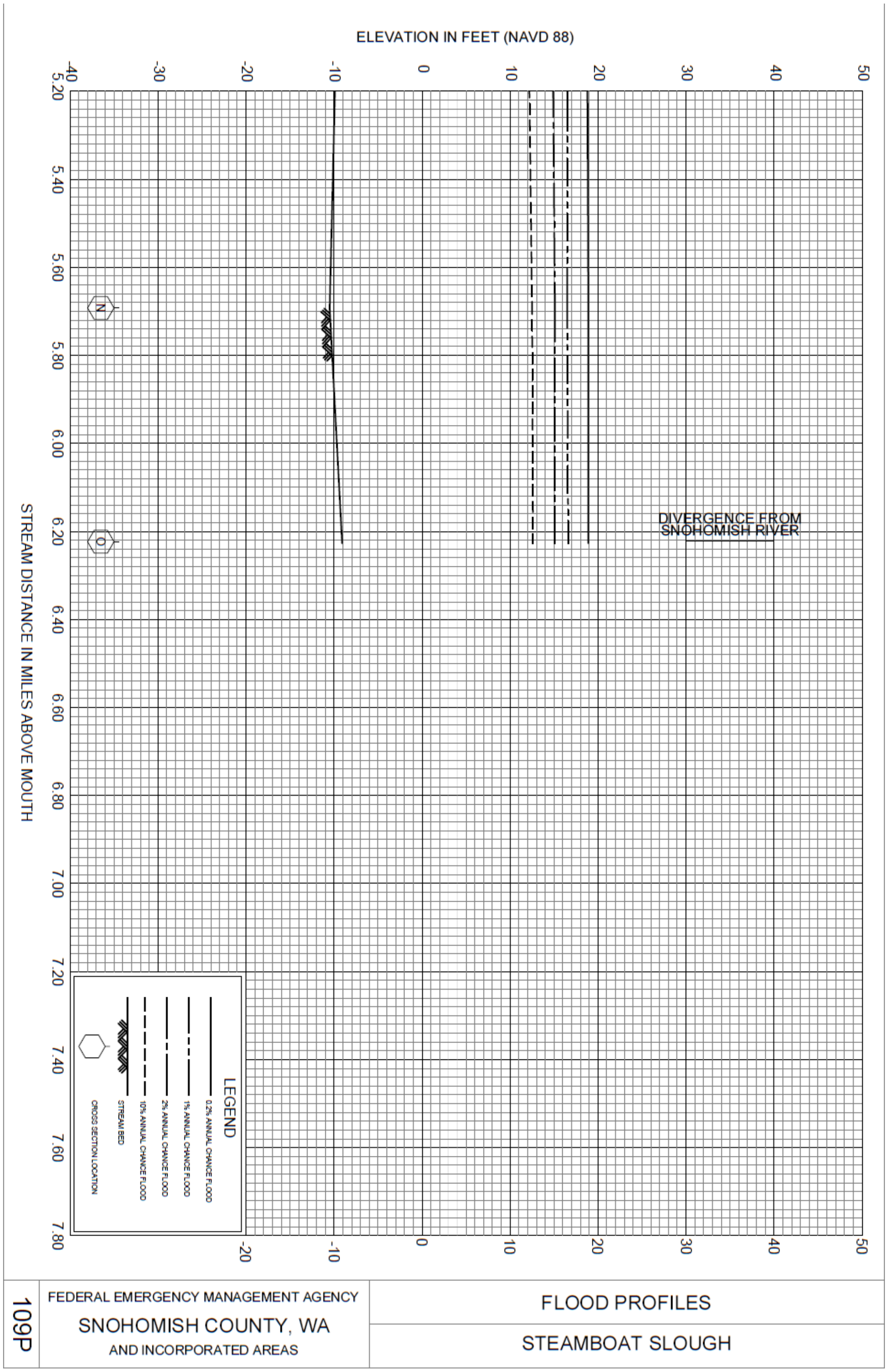


Figure 29. Steamboat Slough flood profiles from effective FEMA FIS (2 of 2)

LOCATION		FLOODWAY			1% ANNUAL CHANCE FLOOD WATER SURFACE ELEVATION (FEET NAVD88)			
CROSS SECTION	DISTANCE[1]	WIDTH (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET PER SECOND)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
A	0.16	2,917	30,510	3.9	*	9.9[2]	9.9[2]	0.0
B	0.80	1,353	21,730	4.7	*	10.9[2]	10.9[2]	0.0
C	1.12	2,889	17,842	4.4	*	11.6[2]	11.9[2]	0.3
D	1.49	1,368	19,526	5.3	*	12.0[2]	12.3[2]	0.3
E	1.62	596	12,265	5.9	*	12.1[2]	12.6[2]	0.5
F	1.72	626	12,730	5.1	*	12.4[2]	12.9[2]	0.5
G	2.15	1,309	17,342	4.8	13.1	13.1	13.8	0.7
H	2.60	1,148	13,451	5.6	13.8	13.8	14.5	0.7
I	3.30	1,150	16,315	4.5	15.0	15.0	15.5	0.5
J	3.76	2,145	22,823	4.5	15.3	15.3	15.9	0.6
K	4.04	2,772	26,253	4.9	15.5	15.5	16.1	0.6
L	4.20	350	6,490	3.5	16.0	16.0	16.6	0.6
M	4.96	349	5,844	2.9	16.7	16.7	17.2	0.5
N	5.70	240	4,566	3.4	16.7	16.7	17.2	0.5
O	6.23	742	10,093	1.6	16.7	16.7	17.2	0.5

[1]STREAM DISTANCE IN MILES ABOVE MOUTH

[2]ELEVATION COMPUTED WITHOUT CONSIDERATION OF BACKWATER FROM PUGET SOUND

*CONTROLLED BY COASTAL FLOODING – SEE FIRM FOR REGULATORY BASE FLOOD ELEVATION

TABLE 25	FEDERAL EMERGENCY MANAGEMENT AGENCY **SNOHOMISH COUNTY, WASHINGTON** AND INCORPORATED AREAS	**DENSITY FRINGE AREA DATA** **FLOODING SOURCE: STEAMBOAT SLOUGH**

Table 14. FEMA FIS floodway table for Steamboat Slough, extents of Spencer Island highlighted

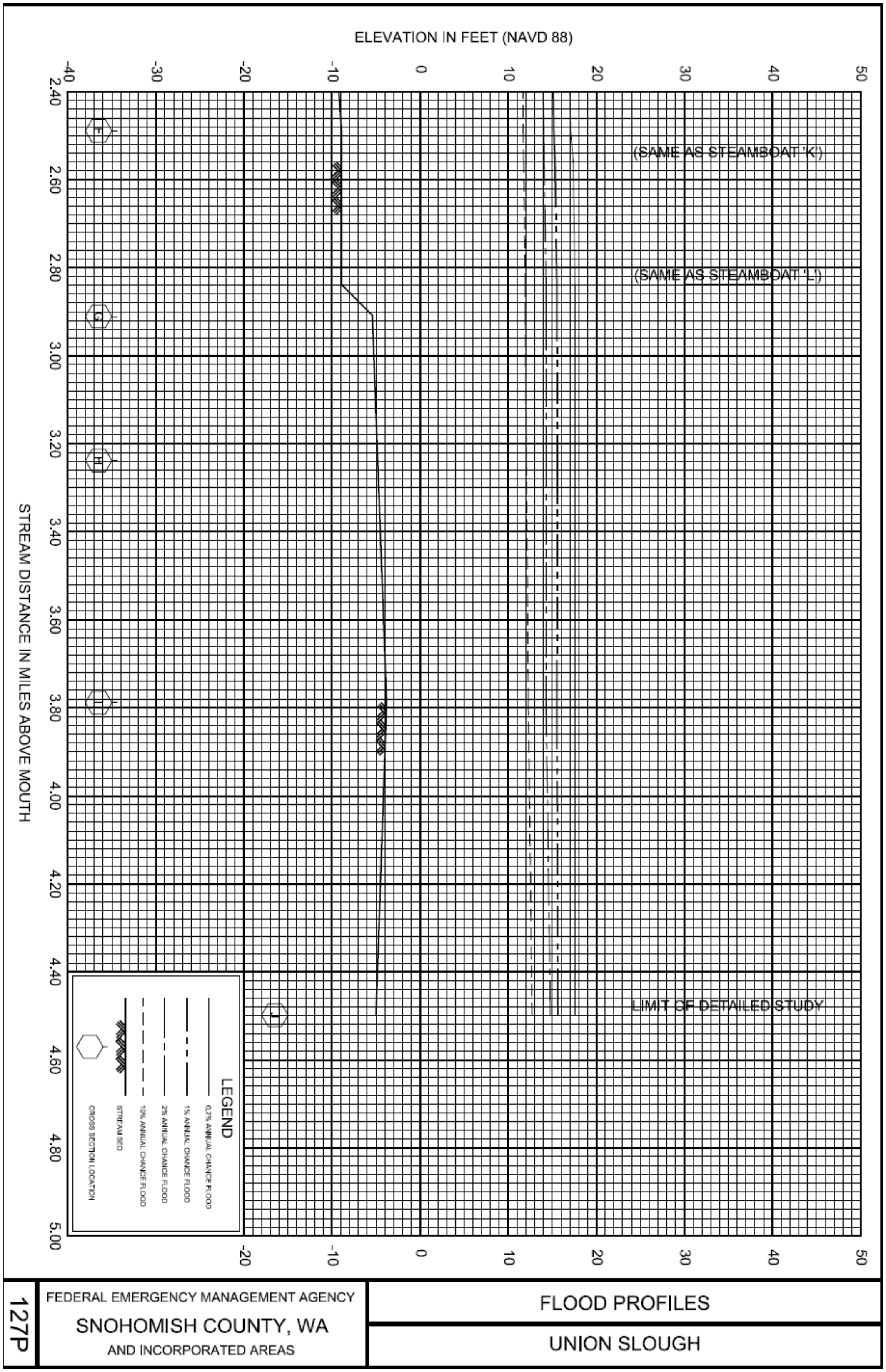


Figure 30. Union Slough flood profiles from effective FEMA FIS

LOCATION		FLOODWAY			1% ANNUAL CHANCE FLOOD WATER SURFACE ELEVATION (FEET NAVD88)			
CROSS SECTION	DISTANCE[1]	WIDTH[2] (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET PER SECOND)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
A	0.17	610	7,084	3.6	*	10.9[3]	10.9[3]	0.0
B	0.23	505	4,798	5.3	*	11.5[3]	11.6[3]	0.1
C	0.88	278	4,356	5.8	*	12.5[3]	13.2[3]	0.7
D	1.08	382	4,948	3.8	13.8	13.8	14.8	1.0
E	1.35	207	3,281	4.9	14.4	14.4	15.0	0.6
F	2.49	309	4,189	4.5	15.2	15.2	15.7	0.5
G	2.91	260	3,250	2.1	15.5	15.5	16.1	0.6
H	3.24	259	3,086	2.1	15.5	15.5	16.1	0.6
I	3.79	272	2,925	2.7	15.5	15.5	16.1	0.6
J	4.50	364	3,413	2.2	15.7	15.7	16.3	0.6

[1]STREAM DISTANCE IN MILES ABOVE MOUTH
[2] WIDTHS TAKE INTO ACCOUNT FLOODWAY FRINGE AND DENSITY FRINGE
[3]ELEVATION COMPUTED WITHOUT CONSIDERATION OF BACKWATER FROM PUGET SOUND
*CONTROLLED BY COASTAL FLOODING – SEE FIRM FOR REGULATORY BASE FLOOD ELEVATION

TABLE 25 — FEDERAL EMERGENCY MANAGEMENT AGENCY
SNOHOMISH COUNTY, WASHINGTON
AND INCORPORATED AREAS

DENSITY FRINGE AREA DATA

FLOODING SOURCE: UNION SLOUGH

Table 15. FEMA FIS floodway table for Union Slough, extents of Spencer Island highlighted

4.4. 2021 Watershed Science and Engineering Study

In 2021 Snohomish County retained Watershed Science and Engineering (WSE) to update existing floodplain modeling with modern channel and floodplain topographic data using the 2D version of HEC-RAS to:

> *"…characterize current floodplain hydraulic conditions in the Snohomish River watershed and assess the projected impacts of climate change on flood depths and inundation extents along the Skykomish, Snoqualmie, and Snohomish rivers. The study area included the Skykomish River as far upstream as Gold Bar, the Snoqualmie River as far upstream as the King-Snohomish County Line, and the entire length of the Snohomish River from near Monroe to Possession Sound.*
>
> *Hydrologic and hydraulic analyses were conducted to characterize floodplain conditions within the study area for historical, mid-century (2040-2069), and late-century (2070-2099) time periods. USGS streamflow records were used to perform flow frequency analyses and create balanced hydrographs representing historical hydrologic conditions. Climate scalars were developed from hydrologic modeling of climate projections and used to scale the historical balanced hydrographs to represent floodplain hydraulic conditions for each of the two future time periods.*

A detailed two-dimensional HEC-RAS hydraulic model was developed, calibrated, and applied to evaluate river-related flooding throughout the study area, with a particular focus on the Skykomish and Snohomish Rivers. The model was configured to directly use observed streamflow data as its hydrologic inputs, allowing users to simulate any flood event in the historical record. The model's computational mesh contained approximately 330,900 cells and covered a combined total of approximately 76 river miles and 70,560 acres of floodplain. The calibrated model was run to produce flood depths, velocities, water surface elevations, and inundation extents, for the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood events for historical, mid-century, and late-century time periods.

This model usedHEC-RAS version 5.0.7 and a bathymetric surface based on 2019 single beam sonar data (of the mainstem and slough channels merged with 2019 terrestrial Lidar data. To aid in analysis of the Spencer Island site the WSE HEC-RAS 2D model, which can take more than 24 hours to run depending on the simulation period, was truncated at the Snohomish River Monroe gage, leaving all other boundary conditions downstream of this cutoff the same. The model was then run with either observed or synthetic flows at the Monroe gage depending on the scenario of interest. A small, detailed model of the Spencer Island site and adjacent slough channels was developed that uses the truncated model for boundary conditions. These model boundaries are shown below in Figure 31.

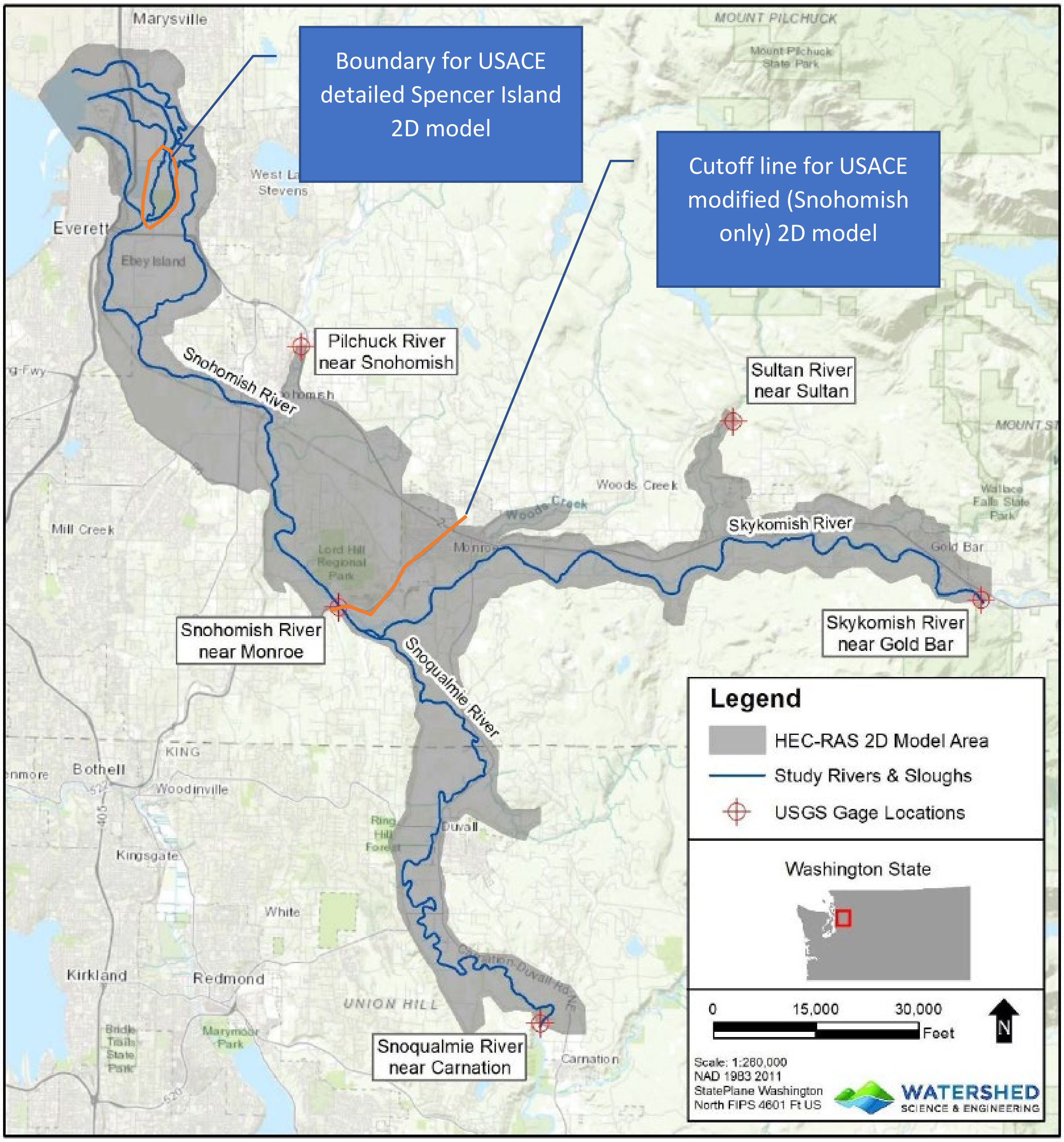


Figure 31. HEC-RAS 2D model extents and stream gage locations

4.5. PSNERP Draft Feasibility Report & EIS Engineering Appendix

USACE Seattle District summarized previous hydraulic studies as part of the original PSNERP feasibility study. Flood flows and elevations are as reported in the FEMA FIS. Impacts of restoration were qualitatively assessed and expected to be minimal but it was recommended that that PED phase activities verify this assumption.

5. Spencer Island Hydraulic Analysis

5.1. Spencer Island 2D Modeling to Support Conceptual Design

The purpose of this 2D HEC-RAS unsteady flow modeling is to compute inundation areas and velocity changes for 8 separate action alternatives and the no action alternative to compute benefits needed to identify a preferred alternative. The model is based on the WSE 2021 model, described previously, truncated to Spencer Island and adjacent sloughs. Boundary conditions (stage-flow time series) were extracted from a Snohomish River only existing conditions 2D model created by USACE run for the same time period (June 2022). The analysis is documented in Annex D4. Refer to the civil design annex for a description of the pertinent features of the conceptual alternatives. The terrain created for the Alternative 8 model was used to develop the grading plan for the selected alternative and is the basis for the 35% design analyzed in the full model and described below.

5.2. Spencer Island 2D Modeling for Feasibility Level H&H Analysis

The purpose of this modeling is to understand on and off-site hydraulic changes and to help inform design phase refinements.

5.2.1. Survey & Terrain data

Several sources were used to build a suitable terrain for our model. This involved multiple surveys, multiple LiDAR sources, and processing using GIS software. LiDAR of the entire Snohomish basin from the Watershed Sciences and Engineering (WSE) model makes up most of the terrain (WSE 2021). The Tulalip Tribe produced rasters of the surrounding sloughs from a multibeam survey (Tulalip Tribes 2020). Inside the Island, survey data was obtained (by USACE) for the bathymetry of some existing channels. Our proposed condition terrain has a modified LiDAR raster that includes proposed changes and disposal areas of the moved material. These sources were all compiled and mosaicked into two rasters (proposed and existing conditions). The cell size for the rasters ranges from about 1.5 to 3. The coordinate reference system is set to NAD83 Washington State Plane North (EPSG 4601) in US feet. The vertical datum is NAVD88.

Terrain modifications were added to both terrains to add dikes and high points throughout the study area. This data came from the National Dike Database (NLD). See Figure 32 for the full terrain. See Figure 33 for the modified proposed conditions LiDAR and the multibeam survey around the Sloughs.

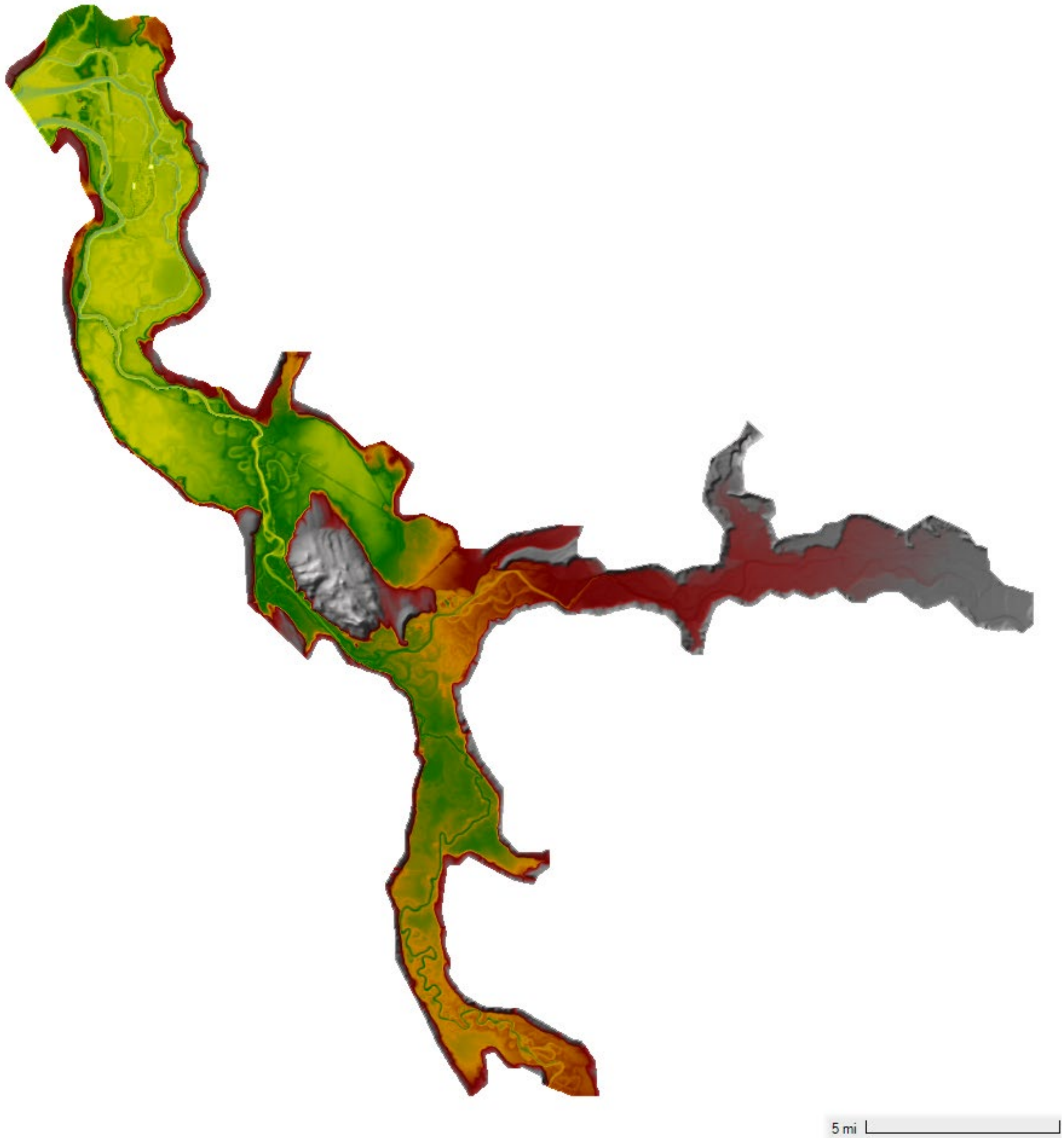


Figure 32. Full Terrain Extent

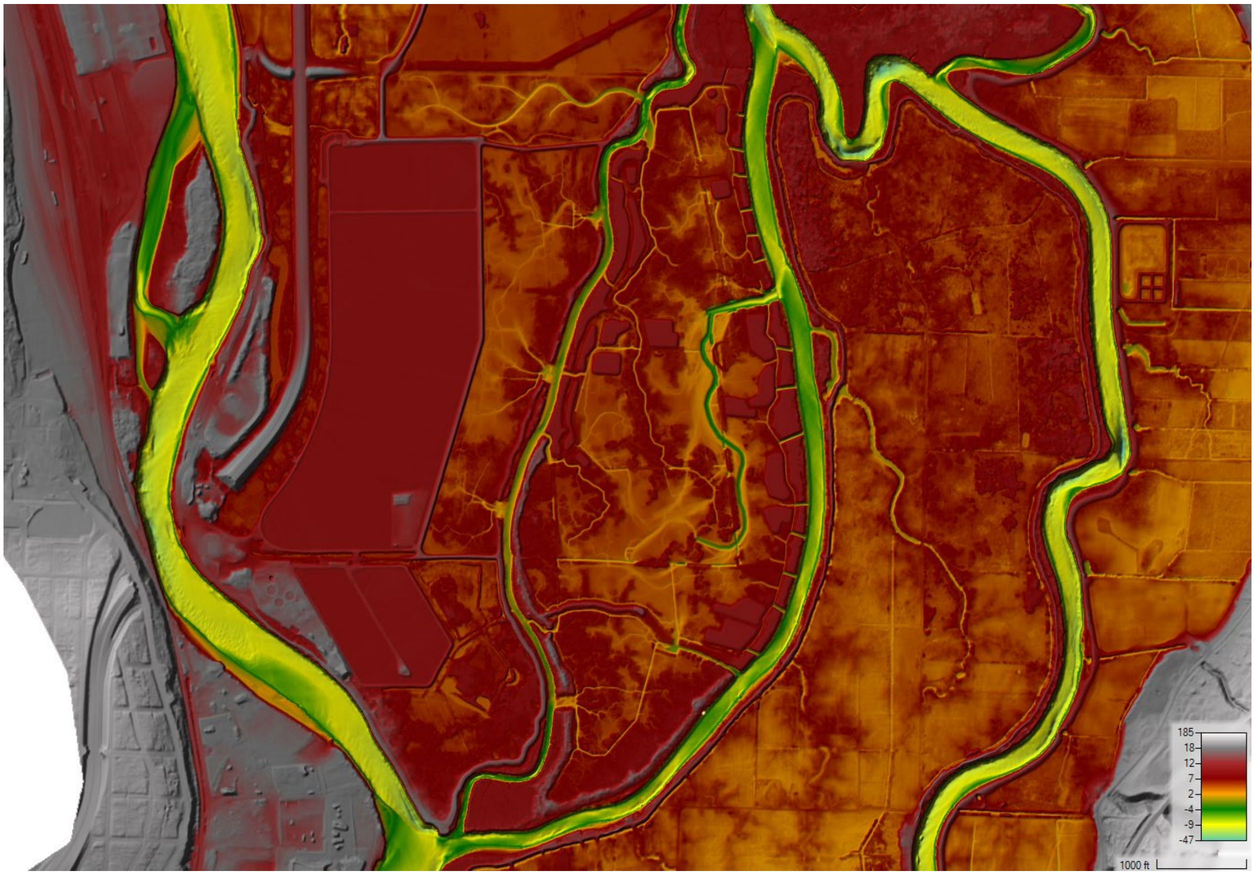


Figure 33. Proposed Conditions terrain. Note the multibeam surveys of the Sloughs.

5.2.2. Geometry

Three versions of the geometry were developed for this model. First, a geometry was used for the validation runs. The validation runs use the original larger model from the 10% Design phase. It did not include the finer geometry features of the actual island itself. This geometry was meant to simulate the surrounding areas to assess our model's accuracy against observed conditions. The remaining two geometries were for the proposed 35% design and the existing conditions scenarios. These two geometries have the same larger basin mesh, with a finer mesh for the Spencer Island area have. For both models, the minimum cell size was 55 sq ft, and the maximum was 70000 sq ft. The maximum cell sizes occur near the downstream tidal boundary condition. The average cell size is approximately 8400 sq ft, and the total ranges from 183650 (existing conditions) to 187441 (proposed conditions) cells. The difference in total cells is due to differences within the island itself.

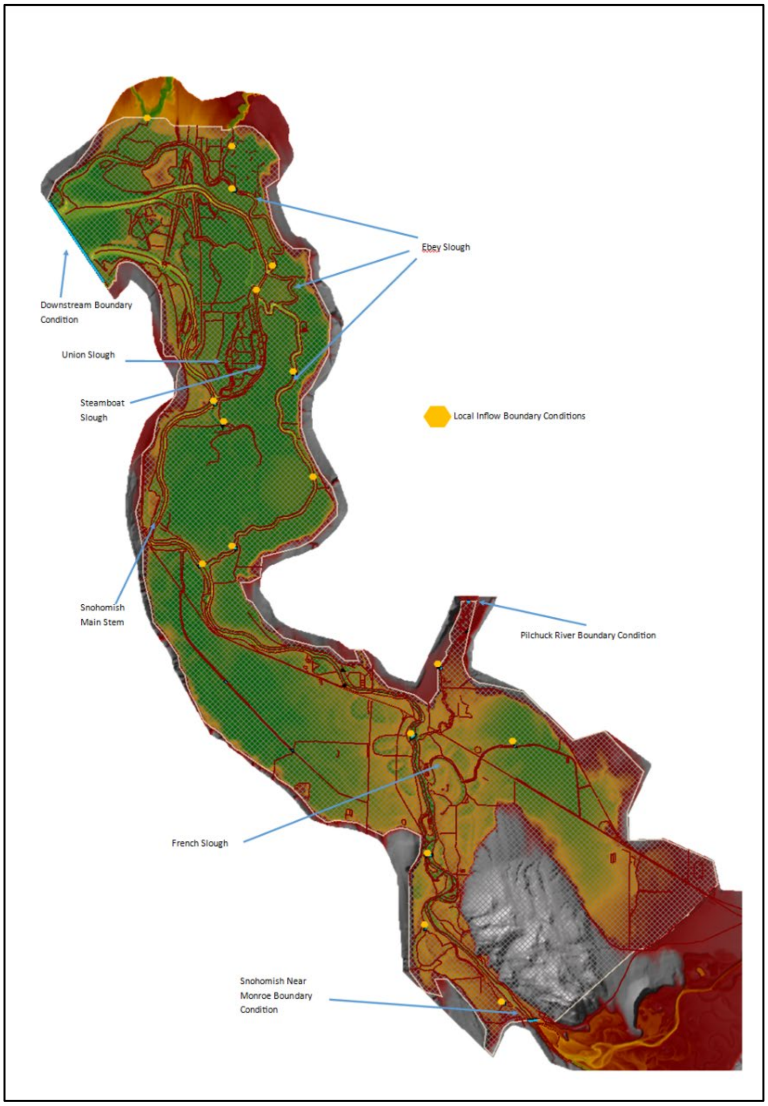


Figure 34. Full Mesh

The larger basin geometries are based on the full Snohomish Basin model from Watershed Science and Engineering. The geometry was modified to start at the USGS Snohomish near Monroe gage, which serves as our upstream boundary condition. Mesh refinements were made throughout the model to accurately model flow around NLD dikes. The Spencer Island area meshes were developed during the 10% design phase. The larger mesh and the finer island area meshes were combined, so the final meshes for the proposed and existing design have both the larger basin mesh as well as the fine Island mesh. The proposed conditions' land use required some roughness overrides inside Spencer Island. See Figure 35 for a comparison of the Spencer Island land use and meshes for both conditions.

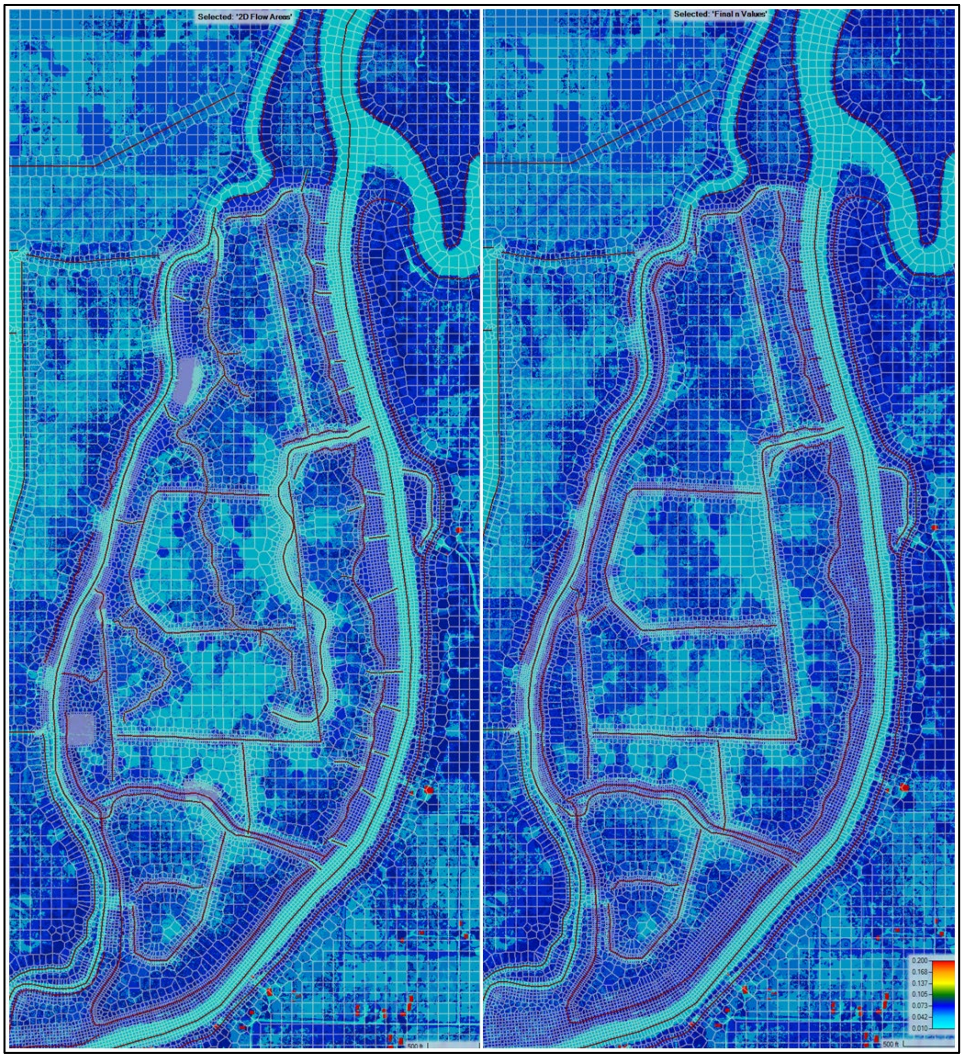


Figure 35. Proposed (left) vs Existing (right) meshes and land use

5.2.3. Model parameters and setup

The latest version of HEC-RAS was utilized (version 6.5, Feb. 2024) for all model runs. All models use the Shallow Water Equations (Eularian/Langrangian Method). Turbulence model is non-conservative, with longitudinal and transverse mixing coefficients set to 0.6. Initial Conditions time is 4 hours, with a ramp up fraction of 0.1. A maximum Courant is set to 2, and a minimum of 0.5. Other adaptive timestep settings vary between the models. Corresponding proposed and existing model runs were set to the same settings. Computation interval was set to 10 seconds. Model run times took anywhere from 18 hours to 38 hours, depending on the amount of inundation throughout the study area and the type of computer used. Because of the long run time, some models were run using restart files.

5.2.4. Boundary conditions and modeling scenarios

The feasibility level modeling includes two validation scenarios, and 30 production runs focused on understanding changes to flood levels resulting from historical and future sea levels and river flows. The production runs were split into 15 scenarios, each with a proposed conditions and existing conditions version.

Model Validation

USACE made several major changes to the existing WSE model and verified model calibration using data from December 2022 and December 2023. December 2022 king tide of record caused widespread flooding near Spencer Island. This event was coupled with high (but not flood) flows on the Snohomish River of 36,000 cfs at the Monroe gage. In December 2023 a high flow of 65,000 cfs occurred at the Monroe gage that had a recurrence interval estimated to be 2.3 years. The Snohomish gage is affected by both tidal backwater and upstream dike overtopping making it a difficult location for reliable measurements.

Two stage gages were used to validate the results: Ebey Slough near Highway 2, and mainstem Snohomish River at French Slough near the pumping station. Both Ebey Slough and Snohomish near Snohomish required conversion from their original datums to the NAVD88. The Ebey Slough conversion was +3.668 feet. The Snohomish near Snohomish conversion was +6.43 feet.

Table 16 shows the maximum observed values in the three gages, as well as the modelled values at the same locations for the two validation events. The delta row is the modelled value subtracted from the observed value. The validation results are illustrated in Figures 33 through 40.

Table 16. Validation maximum WSE results

	2022				2023			
	Max WSE (ft NAVD88)			Flow (cfs)	Max WSE (ft NAVD88)			Flow (cfs)
Condition	French	Snoho	Ebey	Snoho	French	Snoho	Ebey	Snoho
Observed	19.06	16.44	13.82	37800	25.58	21.26	13.14	64,800
Modelled	19.05	16.42	13.39	41100	25.58	21.35	13.01	67800
Delta	0.01	0.02	0.43	-3300	0	-0.09	0.13	-3000

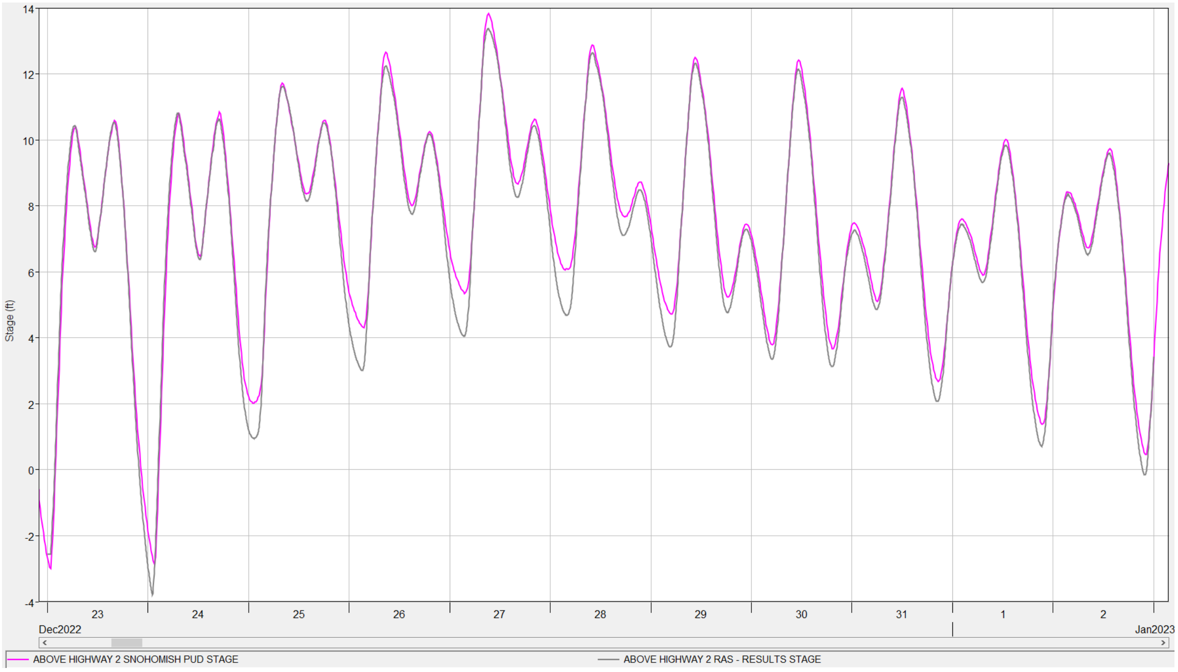


Figure 36. 2022 Validation Run Stage vs Observed Stage, Ebey Slough above Highway 2 gage

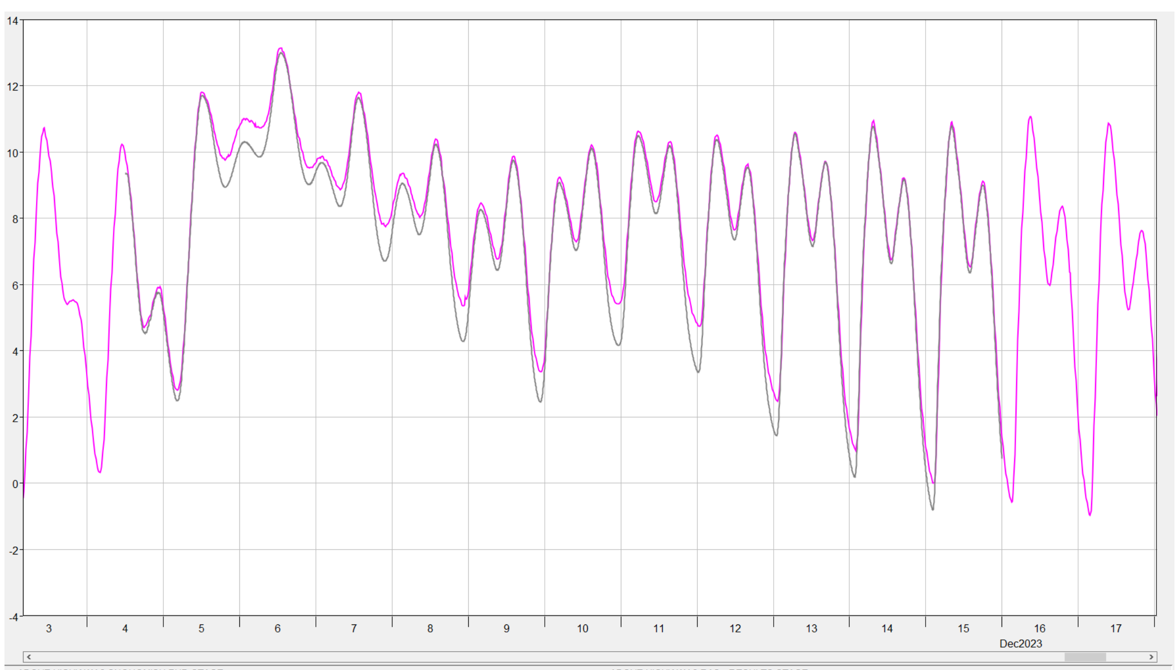


Figure 37. 2023 Validation Run Stage vs Observed Stage, Ebey Slough above Highway 2 gage

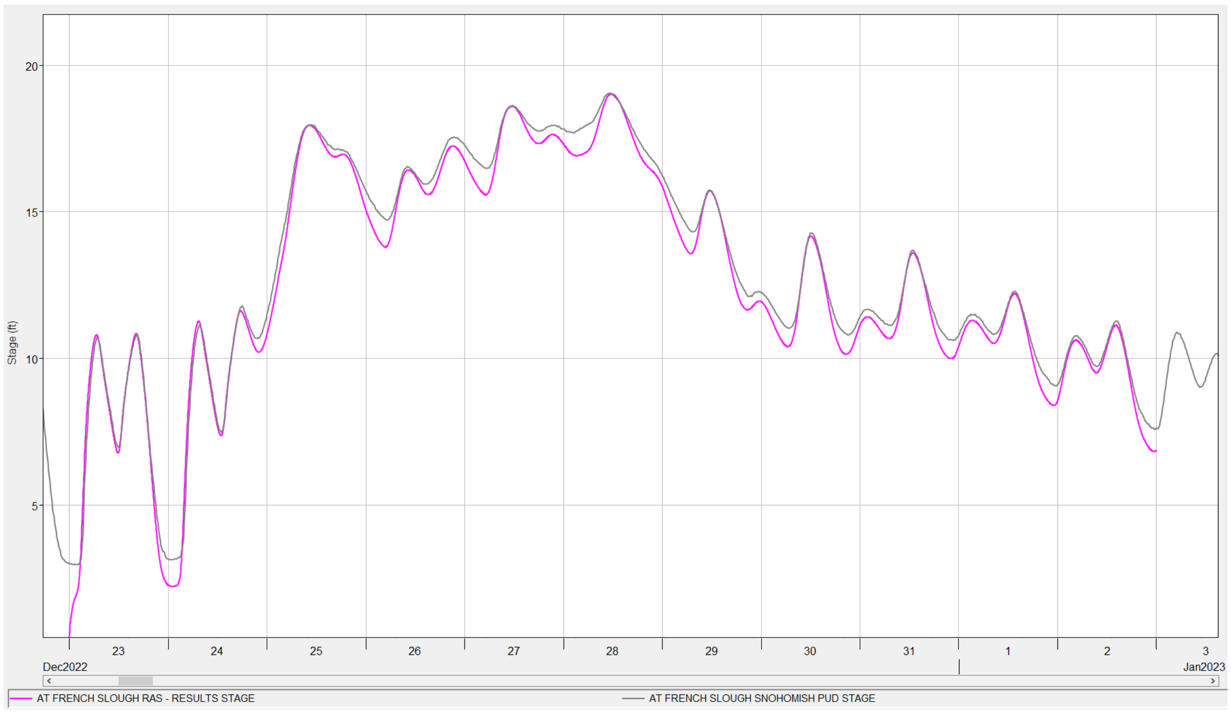


Figure 38. 2022 Validation Run Stage vs Observed Stage, Snohomish River at French Slough gage

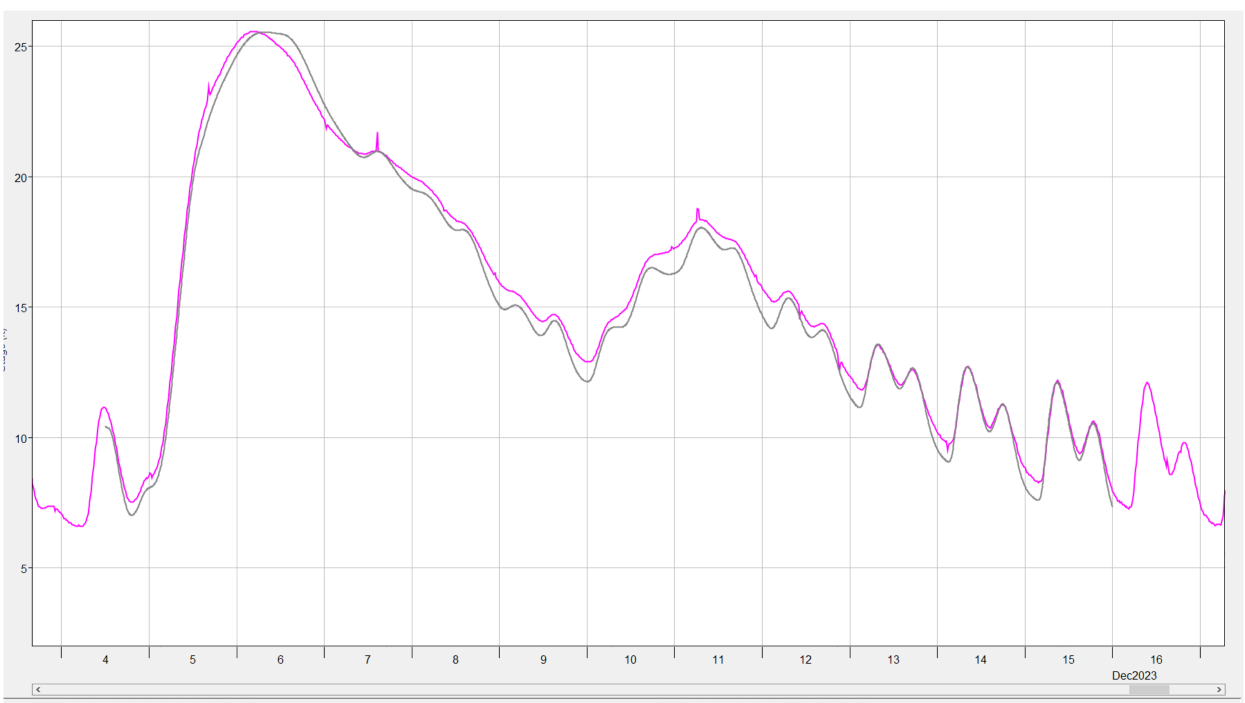


Figure 39. 2023 Validation Run Stage vs Observed Stage, Snohomish River at French Slough gage

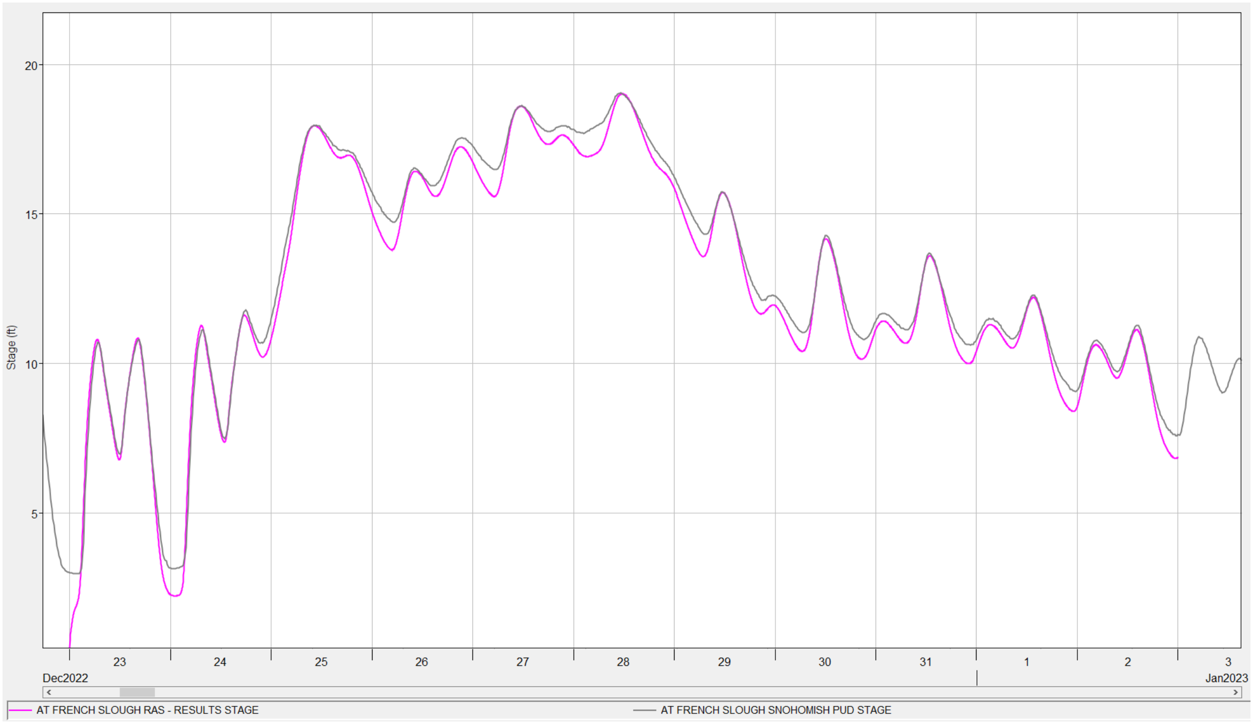


Figure 40. 2022 Validation Run Stage vs Observed Stage, Snohomish River at Snohomish gage

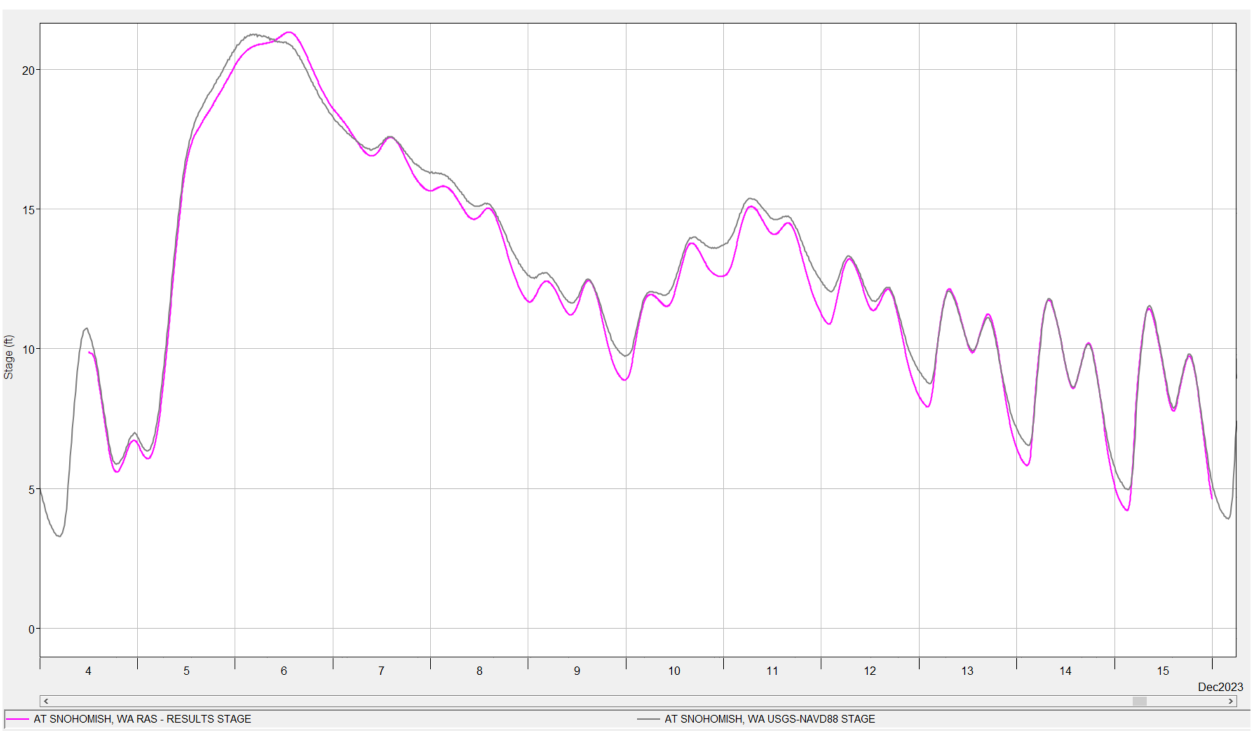


Figure 41. 2023 Validation Run Stage vs Observed Stage, Snohomish River at Snohomish gage

Figure 42. 2022 Validation Run Flow vs Observed Flow, Snohomish River at Snohomish gage

Figure 43. 2023 Validation Run Flow vs Observed Flow, Snohomish River at Snohomish gage

Existing and proposed conditions (historical) flood risk scenarios

Changes in potential flood risk due to the proposed project are analyzed in the following scenarios (Table 17). Scenario designated with an E refer to existing scenarios, scenarios with a P designation refer to proposed scenarios. Scenarios 1 through 11 are intended to bracket the full range of flood stages expected in the project lifetime, assuming stationarity of coastal and riverine boundary conditions, which is consistent with most USACE feasibility level investigations. WSE hydrology refers to flow values from the 2021 study for Snohomish County by WSE. FEMA FIS estimates refer to peak flow estimates provided in the effective FEMA Flood Insurance Study.

Table 17. Existing and proposed historical flood risk scenarios

Scenario	Coastal Boundary Condition	Riverine Boundary Condition	Notes
1E/P	99% AEP / 11.0 feet	99% AEP / 54533 cfs	WSE hydrology
2E/P	50% AEP / 11.26 feet	99% AEP / 54533 cfs	“”
3E/P	10% AEP / 11.71 feet	99% AEP / 54533 cfs	“”
4E/P	2% AEP / 12.2 feet	99% AEP / 54533 cfs	“”
5E/P	1% AEP/ 12.43 feet	99% AEP / 54533 cfs	“”
6 E/P	0.2% AEP/ 13.03 feet	99% AEP / 54533 cfs	“”
7 E/P	MHHW + 1 feet (9.8 NAVD88)	50% AEP / 77562 cfs	FEMA FIS estimates (1)
8 E/P	MHHW + 1 feet (9.8 NAVD88)	10% AEP / 129600 cfs	“”
9 E/P	MHHW + 1 feet (9.8 NAVD88)	2% AEP / 186500 cfs	“”
10 E/P	MHHW + 1 feet (9.8 NAVD88)	1% AEP / 210100 cfs	“”
11 E/P	MHHW + 1 feet (9.8 NAVD88)	0.2% AEP / 260100 cfs	“”

(1) 50% AEP estimate obtained by linear regression of FIS annual peak flow frequency data

All coastal boundary conditions are set as a constant stage (the value on the respective row). Riverine boundary conditions are based on synthetic hydrographs from the FEMA FIS UNET models. The 10% hydrograph was scaled to the 50% AEP flows and 99% AEP flows, which were not a part of the initial UNET model. Note that some UNET flows have higher peaks than listed for volume accounting.

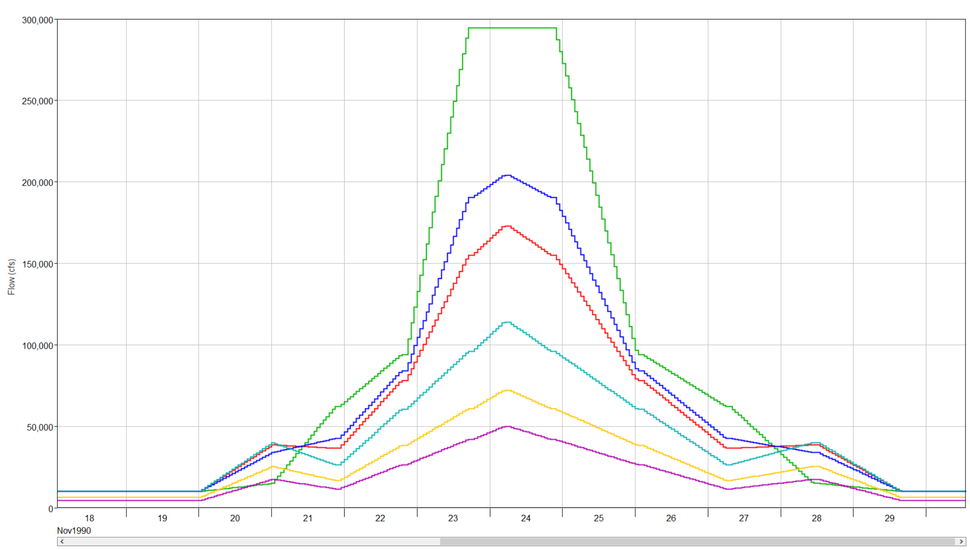


Figure 44. Balanced inflow hydrographs for 99% through 0.02% AEP historical floods at Monroe gage

The figure above shows the hydrographs of the Snohomish River near Monroe. This data forms the upstream most boundary condition, and accounts for most of the flow going into the model.

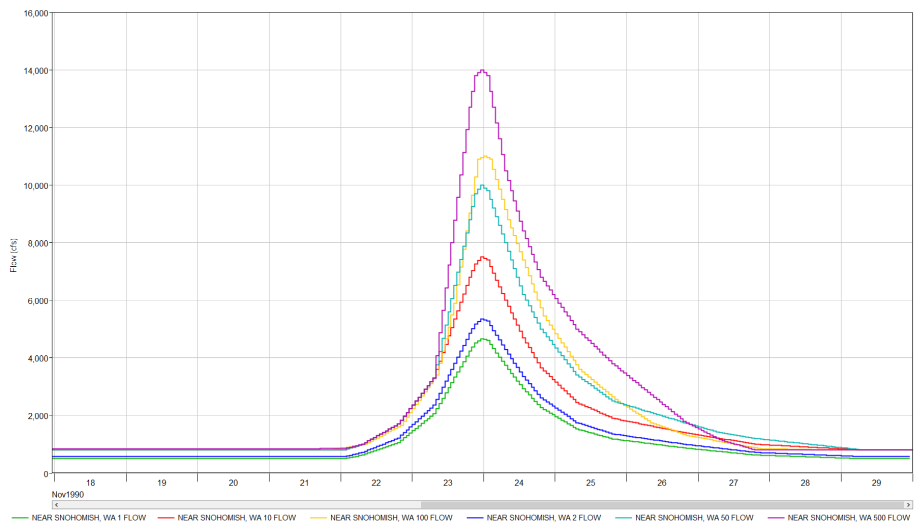


Figure 45. Coincident lateral inflow hydrograph for Pilchuck River for 99% AEP through 0.02% AEP events

The figure above shows the lateral inflow hydrographs for Pilchuck river tributary inflows which enter the model upstream of Snohomish. Lateral inflow hydrographs in the WSE hydrology for smaller ungaged basins scale these hydrographs by drainage area ratio.

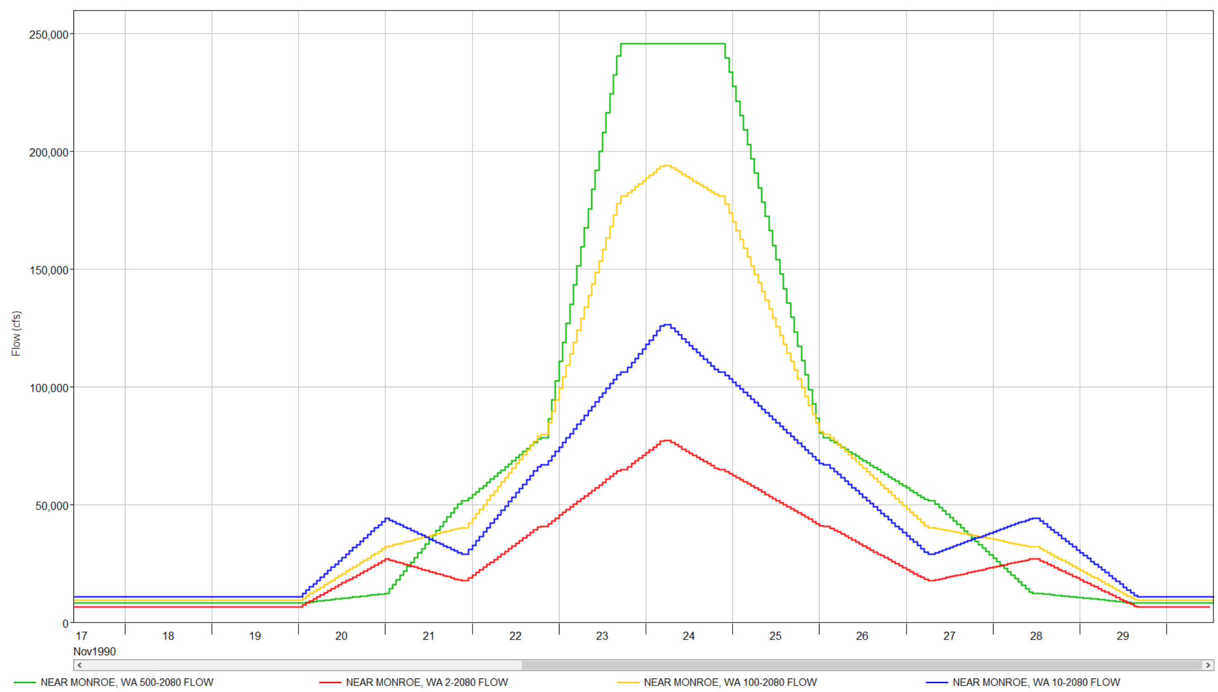
Future flood risk scenarios

WSE completed an evaluation of potential floodplain changes for intermediate SLR estimates of 1.67 feet and scaled peak streamflows based on a UW CIG analysis of climate modified hydrology (UW CIG 2014). Refer to the WSE 2021 report for more details of that analysis. These scenarios are provided for informational purposes (not used for design). The higher projected flows from WSE were used to scale the existing UNET hydrographs to their new values. The 0.2% UNET flows were scaled to the new 2080 0.2% flows, the 1% UNET to the new 2080 1% flows, and so on.

Table 18. 2080s conditions (intermediate scenario SLR) + CIG forecasted inland hydrology

Scenario	Coastal Boundary Condition	Riverine Boundary Condition	Notes
12 E/P	MHHW + 1-foot 2080 (11.47ft NAVD88)	2080 50% AEP / 77,400 + 7,370 cfs	WSE 2021
13 E/P	MHHW + 1 foot 2080	2080 10% AEP / 126,500 + 12,700 cfs	“”

14 E/P	MHHW + 1 foot 2080	2080 1% AEP / 194,200 + 19,000 cfs	“”
15 E/P	MHHW + 1 foot 2080	2080 0.2% AEP / 245,900 + 23,300 cfs	“”



2080s balanced inflow hydrographs for 99% through 0.02% AEP historical floods at Monroe gage based on WSE 2021 hydrology

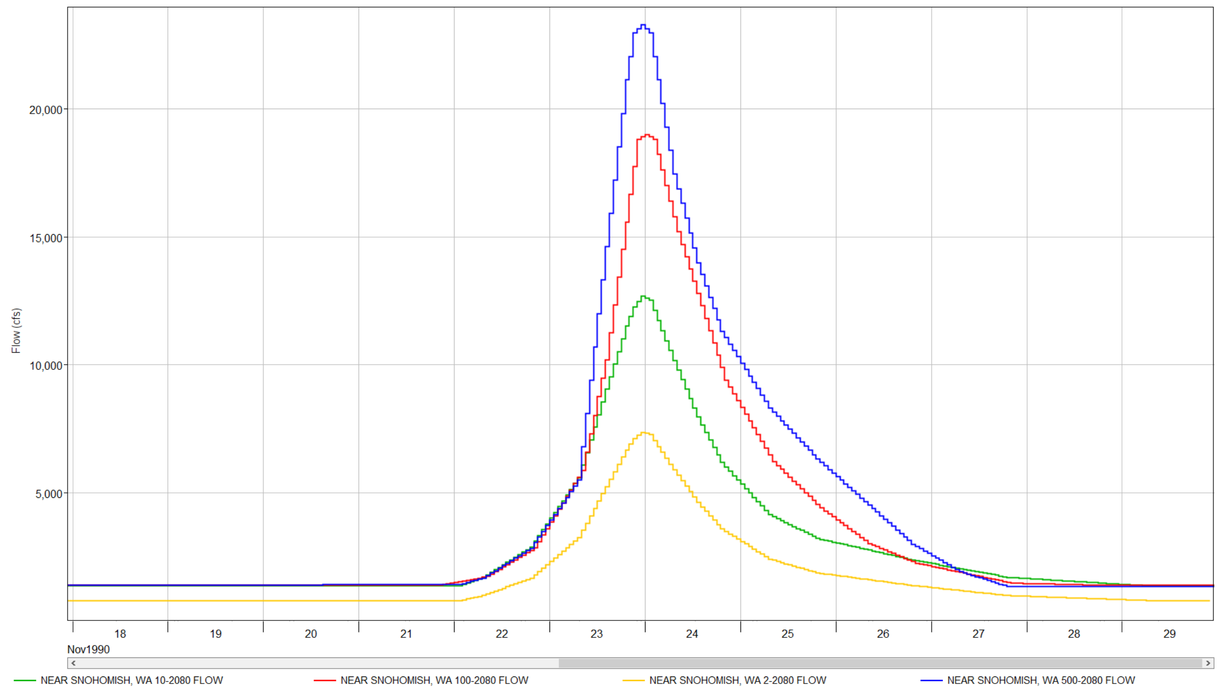


Figure 46. 2080s coincident lateral inflow hydrograph for Pilchuck River for 99% AEP through 0.02% AEP events

6. Existing and Future with and Future Without Project Hydraulic Analysis Results

6.1. Water Surface Profiles and Inundation Maps

This section summarizes the results shown in Annex D2 for the scenarios presented in Table 17 and Table 18. Key results and findings are presented. Note that the modeling shows that water surface elevations do not change for coastal flood scenarios, so only the results for the riverine flood scenarios are discussed here. Refer to Annex D2 for results for all scenarios. For discussions of potential changes in velocity and implications refer to Annex D3.

Along the mainstem Snohomish River between Puget Sound and the Ebey Slough (Figure 47) all riverine flooding scenarios show very small decreases in maximum water surface profiles. The decrease is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Note that the split from the mainstem to Union/Steamboat Slough is river mile 4.

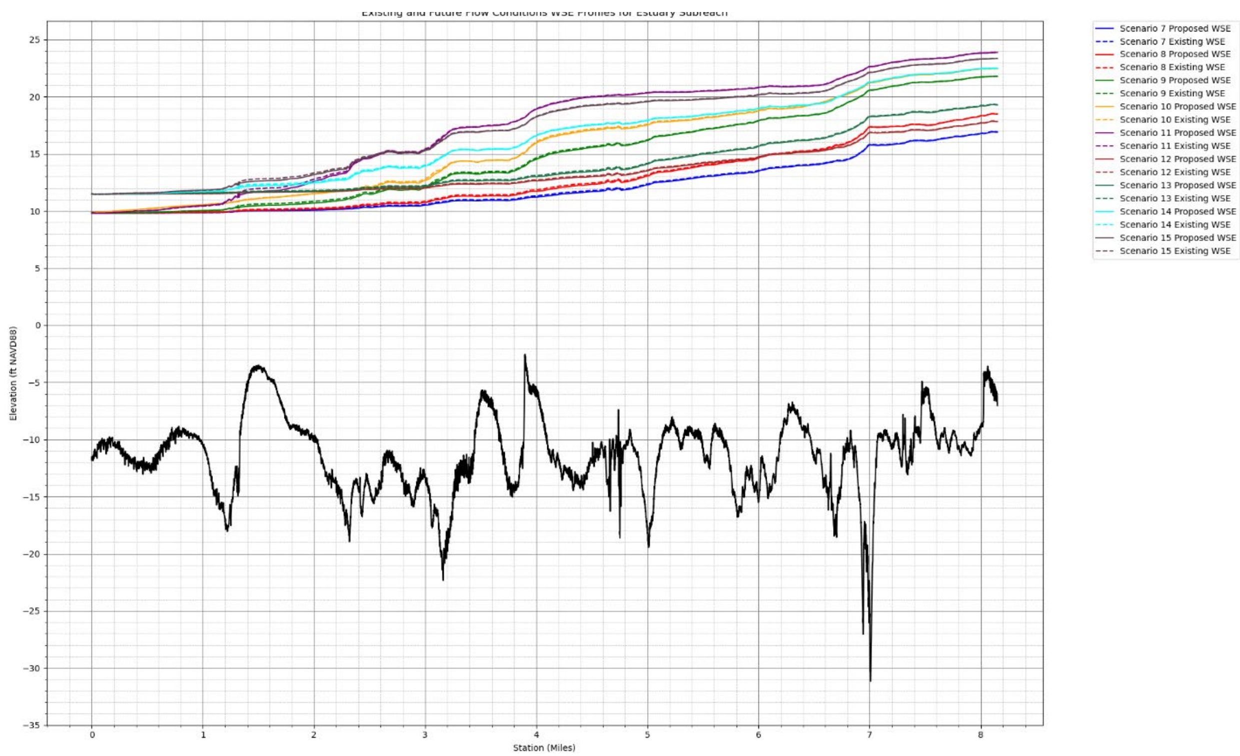


Figure 47. Mainstem Snohomish River water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

Along Steamboat Slough, between Puget Sound and upstream connection with the Snohomish River, modeled flooding scenarios (Figure 47) predict larger decreases in maximum water surface profiles than in other distributary channels. The decrease is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Spencer Island spans from RM 4.5 to 6.6 in the plot below.

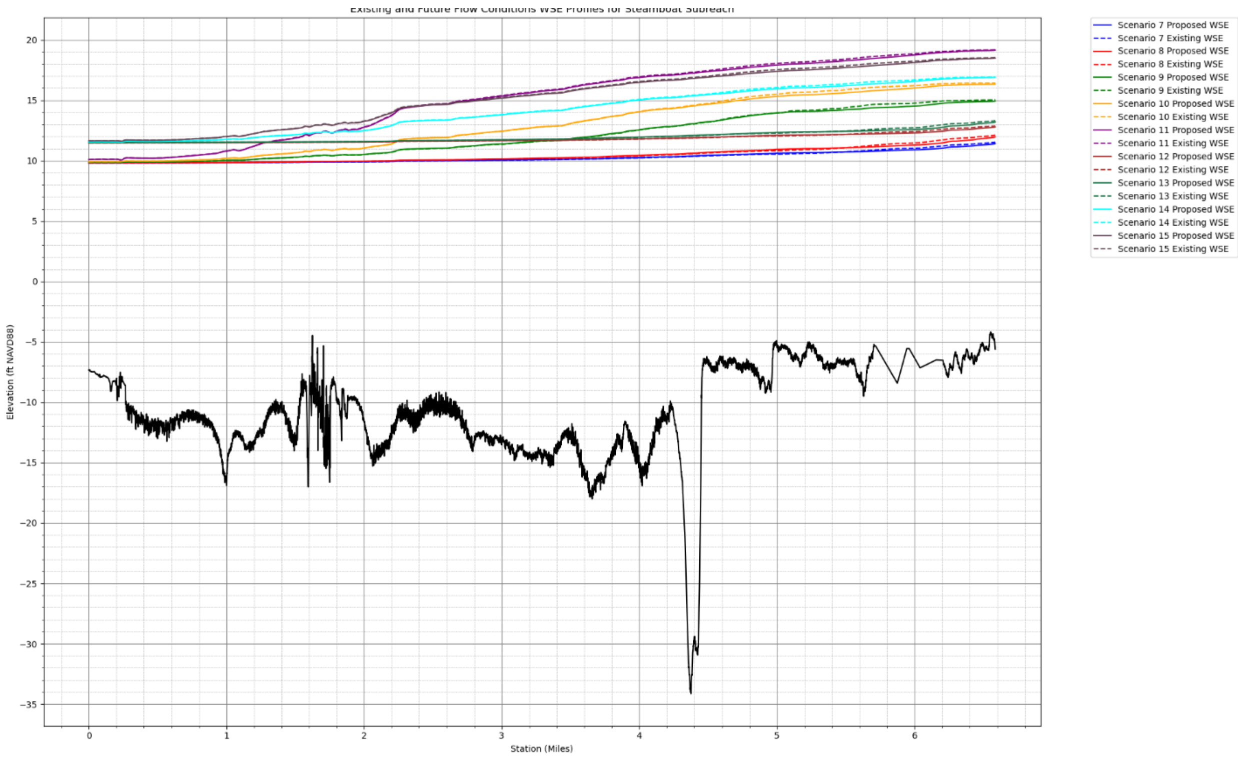


Figure 48. Steamboat Slough water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

Along Union Slough, between Puget Sound and upstream connection with the Snohomish River, modeled flooding scenarios (Figure 48) predict small changes predict small increases and decreases in maximum water surface profiles. Decreases in water surface occur in the upstream most part of Union Slough, immediately after the junction where Steamboat and Union sloughs branch off the mainstem Snohomish. This slight decrease is observed in Scenarios 7, 8, 9, 12, and 13. This decrease in water surface is minimal and is imperceptible in the profile plots. It can be seen in an inundation/depth difference plot. Figure 50 plots the differences in depth between proposed and existing conditions for scenario 8. In Figure 50 existing water surface elevations are subtracted from 35% conditions. Areas that are shaded blue are deeper, and orange are shallower. Grey areas fall between +/- 0.1 feet, in recognition of typical survey tolerances and modeling accuracy limitations.

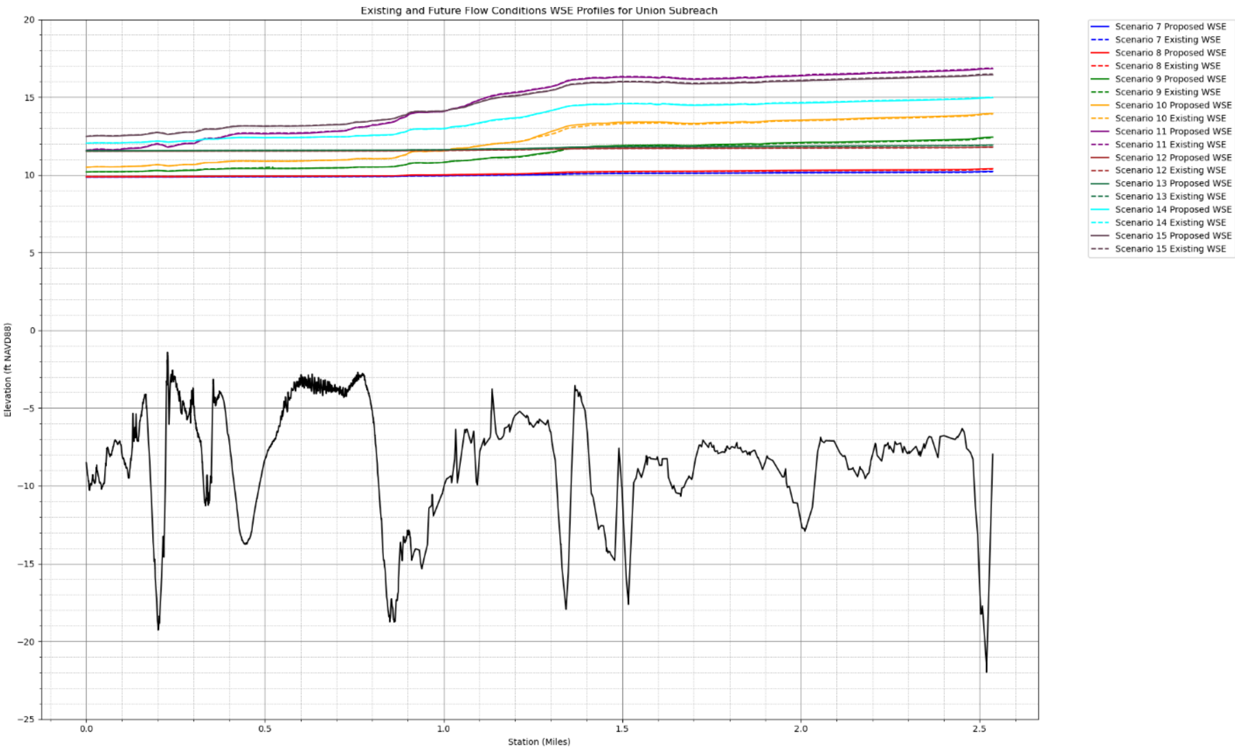


Figure 49. Union Slough water surface profiles from USACE HEC-RAS 2D model for historical and 2080 river flood scenarios

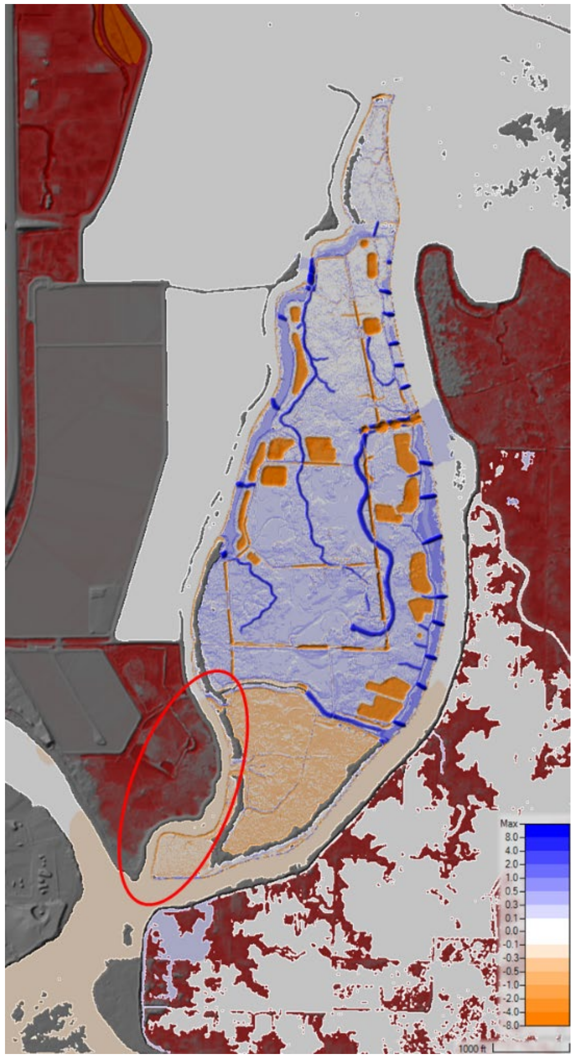


Figure 50. Inundation depth difference map for Scenario 8. Red circle marks decrease in WSE in Union Slough.

Increases in water surface elevations occur around river miles 1.25-1.75. The increases occur for Scenarios 9, 10, 11, 14, and 15 and is caused by dike removal at Spencer Island which allows for diversion of more floodwater toward Smith Island and Union Slough which aligns with the project goal to improve connectivity between Steamboat and Union Slough restoration projects. Figure 51 plots the existing vs proposed conditions for scenario 10. This plot shows the most dramatic changes in water surface.

Discussions between NWS and NWD planning and engineering and OC led to several refinements of the grading plans and models to minimize any increases in flood elevation, as they are likely to result in increased overtopping of adjacent levees along Union Slough just west of Spencer Island. Several revisions to the project grading plans were tested. It was found that the configuration that does not result in unacceptable impacts to the environment, project budget, or increases in flooding to developed properties, requires increasing floodplain conveyance through widening an existing levee breach along Union Slough just west of the project at an existing City of Everett owned wetland mitigation site. Models for scenarios 7, 8, 9, 10 and 11 (50%, 10%, 2%, 1% AEP, 0.2% AEP riverine floods) were updated to include a wider levee breach at Union Slough as these are the only scenarios where flood elevations were affected by the breach widening at Smith Island.

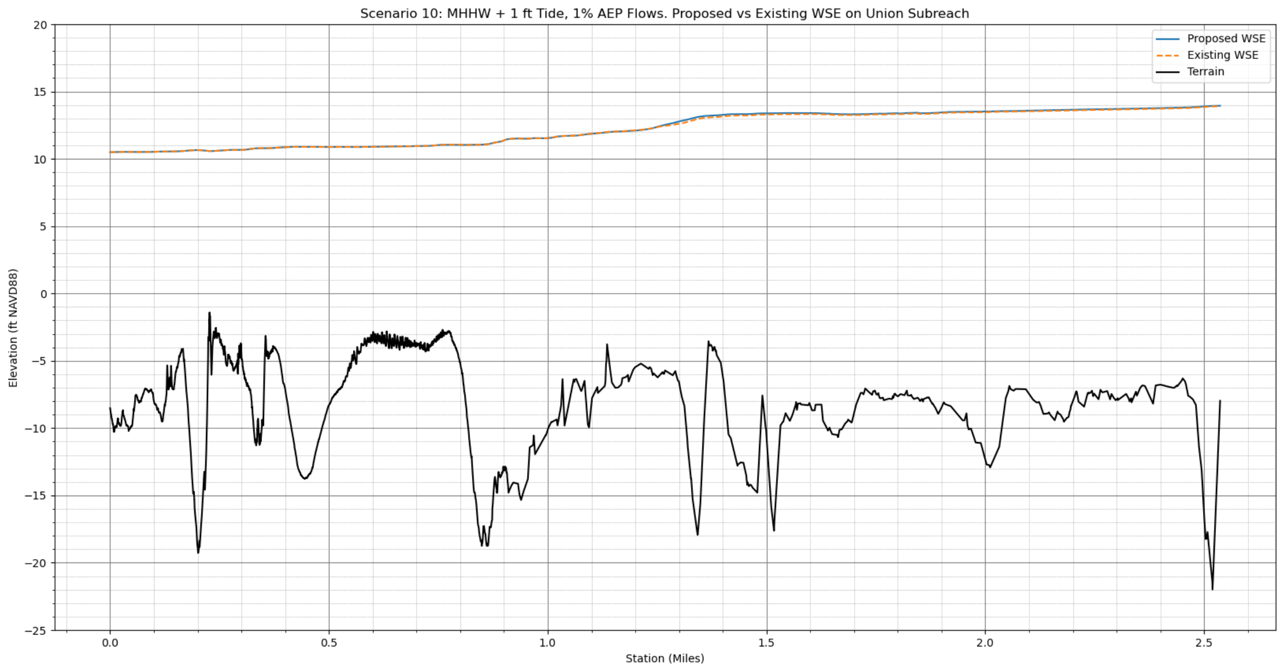


Figure 51. Proposed vs. Existing Conditions water surface profile at Union Slough sub reaches for the 1% AEP (historical) condition

With project and existing conditions velocities were compared for the 2-year, 10-year, and 100-year existing conditions hydrology river flood flows. Within Spencer Island there are changes present in all 3 scenarios. For all scenarios, there appears to be an increase in velocities within the center part of the island. The upstream most part of Steamboat Slough shows an increase in velocity, and the more downstream parts show a decrease. Union Slough has a decrease in velocity at its upstream most portion. For the 100-year flows, Union Slough's velocity increases at the downstream end of the Island. There are also small differences in velocity inside Smith Island where overtopping occurs. Figure 52 shows the differences in velocity for the 100-year flow event (scenario 10). Refer to Annex D2 for more plots. Because existing conditions velocities are low, the small increases are not considered significant.

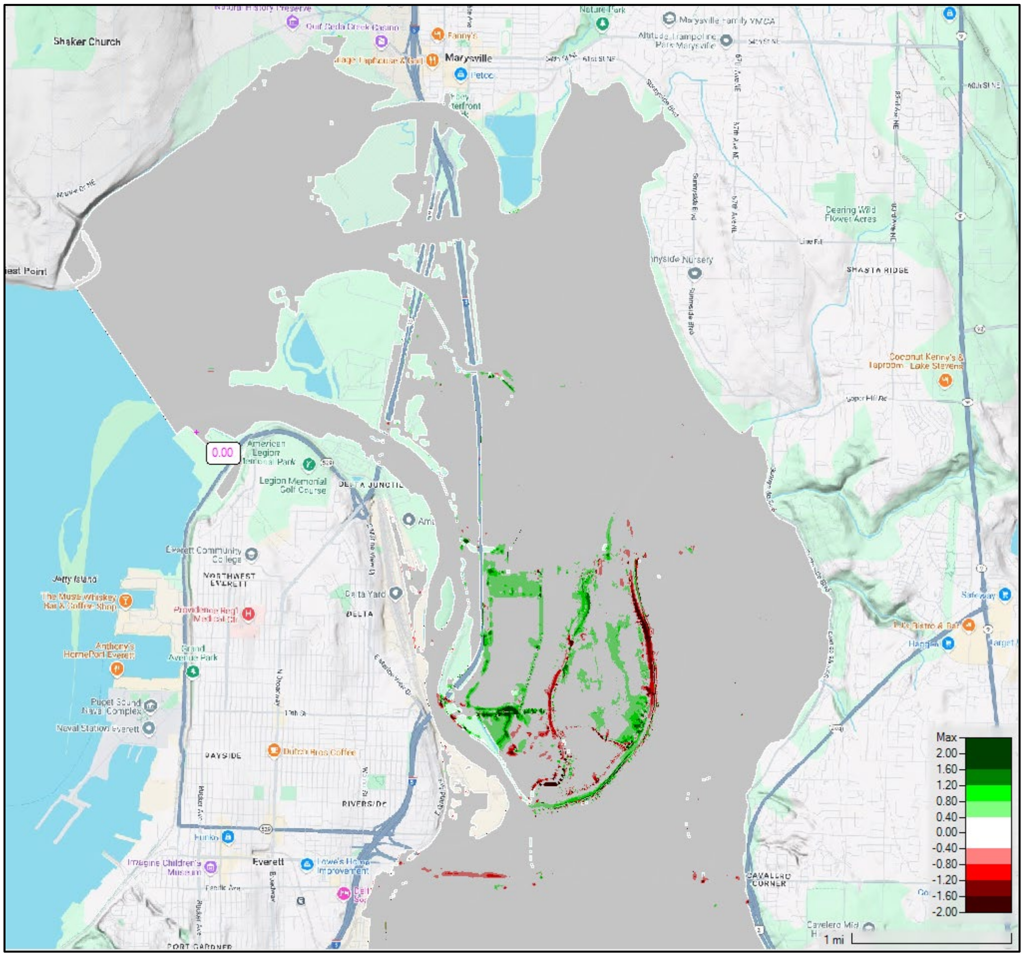


Figure 52. Velocity differences for 100-year (historical) flows

6.2. Riverine water surface elevation comparisons between USACE 2D model and effective FEMA FIS model

The 2D simulation maximum modeled water surface elevations within and around Spencer Island were extracted for the 0.99 through 0.002 AEP events. Stages for the 0.99 AEP event are essentially flat (elev. 9.3 feet). Note that this model presumes a steady downstream tide, and that the equivalent 0.99 AEP high tide event is higher by 0.8 to 1.65 feet depending on which method is used to compute annual maximum total water level exceedance statistics. Modeled stages that are lower than the coastal 0.002 AEP event (12.66 feet) are highlighted in blue in the tables below. These locations and events would be more influenced by coastal flooding than riverine flooding. All locations near Spencer Island are controlled by riverine flooding for the largest events. Higher fluvial flows result in a progressive increase in the down-valley slope in the water surface profiles (due to the effects of overbank roughness and dikes). Figure 53 shows the locations where water surface elevation data was extracted from the model. The cross sections are from the original FEMA UNET model.

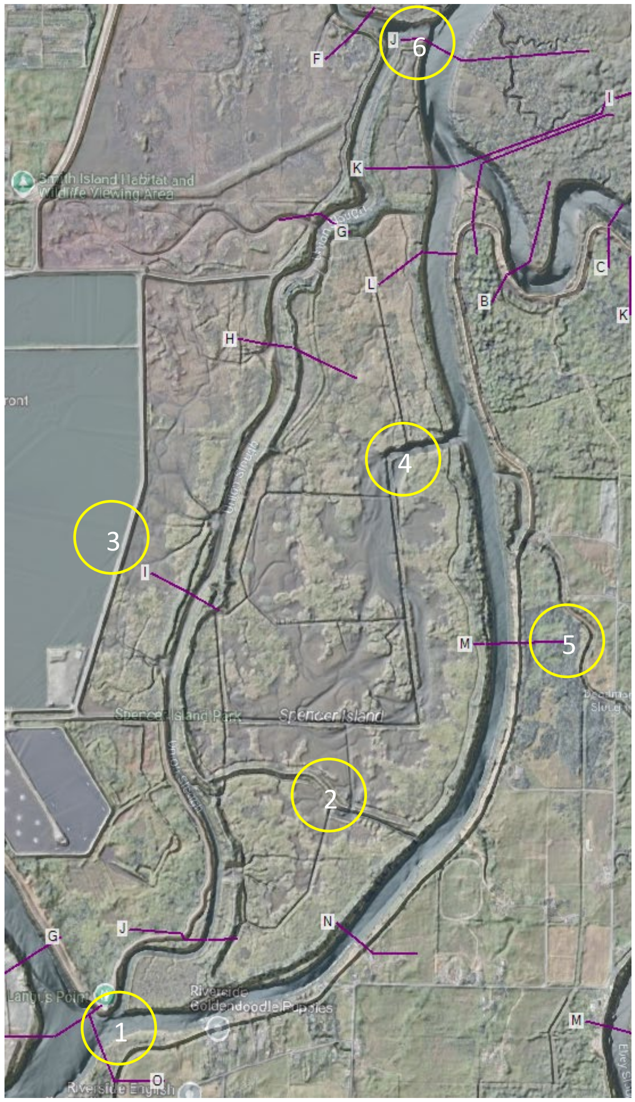


Figure 53. Output locations for WSE data

Table 19. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for existing, historical (observed) conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	11.74	10.93	10.63	10.51	10.68	10.31
0.1	10	12.39	11.33	10.95	10.80	11.02	10.51
0.02	50	15.51	14.14	13.85	13.93	14.88	12.95
0.01	100	16.86	15.74	15.10	15.51	15.96	14.49
0.002	500	19.48	18.39	17.77	18.07	18.39	17.22

Table 20. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for 35% design, historical (observed) conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	11.65	10.72	10.65	10.63	10.70	10.34
0.1	10	12.29	11.07	10.98	10.95	11.05	10.55
0.02	50	15.44	14.20	14.03	13.99	14.83	12.95
0.01	100	16.76	15.62	15.44	15.35	15.81	14.43
0.002	500	19.43	18.31	17.98	17.93	18.27	17.14

Table 21. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for existing, 2080 flow conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	13.09	12.27	12.09	12.03	12.15	11.85
0.1	10	13.60	12.52	12.34	12.27	12.42	12.02
0.01	100	17.24	16.26	15.64	16.07	16.41	15.34
0.002	500	18.82	17.81	17.2	17.54	17.85	16.79

Table 22. Peak elevations (NAVD 88, feet) at Spencer Island computed in USACE 2D model for 35% design, 2080 flow conditions

AEP	Flood Event R.I. (year)	Steamboat/Union Slough - XS O	Bridge S. of Cross Dike	Union Slough XS I	North End of main ditch	Steamboat XS M	Buse Cut - Steamboat XS J
0.5	2	13.03	12.18	12.13	12.11	12.16	11.87
0.1	10	13.51	12.44	12.38	12.35	12.42	12.04
0.01	100	17.18	16.22	16.03	15.96	16.30	15.28
0.002	500	18.76	17.23	17.46	17.41	17.72	16.71

Differences between the FEMA UNET 1D model and the USACE HEC RAS 2D model with respect to the FEMA base flood elevation (0.01 AEP) are shown in Table 26. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE existing conditions 2D 1% AEP flood stages near Spencer Island and Table 27 for the cross sections along Union and Steamboat Slough and the storage area that represents Spencer Island. For existing conditions, differences between the modeled stages range from 0.2 feet on the upstream end of Steamboat Slough to 1.3 feet on the downstream end of Union Slough. The FEMA WSE values are uniformly higher than the USACE 2D values. If the FEMA high tide of elevation 10.0 feet was used in the USACE 2D model stages would be higher reducing the magnitude of these differences.

Until the USACE 2D model is re-run with the FEMA model tide stage it is premature to say that the FEMA model over-predicts flood stages relative to the USACE 2D model.

Table 23. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE existing conditions 2D 1% AEP flood stages near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	FEMA regulatory WSE (ft)	FEMA BFE (NAVD88, ft)	USACE 2D 1%AEP Exist. WSE (ft)	FEMA regulatory minus USACE 2D (ft)	FEMA BFE minus USACE 2D (ft)
Snohomish River	G	3.68	15.4	16.1	14.7	0.7	1.4
Steamboat Slough	O	6.23	16.7	17.2	16.5	0.2	0.7
Steamboat Slough	N	5.7	16.7	17.2	16.4	0.3	0.8
Steamboat Slough	M	4.96	16.7	17.2	15.8	0.9	1.4
Steamboat Slough	L	4.2	16	16.6	15.1	0.9	1.5
Steamboat Slough	K	4.04	15.5	16.1	14.7	0.8	1.4
Steamboat Slough	J	3.76	15.3	15.9	14.3	1.0	1.6
Union Slough	J	4.5	15.7	16.3	15	0.7	1.3
Union Slough	I	3.79	15.5	16.1	15.1	0.4	1.0
Union Slough	H	3.24	15.5	16.1	15.2	0.3	0.9
Union Slough	G	2.91	15.5	16.1	14.3	1.2	1.8
Union Slough	F	2.49	15.2	15.7	13.9	1.3	1.8
All Cross Section Average			15.8	16.4	15.1	0.7	1.3
Spencer Island	SA#11		Not published	16.0	15.6	NA	0.4

Table 24. Comparison of FEMA regulatory and Base Flood Elevations (BFEs) to USACE 35% Design conditions 2D 1% AEP flood stages near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	FEMA regulatory WSE	FEMA BFE (NAVD88, ft)	USACE 2D 1%AEP 35% WSE (ft)	FEMA regulatory minus USACE 2D (ft)	FEMA BFE minus USACE 2D (ft)
Snohomish River	G	3.68	15.4	16.1	14.8	0.6	1.3
Steamboat Slough	O	6.23	16.7	17.2	16.4	0.3	0.8
Steamboat Slough	N	5.7	16.7	17.2	16.3	0.4	0.9
Steamboat Slough	M	4.96	16.7	17.2	15.7	1.0	1.5
Steamboat Slough	L	4.2	16	16.6	15	1.0	1.6
Steamboat Slough	K	4.04	15.5	16.1	14.6	0.9	1.5
Steamboat Slough	J	3.76	15.3	15.9	14.3	1.0	1.6
Union Slough	J	4.5	15.7	16.3	15.3	0.4	1.0
Union Slough	I	3.79	15.5	16.1	15.3	0.2	0.8

Union Slough	H	3.24	15.5	16.1	15.1	0.4	1
Union Slough	G	2.91	15.5	16.1	14.4	1.1	1.7
Union Slough	F	2.49	15.2	15.7	14	1.2	1.7
All Cross Section Average			15.8	16.4	15.1	0.7	1.3
Spencer Island	SA#11		Not published	16.0	15.4	NA	0.6

Table 25. Comparison of USACE 35% Design conditions 2D 1% AEP flood stages to USACE Existing conditions near Spencer Island

Location	FEMA XS ID	UNET Station (RM)	USACE 2D 1%AEP 35% WSE (ft)	USACE 2D 1%AEP Exist. WSE (ft)	35% minus Existing (ft)
Snohomish River	G	3.68	14.8	14.7	0.1
Steamboat Slough	O	6.23	16.4	16.5	-0.1
Steamboat Slough	N	5.7	16.3	16.4	-0.1
Steamboat Slough	M	4.96	15.7	15.8	-0.1
Steamboat Slough	L	4.2	15	15.1	-0.1
Steamboat Slough	K	4.04	14.6	14.7	-0.1
Steamboat Slough	J	3.76	14.3	14.3	0.0
Union Slough	J	4.5	15.3	15	0.3
Union Slough	I	3.79	15.3	15.1	0.2
Union Slough	H	3.24	15.1	15.2	-0.1
Union Slough	G	2.91	14.4	14.3	0.1
Union Slough	F	2.49	14	13.9	0.1
All Cross Section Average			15.1	15.1	0.0
Spencer Island	SA#11		15.6	15.6	0.2

6.3. Peak flow changes near Spencer Island and differences

The routed unsteady peak flows at each distributary channel were compared to the upstream inflow at Monroe near Spencer Island for the FEMA UNET model, the WSE 2D model, and the USACE 2D model. Table 19 compares flows for the 10% through 0.2% AEP events at Monroe and at the head of all distributary channels near Spencer Island. Total system flow appears to decrease with increasing discharge in these models, presumably because overbank attenuation is occurring. However, when comparing to the WSE and USACE 2D models, which show far less attenuation, it is possible the modeled loss of flow is a result of UNET model limitations (unsteady flow computation methods or underlying survey data).

It is notable that the total flow in the WSE 2D model near Spencer Island (Table 20) for the 0.01 AEP (100-year) event (173,200 cfs) is about 40,000 cfs more than the UNET model total system flow, and 101% of the gaged inflow at Monroe. The USACE 2D model (Table 21), which uses the same boundary conditions as the UNET model and similar 2D mesh as the WSE model, results in a peak flow through the I-5 corridor near Spencer Island of 206,750 cfs (98% of gaged inflow at Monroe). The WSE model includes several local inflows that the FEMA and USACE model do not, which add to the peak flow rates modeled by WSE. For consistency with the FEMA model these local inflows are not included in USACE modeling.

Flows in the distributary channels near the I5 bridges were summarized and compared in the USACE 2D Model in Table 21 to see if the project impacts flood flows at the bridges. At the Snohomish mainstem peak flows decrease for the 50% through 1% AEP events from 2.1% to 0.9%. At Union Slough flows increase form 4.1% for the 10% AEP event to 2.5% for the 1% AEP event. Flows in Ebey Slough at I-5 decrease 0.1% for the 1% AEP event and increase 3.2% for the 10% AEP event. Flows in Steamboat Slough at I-5 increase 0.1% for the 1% AEP event and increase 3.1% for the 10% AEP event. Flows in the mainstem range from 59% for the 50% to 10% AEP events when flows remain within dikes but decrease to 45% for the 1% AEP when widespread dike overtopping is occurring. In general, the changes in flow are low, as expected, given that the dikes are already breached at Spencer Island. The detectable changes in flow in the model indicate that the dikes are interfering with conveyance in large floods and removing them will help restore more natural floodplain connectivity.

Modeled flows at Spencer Island are a result of the combined influences of: upstream inflow hydrographs (timing, peak and volume); downstream tidal boundary assumptions; geometry for the channel, dikes, and overbanks; floodplain storage effects; and local runoff assumptions.

Table 26. FEMA UNET model total system flow near Spencer Island vs. Monroe

	RM/AEP	Q10 peak (cfs)	Q50 peak (cfs)	Q100 peak (cfs)	Q500 peak (cfs)
AEP		0.1	0.02	0.01	0.002
Reach 1 mainstem US	20.5	113,998	172,933	203,998	294,500
Reach 3 mainstem US	3.8	51,604	78,866	89,110	108,567
Total system flow Spencer	S 3, US 4, SS 5, ES 8	89,787	116,825	133,180	163,589
Total system / Monroe		79%	68%	65%	56%

Table 27. WSE 2D model total system flow near Spencer Island vs. Monroe

Flood Event recurrence interval	1.01	2	5	10	25	50	100	500
Location AEP	0.99	0.5	0.2	0.1	0.04	0.02	0.01	0.002
Mainstem near Spencer Island	14,400	34,900	47,200	49,600	56,500	74,100	84,800	98,700
Spencer Island west half + Union + floodplain	500	1,300	1,800	1,900	2,200	4,600	7,800	17,400
Spencer Island east half + Steamboat + Ebey + floodplain	8,200	20,400	27,300	30,200	35,500	62,900	80,600	113,800
Total system flow near Spencer Island	23,100	56,600	76,300	81,700	94,200	141,600	173,200	229,900
Monroe gage modeled peak	22,200	58,300	82,500	104,100	130,600	150,600	171,100	225,400
Total system / Monroe	104%	97%	92%	78%	72%	94%	101%	102%

Table 28. USACE 2D model total system flow near Spencer Island at I-5 Corridor vs. Monroe

Scenario	50% AEP			10% AEP			1% AEP		
Reach/Area	Prop.	Exist.	% Diff.	Prop.	Exist.	% Diff.	Prop.	Exist.	% Diff.
Snohomish Mainstem @ I-5	42,440	43,370	-2.1%	50,160	51,150	-1.9%	92,740	93,590	-0.9%
Highway overtopping @ I-5	-	-	N/A	-	-	N/A	620	420	47.6%
Union Slough @ I-5	5,260	5,060	4.0%	6,310	6,060	4.1%	23,450	22,870	2.5%
Steamboat Slough @ I-5	20,960	20,340	3.0%	24,910	24,150	3.1%	72,520	72,440	0.1%
Ebey Slough @ I-5	4,350	4,230	2.8%	5,220	5,060	3.2%	17,420	17,430	-0.1%
Total Flow @ I-5	73,010	73,000	0.0%	86,600	86,420	0.2%	206,750	206,750	0.0%
Snohomish @ Monroe	77,560	77,560		129,600	129,600		210,100	210,100	
Mainstem @ I-5 / Total @I-5	58%	59%	-2.2%	58%	59%	-2.1%	44.9%	45.3%	-0.9%
Total @I-5 / Monroe	94%	94%	0.0%	67%	67%	0.2%	98%	98%	0.0%

6.4. Floodplain management implications

The average change in the FEMA cross sections near Spencer Island is 0.0 feet, and the USACE computed water surface elevations (WSE) are on average 0.7 feet lower than published regulatory WSEs. Small rises in the 1% AEP WSE are possible along Union Slough at cross sections F, G, I and J and within Spencer Island (0.2 feet). To address this potential impact a portion of the existing Smith Island restoration project levee will be lowered adjacent to an existing constructed levee breach. Expansion of this breach diverts water north into restored tidal wetlands, increasing stages and flows in locations intended for that purpose. This mitigation approach was developed through several iterations of modeling and is the most practical solution the team could find that is still feasible within the constraints of the authorization. The floodmaps shown in Annex D-2 reflect this condition for the 10, 50, 100, and 500 year runs. See section 6.5 for more discussion of this configuration and potential effects on restored tidal wetlands.

For context it should be noted that the CLOMR modeling report (Otak, 2015) / no-rise analysis for the nearby Smith Island restoration project constructed by Snohomish County indicated potential rises of more than 0.5 feet at the outlet of the primary tidal channel near I-5. The effects of Spencer Island are considerably less because the dikes are already breached and the reconnected marsh area is much less than at Smith Island.

Note that the USACE 2D models described above are set up very differently than the effective FEMA Flood Insurance Study model, which uses the HEC-UNET code (now RAS 1D) to route an unsteady flow hydrograph through a branching river network (represented by 1D cross sections) where the channel is connected to storage areas with lateral weirs at the locations of dikes. This model was used to map the floodplain and floodway and uses a steady high tide for all simulations. Overflows of dikes treat the entire structure as a weir, use a constant discharge coefficient. Flows enter and leave a storage area instantaneously based only on available storage volume and elevation difference between the channel and storage area. Conveyance in storage areas resulting in a spatially varied water surface elevation (evident in the 2D modeling) is not computed or accounted for.

The combined effect of the 1D unsteady model limitations is a simplification of complex hydrodynamic processes and is likely contributing to the elevation differences between the models. As a practical engineering tool, the 1D unsteady model is outdated and unreliable for predicting the response to project configurations through a no-rise analysis, however the model is still effective and for compliance with the National Flood Insurance Program it needs to be updated to include the proposed modifications. Because all the proposed modifications will seek to balance cut and fill, no change to the elevation volume (storage area) curve is anticipated (See Annex D-3 for more information). Because of existing and new dike breaches, the storage area connections will need to be modified. These will allow water to enter storage areas earlier in the flood event, reducing available storage during the peak. It is possible this will result in a numerical rise of the BFE that could be physically unrealistic.

Running UNET is not possible given the age of the software, the model needs to be migrated into HEC-RAS unsteady for a no-rise analysis. Work completed previously by Otak consultants at Smith Island and work currently underway (Snohomish River FPMS study) can provide a working RAS model to aid in this work. A no-rise analysis will be completed in PED. Coordination with Snohomish County and FEMA will be necessary to scope this work. The effective model is outdated, and USACE will likely need to request acceptance of a model based on that used for this study, or the pending updates to the model being developed as part of a separate Floodplain Management Services project, which USACE is undertaking to update the hydrology and hydraulic modeling used for mapping the Special Flood Hazard Area of the Snohomish River.

Discussions with Snohomish County (Kit Crump, personal communication) indicate that the County strongly supports utilizing recent 2D and 1D/2D models developed by USACE in their restoration work on Ebey Slough and in future improvements to the FEMA floodplain models and maps. Proposed floodway modeling changes to include the effects of levee lowering/breaching and marsh/floodplain restoration are shown in Figure 54 below. This model update could result in a situation where the effective floodplain model used for no-rise analysis includes the grading plans for completed and funded restoration projects (and thus ensure a no-rise condition). Any update to the regulatory floodway boundaries needs to be approved by the County before it will be incorporated into updated modeling. The timeline for this is uncertain at present.

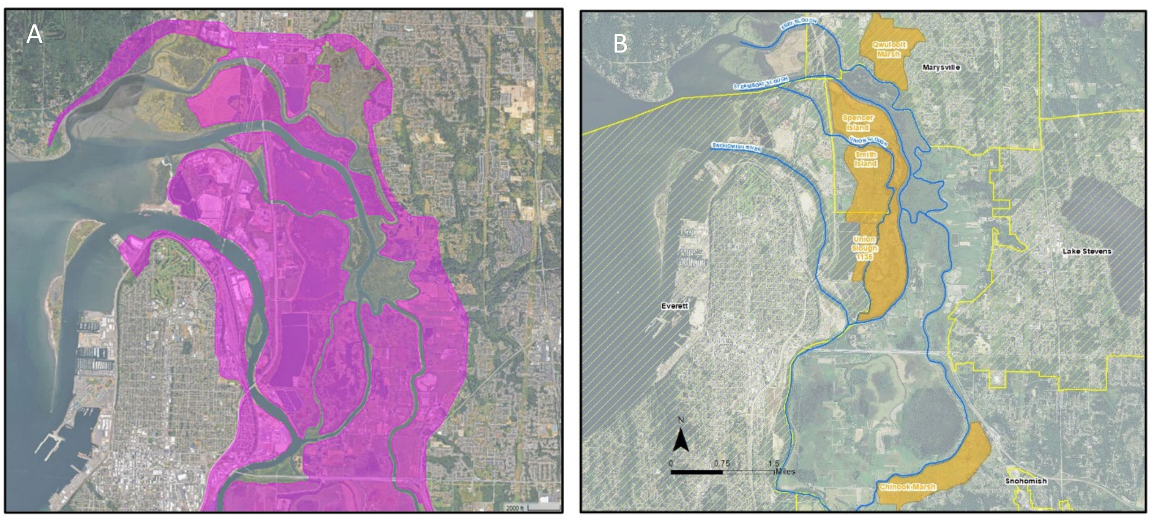


Figure 54. A) Snohomish River FEMA floodplain model density fringe (magenta areas) and B) recently completed or pending large scale restoration projects. The areas along channels not shaded magenta shown in A are mapped as floodway presently. The proposed change would convert the retsoraton areas shown in orange to floodway.

Once the hydrology and hydraulic model updates are complete, it is expected that the new maps will have lower flood elevations and inundation limits than are presently indicated. Dike lowering and floodway expansion associated with several restoration projects has increased conveyance in the lower valley. Based on preliminary model runs, expansion of the floodway as indicated, and use of updated models and terrain data would significantly reduce regulatory BFEs (greater than a foot in several locations). Updates to the hydrology are also underway to improve flood frequency estimates at the Monroe gage. The hydrology updates are likely to decrease the estimated 1% AEP peak discharge. The combined effect of changing the hydrology, expanding the floodway, and improvements in the modeling are likely to reduce regulatory flood elevations, however, these potential reductions would eventually be offset by climate affected hydrology (higher annual peaks, sea level rise) and need to be considered in that context.

The December 2025 was a near historical flood for the Snohomish. High water marks and levee failure data should be reviewed to help refine the model. Existing dikes and levees that frequently breach may need to be removed from the model (natural valley condition) if that better represents recently observed flooding. Unmaintained dikes on Spencer Island that frequently overtop and have a history of failure during high flow events are not expected to be repaired after future breach events as there is no longer an active diking district. This means that simulations that assume high ground depicted in in the lidar data will effectively contain water are likely conservative from the standpoint of estimating water levels in the channel, but non-conservative for depicting flooding on the landward side of levees.

6.5. Hydrologic evaluation of potential effects on City of Everett and Snohomish County restoration projects

At the request of the City of Everett the 2D hydraulic models for existing conditions and proposed conditions were used to assess the hydrologic changes that could result at the City of Everett Smith Island Union Slough ecosystem restoration and mitigation projects and the joint City and County Smith Island Estuary Restoration Project (Figure 55), which includes the Smith Island Advanced Mitigation site. The month of December 2022 which included the king tide of record was used as representative for the period of analysis. Model output locations used in the analysis are shown in Figure 56.

City of Everett Advance Mitigation Site and Smith Island Ecosystem Restoration Project

As shown in Figure 57 tidal flows through the main breach increase significantly because of restoration. Positive flows reflect flows from Union Slough into the mitigation site. Overall tidal flows into the site increase by about 120 cfs on average, or about 44%. Most of this increase is because of levee lowering and breaching on Spencer Island, increasing flux on the distributary channels, and due to widening of the existing breach. The maximum flow into the site increases by 500 cfs, or about 19%. The minimum flow (ebb tide discharge) decreases by about 30 cfs, or 3%.

One of the bigger differences observed is the influence of water draining from Spencer during the high tides into Union Slough (see star), which fills up the 1135 wetland, and causes the flow leaving the City advance mitigation site on Smith Island (under existing conditions) to reverse to the north, since Union Slough will primarily be fed by flows from Spencer on a high tide. Note that at this stage water freely flows into the adjacent wetland to the north. At lower low tides total outflow from the wetland is essentially unchanged.

If increasing tidal inflows to the wetland is associated with habitat improvements, then we would expect this site to benefit from restoration actions on Spencer Island, and thus the County owned portion of the site as well.

As shown in Figure 58, in the main channel near well 1, tides (MLLW, MHHW, mean) are not significantly altered by the Spencer Island Restoration or conveyance (additional levee lowering near well 1, despite increased flows into the site at high tide. No effects to the wetland plant community would be expected from these small changes in stage.

In the main channel near well 3, located at the west end of the site, tides (e.g. MLLW, MHHW, MTL) are not significantly altered by the Spencer Island Restoration or conveyance (additional levee lowering near well 1, despite increased flows into the site at high tide. No effects to the wetland plant community would be expected from these small changes in stage. See Figure 59.

Water surface elevation hydrographs along the Smith Island setback levee show no significant changes compared to existing conditions for day-to-day tidal conditions, effects insignificant (see Figure 60, Figure 61).

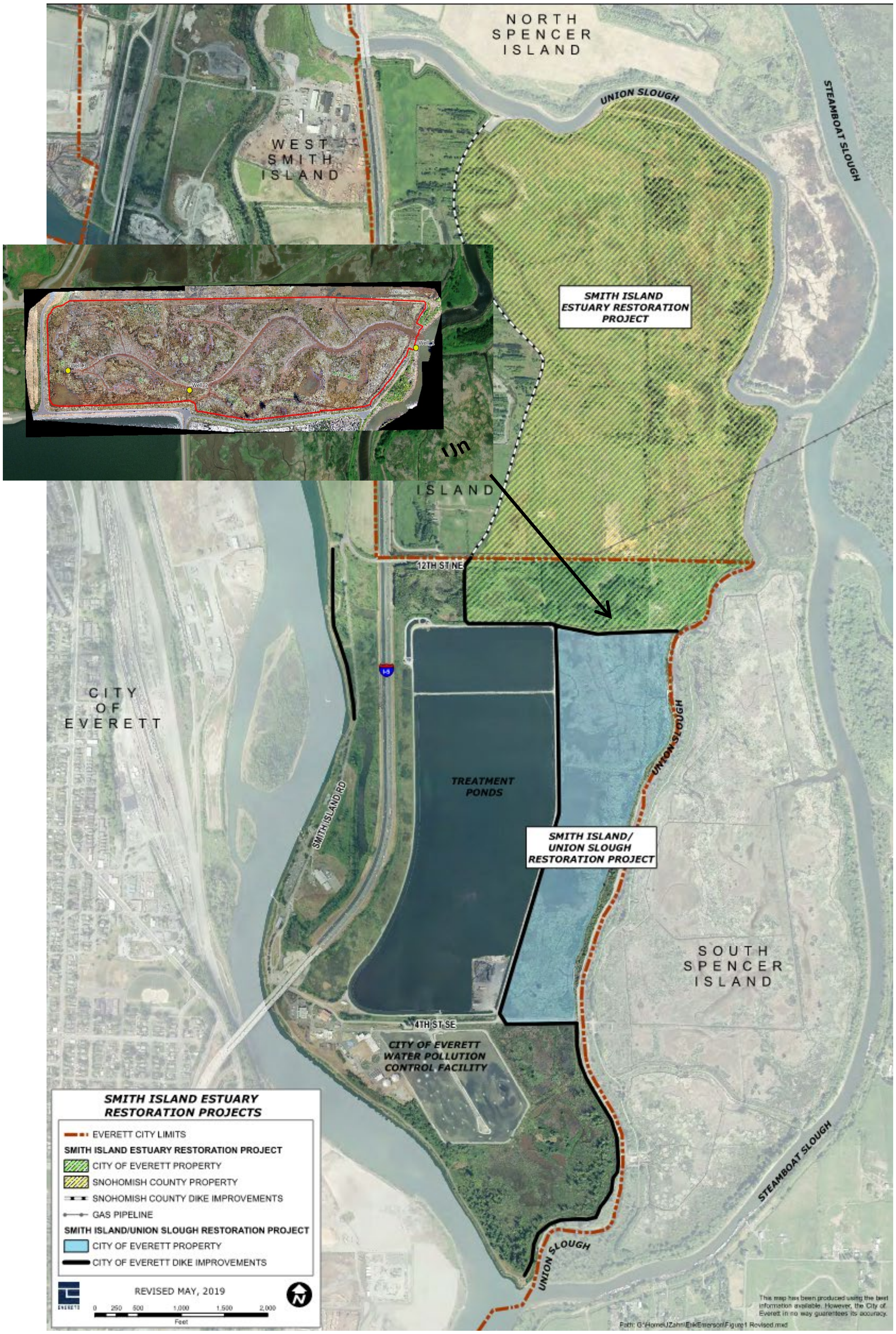


Figure 55. Constructed/restored tidal wetlands in the vicinity of Spencer Island

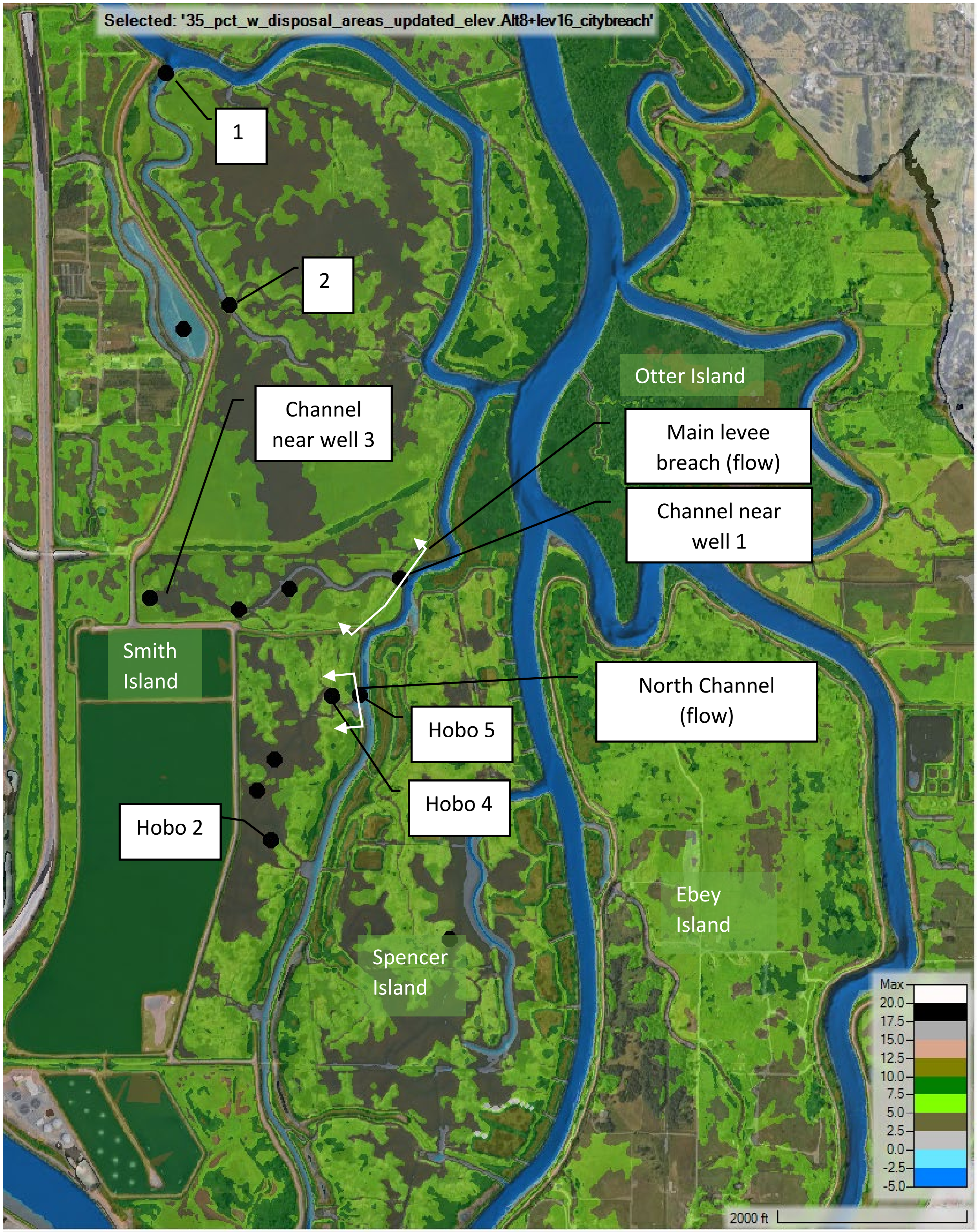
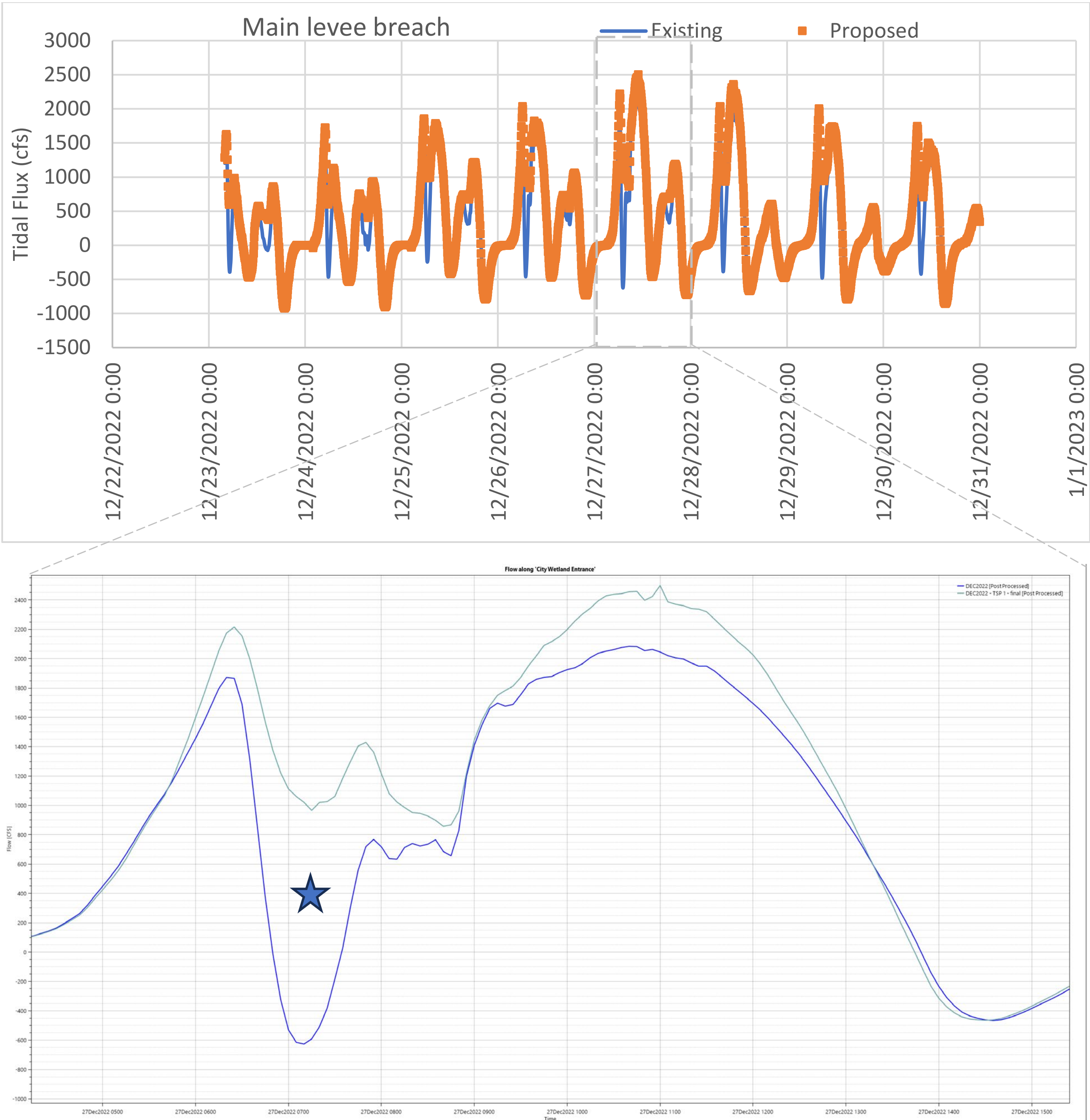
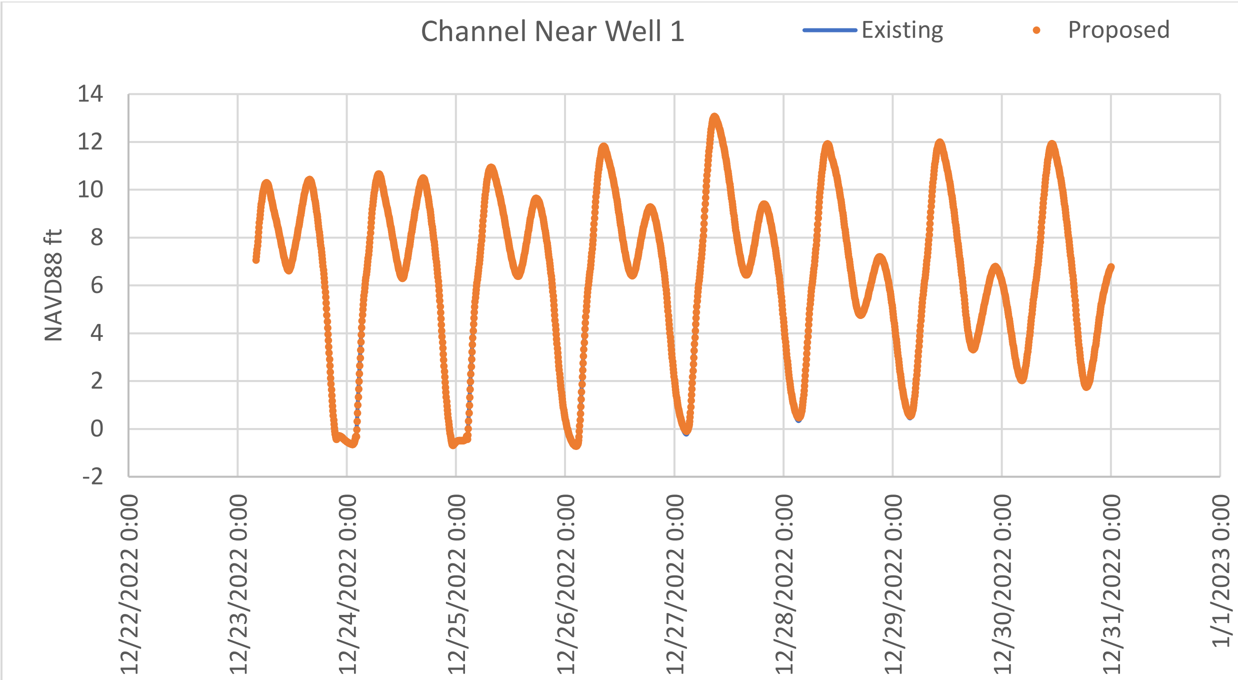


Figure 56. WSE and flow comparison points for December 2022 simulation, showing existing terrain and proposed grading plan



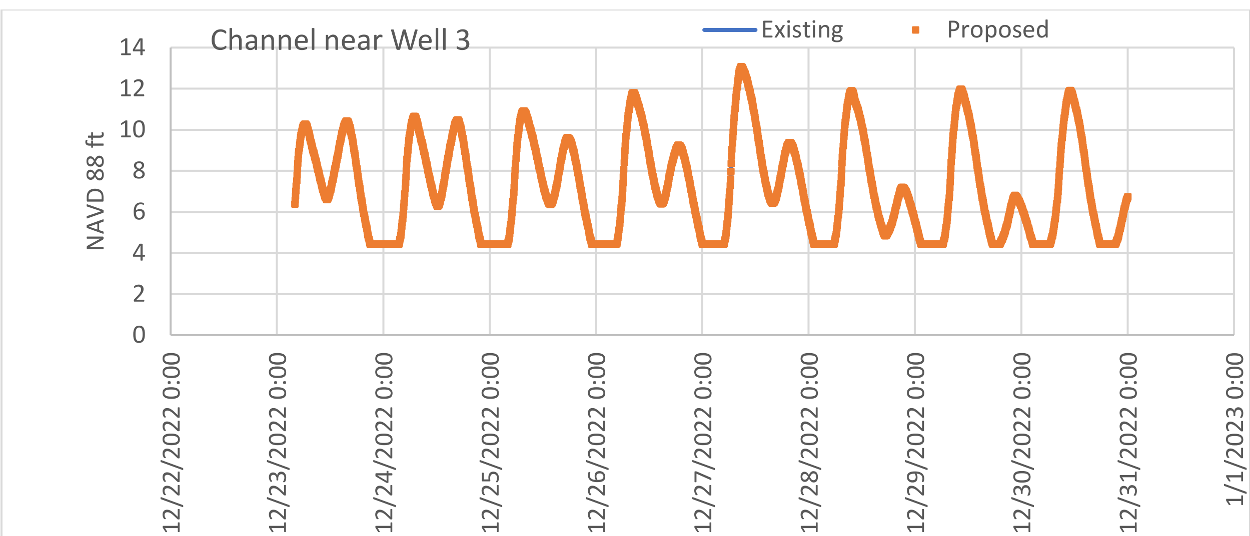
Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-960.264	-926.412	2084.43	2498.881	267.6407	389.9591

Figure 57. Tidal flux through main breach, with and without grading of existing levee breach



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
-0.776	-0.72	13.067	13.072	6.40522	6.435574

Figure 58. Tidal channel near Well 1 at City advance mitigation site



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
4.446	4.446	13.065	13.069	7.173679	7.198134

Figure 59. Tidal channel near Well 3 at City advance mitigation site

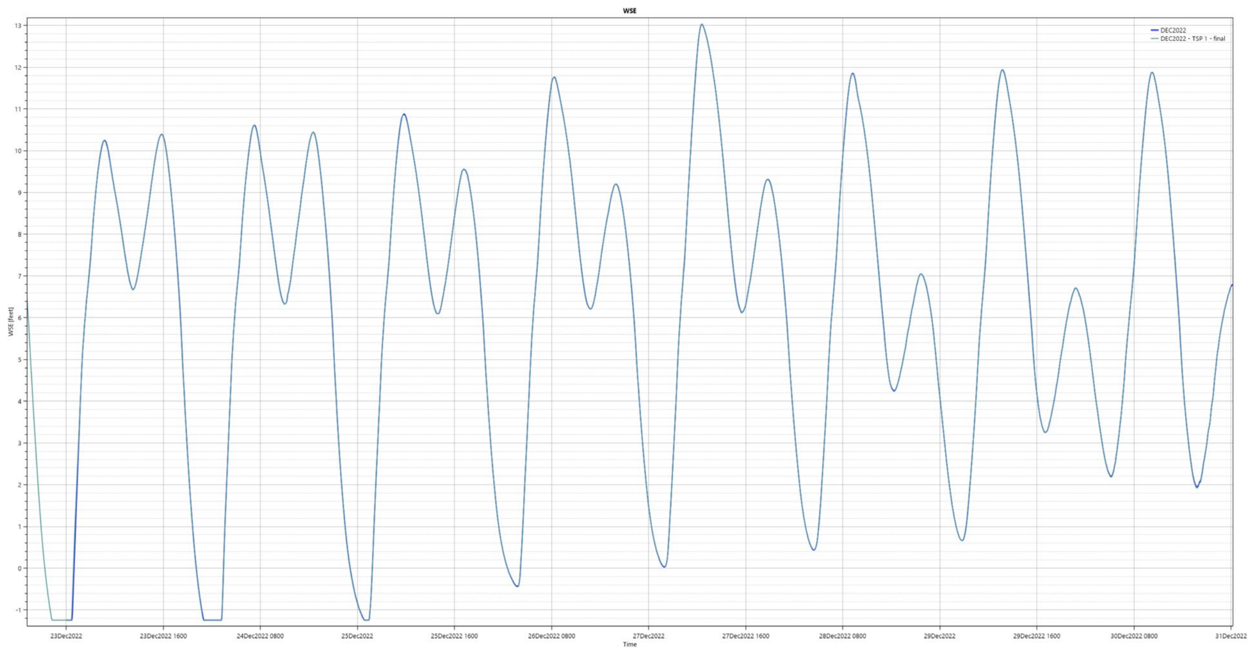


Figure 60. Stage at north end connection with Union Slough (point 1) – no detectable difference between existing and proposed conditions

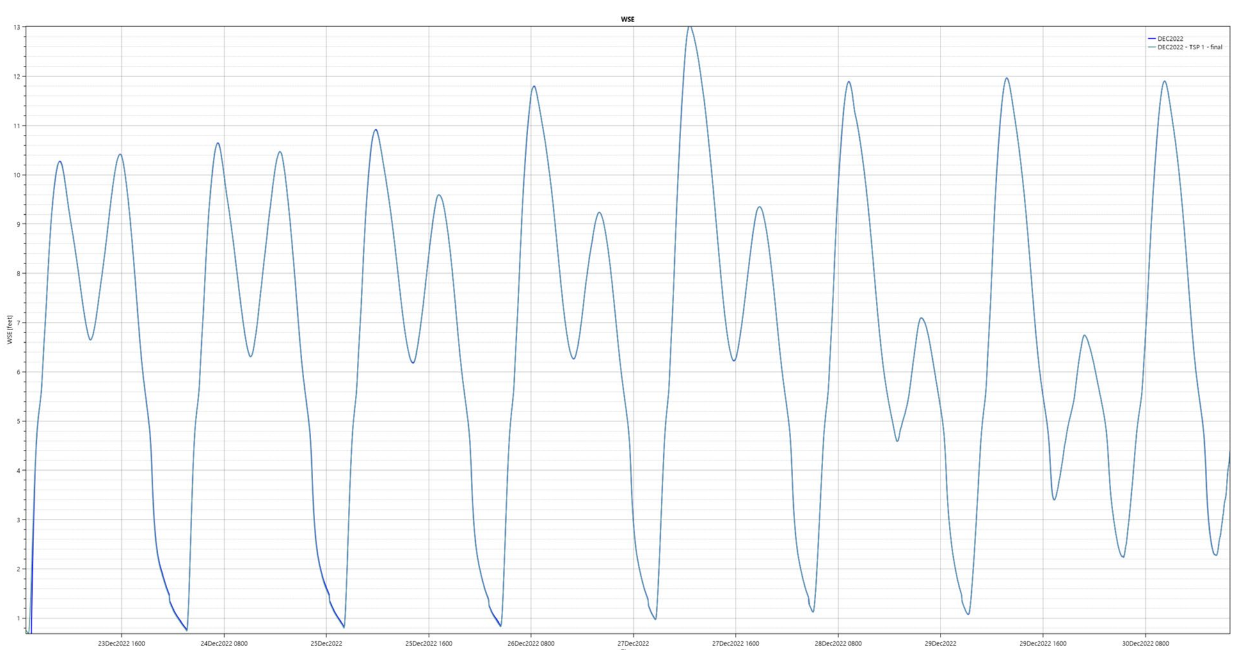


Figure 61. Stage hydrograph near dogleg point of setback levee (point 2) - no detectable difference between existing and proposed conditions

City of Everett Smith Island Union Slough Mitigation Site and Section 1135 Ecosystem Restoration Project

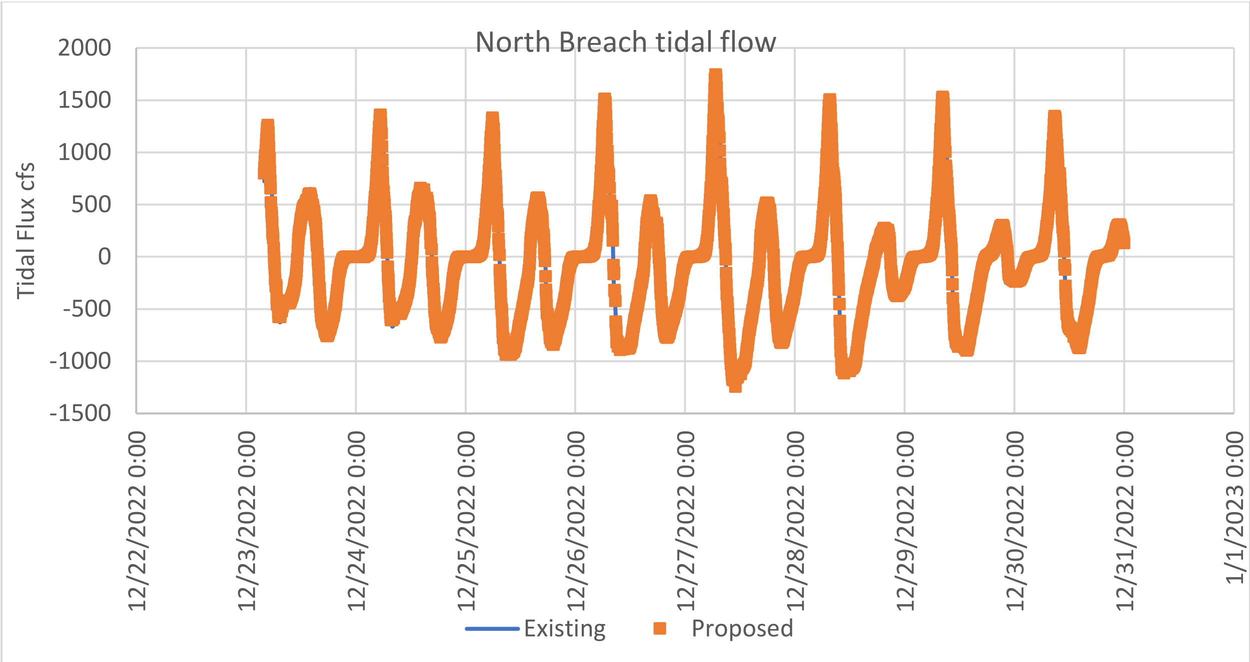
As shown in Figure 62 tidal flow into the north channel of the Union Slough advance mitigation site does not significantly change. Note that negative flows are flows out of the site, and positive flows are flows into the site. Outflows from the site appear to increase slightly, this is most likely due to water that is passing through Spencer and into the middle and south breaches into this wetland complex flowing north with the outgoing tides and exiting back to Union Slough here. The minimum flow increases by -130 cfs, which is roughly 10%. The maximum inflow decreases slightly, by 40 cfs, or about 2%. The average flow (-90 cfs) is essentially unchanged. The average reflects the typical condition for this location (flows returning from the wetland to Union Slough).

At the HOBO 5 monitoring station in Union Slough the with-project tidal range increases, with a lower low tide elevation (decrease of 0.6 ft), due to restoration. The mean tide decreases about 0.1 feet. This is likely due to increases in connectivity to Union Slough and Steamboat Slough, allowing for more efficient drainage of Union Slough, and also due to increased outflow from adjacent marshes which will aid in further tidal channel development. The high tide elevation remains unchanged. See Figure 63.

At the HOBO 4 monitoring station which is located within the mitigation site upstream of the Union Slough connection, the with-project tidal range increases, with a significantly lower (~1 ft) MLLW tide elevation, because of the Spencer Island restoration project. The mean tide decreases about 0.2 feet. This decrease is presumably due to increases in connectivity to Union Slough and Steamboat Slough, allowing for more efficient drainage of Union Slough, and also due to increased outflow from adjacent marshes which will aid in tidal channel development and vegetation establishment. The high tide elevation remains unchanged. See Figure 64.

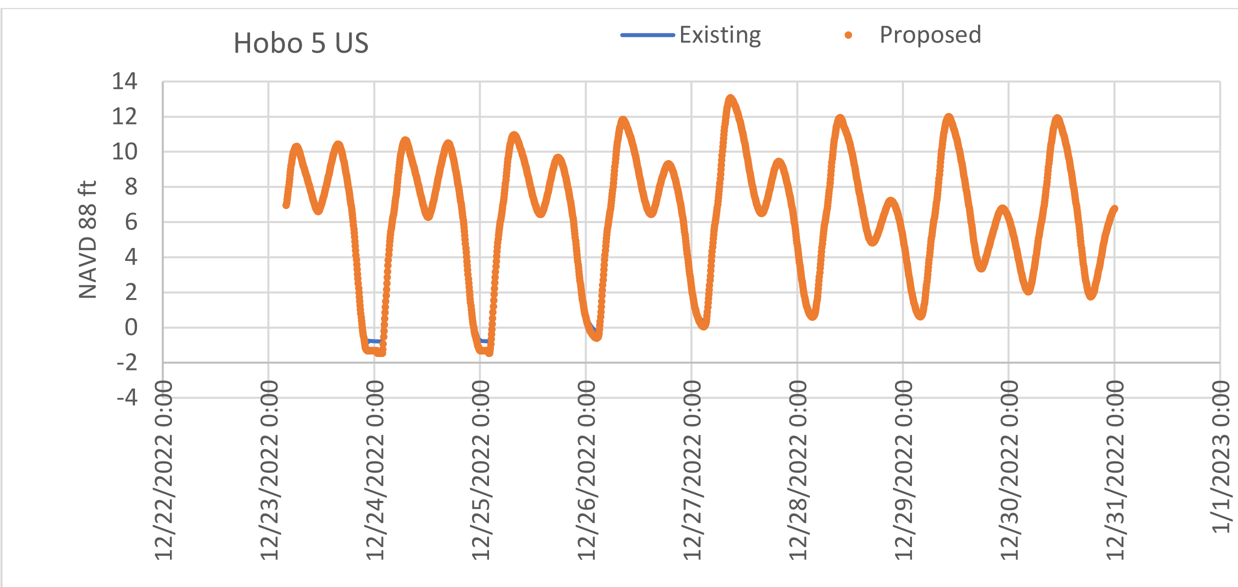
At the HOBO 2 monitoring station which is located within the mitigation site near the setback levee, the with-project tidal range does not change significantly because of the Spencer Island restoration project. The mean tide does not change, and the changes to the high tide and mean tide are too small to be meaningful. The lack of change is likely due to the persistence of hindered drainage from the wetland (ponding) near the most deeply subsided portion of the site. The increase in tidal range and the decrease in the MLLW at station 4 suggest channel erosion from the outlet back into the marsh could increase, which would be beneficial from the standpoint of draining ponded areas in the distal portions of the marsh. See Figure 65.

The overall assessment of the potential effects to the city mitigation sites are as follows: no significant change in the MHHW or MTL elevation are likely, but a modest decrease in the MLLW elevation is possible, with the magnitude inversely related to distance from the north outlet channel connection to Union Slough. The decrease in the MLLW elevation will result in an increase in the effective tidal range and the duration that water drains from the site daily. This increase in drainage could beneficially deepen existing channels through erosion, and if this erosion extends far enough into the marsh, some ponded areas could experience improved drainage and water quality. No change to wetland plant conditions is expected since the average and high tide elevations will remain unchanged. It should be noted that the proposed breaches and levee lowering on Spencer Island significantly increase the exchange of water in a normal tide cycle and during floods. This allows fish to more easily swim between Otter Island, Smith Island, and Spencer Island improving connectivity, a primary restoration objective.



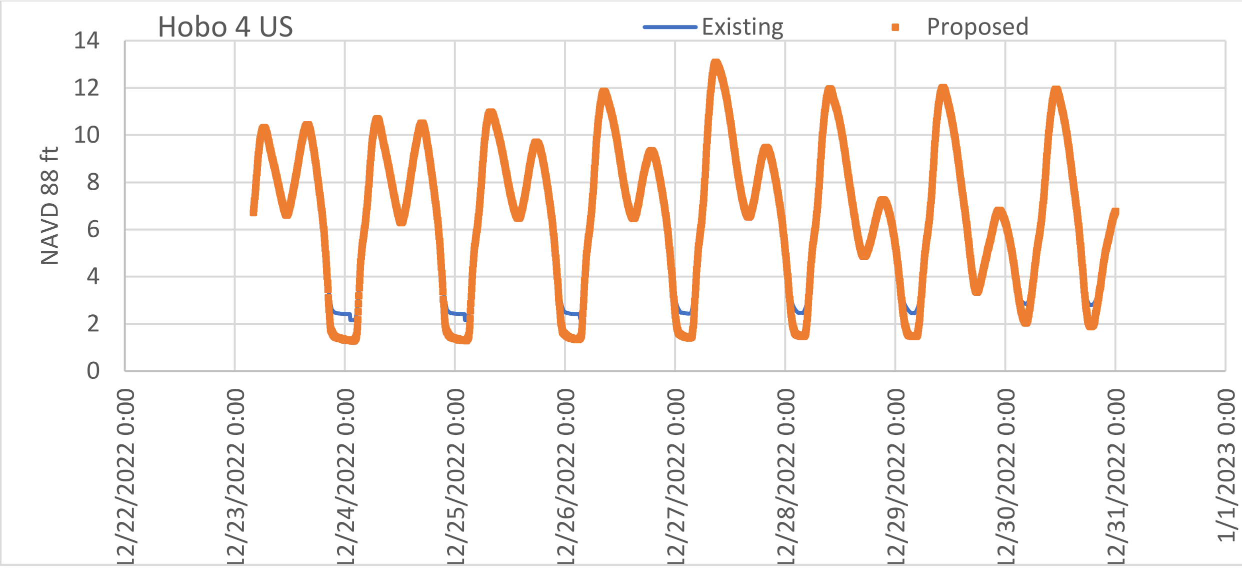
Existing	Proposed	Existing	Proposed	Existing	Proposed
min	min	max	max	mean	mean
-1107.18	-1245.18	1785.035	1745.242	-91.562	-92.6128

Figure 62. Tidal flux (flow) at North Breach (Smith Island/Union Slough Restoration Project)



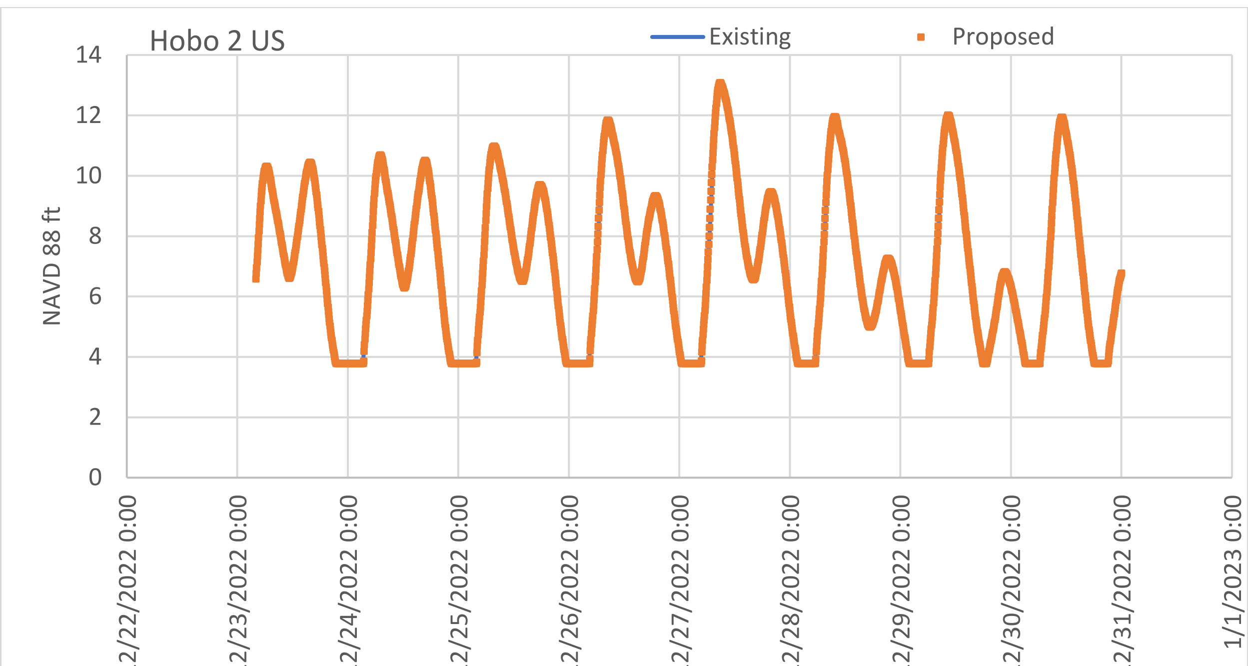
Existing	Proposed	Existing	Proposed	Existing	Proposed
min	min	max	max	mean	mean
-0.843	-1.447	13.08	13.081	6.507352	6.446531

Figure 63. WSE at HOBO logger #5 (Smith Island/Union Slough Restoration Project)



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
2.154	1.285	13.081	13.081	6.836635	6.669405

Figure 64. WSE at HOBO logger #4 (Smith Island/Union Slough Restoration Project)



Existing min	Proposed min	Existing max	Proposed max	Existing mean	Proposed mean
3.785	3.785	13.082	13.084	7.08278	7.100881

Figure 65. WSE at HOBO logger #2 (Smith Island/Union Slough Restoration Project)

7. Summary and Conclusions

The following summarize main findings from this analysis:

1. No updates to hydrology were made as part of this study. It has been used without adjustment. Review of available data suggest revision of the effective model hydrology is warranted given that two decades have elapsed since the last analysis was conducted.
2. Use of the FEMA effective 1D model for design of the tidal marsh restoration project is insufficient to confidently size and orient tidal channels and locate dike breaches or determine effects of the project on nearby reaches. For this reason, the Snohomish County 2D model prepared by WSE was utilized subject to the modifications described herein.
3. The modified 2D model reproduced observed flood elevations at Ebey Slough and the Snohomish Mainstem. Peak stages matched between 0.01 and 0.43 feet for the December 2022 event, and between -0.09 and 0.13 feet for the December 2023 event. Peak flows at Snohomish were reproduced within -8.7% and -4.6% for the December 2022 and 2023 validation events respectively.
4. The USACE 2D existing conditions model shows less water surface elevation values than the FEMA FIS study. On average, the 1% flows show 0.7 feet less on the USACE 2D existing model compared to the FEMA regulatory water surface elevation, and 1.3 feet compared to the FEMA BFE water surface elevation.
5. Coastal (tidal) flood elevations exceed riverine flood elevations within Spencer Island for all floods events with 99% to 10% AEP. Riverine flood elevations are higher than coastal flood elevations for less frequent floods (<10% AEP). Restoration actions (levee lowering, breaching) will not influence tidal flooding in the vicinity of Spencer Island, however these actions will influence flood elevations in large fluvial flood events.
6. Small changes in WSE are possible within and around Spencer Island for fluvial flooding. Changes are generally less than 0.1 feet. Flood elevations generally decrease within Steamboat Slough, Ebey Island, and south of Spencer Island. Flood elevations are expected to increase slightly in Union Slough west of Spencer Island, and more so in the City/County mitigation wetland immediately northwest of Spencer Island. With inclusion of mitigation for induced flooding as part of the restoration project (consisting of expansion of the existing levee breach on Smith Island), the potential increase in inundation (induced flooding) on developed portions of Smith Island can be avoided. This will induce flooding instead on tidal wetlands that were purposefully restored to allow flooding to occur.
7. Evaluation of the effects of the Smith Island conveyance improvement were completed at the request of the City of Everett. Widening of the existing breach into the city of Everett mitigation site will normalize (improve) tidal hydrology for the City and County wetlands and increase conveyance of floodwaters across the city mitigation site and into the Snohomish County Smith Island tidal marsh restoration project. This will locally increase inundation in these restored wetlands, while reducing flood elevations (and potential levee overtopping) upstream along the Union Slough 1135 levee. USACE anticipates purchase of flowage easements in the tidal wetlands to accommodate these changes, and affected parties have been coordinated with in advance.
8. The project repositions fill within an existing density fringe area, increasing conveyance. While the changes in WSE due to proposed grading at Spencer Island are small, the FEMA flood

insurance rate maps likely require a Conditional Letter of Map Revision once the 60% plans are ready.

8. Recommendations for PED Phase

Isolated geometry changes were made to the model geometries to improve the accuracy of the high flow runs where dike overtopping is widespread. Due to time constraints, these geometry updates were not included in plans where dike overtopping is not occurring. The geometry changes were mainly made to tighten breaklines and cell perimeters around dikes and highpoints. For PED phase, all existing conditions and with project plans should be synced to use the same respective geometry and terrain data sets.

Surveys of levees on Ebey Island and Spencer Island are needed to ensure levee overtopping near Spencer Island is accurately estimated. Partial topographic survey of the levees was completed in September 2025 by the NFS, after completion of modeling. Review of this survey data indicates the levees in the lidar DEM are higher by about 2 feet than actual surveyed elevations, which means that existing conditions elevations along dikes in the hydraulic models are artificially high by the same amount. The existing topo survey will be combined with additional topo and bathymetric survey of the remainder of the levees and ditches in March 2026. The survey data will be used to replace the topography for the levees being used in the civil grading plans and hydraulic modeling. Once the model is updated with lower topographic elevations for the existing levees the modeled overflows from the sloughs into Spencer Island will increase. This will reduce the differences between FWP and FWOP inundation and reduce the need for the Smith Island conveyance improvement.

The model should be migrated to RAS 2025 due to superior meshing tools and computational efficiency. Mesh faces along channels and levees should be refined. Recalibration can be considered if the run times can be significantly reduced. Near historic flooding occurred in December 2025. High water marks should be acquired to improve the calibration.

Discussions with Snohomish County regarding status of unaccredited levees in the model and assumptions regarding levee breaching are necessary to complete the no-rise analysis. This work will be done using a separate FEMA flood map and model update underway as part of ongoing FPMS study in FY 26.

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Engineering and Construction Bulletin (ECB)

- ECB 2016-25
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- ERDC TN-EMRRP SR-29
  Fischenich, C. (2001). "Stability Thresholds for Stream Restoration Materials," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Feasibility Report Engineering Appendix

Spencer Island Ecosystem Restoration HH&C Annex D2: Hydrology & Hydraulics for Feasibility Phase

Supplemental Results

Snohomish County, WA

20-Jan 2026 35% ATR

Prepared by

US Army Corps of Engineers®
Seattle District

Contents

Figures

1. Overview

This annex is meant to show the results from the hydraulic modelling analysis. Because of the large number of models, a table is included that describes each scenario and its flow inputs. The scenario number and descriptions are used interchangeably throughout the results. See table 1 below.

Scenario	Plan	Plan File	Description
1	1P	p03	99% AEP Tide, 99% AEP Flows
	1E	p15	99% AEP Tide, 99% AEP Flows
2	2P	p04	50% AEP Tide, 99% AEP Flows
	2E	p16	50% AEP Tide, 99% AEP Flows
3	3P	p05	10% AEP Tide, 99% AEP Flows
	3E	p17	10% AEP Tide, 99% AEP Flows
4	4P	p06	2% AEP Tide, 99% AEP Flows
	4E	p18	2% AEP Tide, 99% AEP Flows
5	5P	p07	1% AEP Tide, 99% AEP Flows
	5E	p19	1% AEP Tide, 99% AEP Flows
6	6P	p08	0.2% AEP Tide, 99% AEP Flows
	6E	p20	0.2% AEP Tide, 99% AEP Flows
7	7P	p09	MHHW + 1ft, 50% AEP Flows
	7E	p21	MHHW + 1ft, 50% AEP Flows
8	8P	p10	MHHW + 1ft, 10% AEP Flows
	8E	p22	MHHW + 1ft, 10% AEP Flows
9	9P	p11	MHHW + 1ft, 2% AEP Flows
	9E	p23	MHHW + 1ft, 2% AEP Flows
10	10P	p13	MHHW + 1ft, 1% AEP Flows
	10E	p24	MHHW + 1ft, 1% AEP Flows
11	11P	p14	MHHW + 1ft, 0.2% AEP Flows
	11E	p25	MHHW + 1ft, 0.2% AEP Flows
12	12P	p37	2080 MHHW + 1ft, 2080 50% AEP Flows
	12E	p33	2080 MHHW + 1ft, 2080 50% AEP Flows
13	13P	p38	2080 MHHW + 1ft, 2080 10% AEP Flows
	13E	p34	2080 MHHW + 1ft, 2080 10% AEP Flows
14	14P	p39	2080 MHHW + 1ft, 2080 1% AEP Flows
	14E	p35	2080 MHHW + 1ft, 2080 1% AEP Flows
15	15P	p40	2080 MHHW + 1ft, 2080 0.2% AEP Flows
	15E	p36	2080 MHHW + 1ft, 2080 0.2% AEP Flows

Table 1. Flow Scenarios and Descriptions

1.1 Depth Inundation Comparison Maps

After HEC RAS model runs were completed using the input flows and tidal stages specified in Annex D1, plots were created comparing the depths of proposed and existing conditions. These plots were created using the RAS calculated layer functionality. The actual scripting was done in C#. See Figure 1 for the script used.

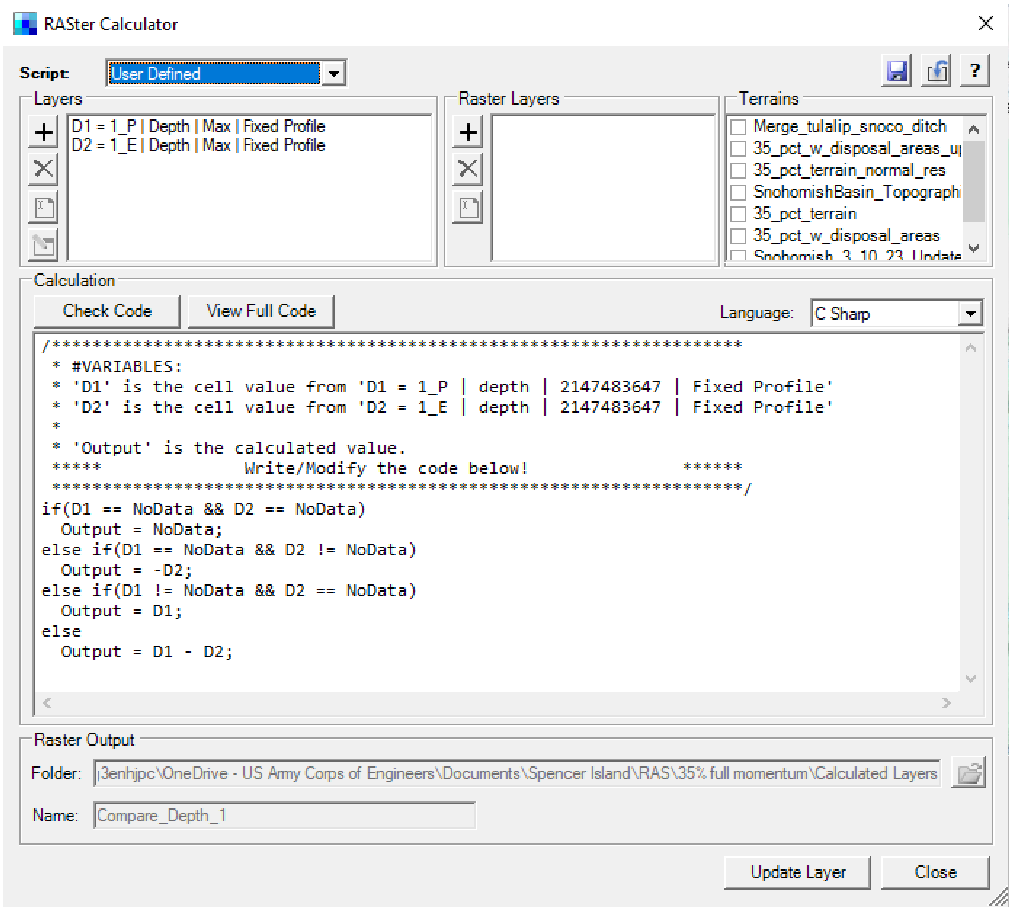


Figure 1. C# script used to generate plots

A fairly straight forward script, most of the values are the proposed conditions depth minus the existing conditions depth. If there is no data for either at a given location, the corresponding raster point is set to no data as well. If there is only existing conditions data, it will be set to the negative existing conditions value. Likewise, if there is only proposed conditions data, it will be set to the proposed conditions value at that location. The plots are meant to be interpreted as follows: If the location is blue, it means that the proposed conditions show increased depth at that location. If the location orange, it means less depth for proposed conditions at that area.

1.2 Water Surface Profile Plots

Profile lines were drawn throughout various reaches of the study area. See Figure _ for a map of the different reaches. Water surface elevations throughout the profile lines were extracted and plotted. The "Other" reach on the map is not plotted, just included in the map so locations are easier to identify.

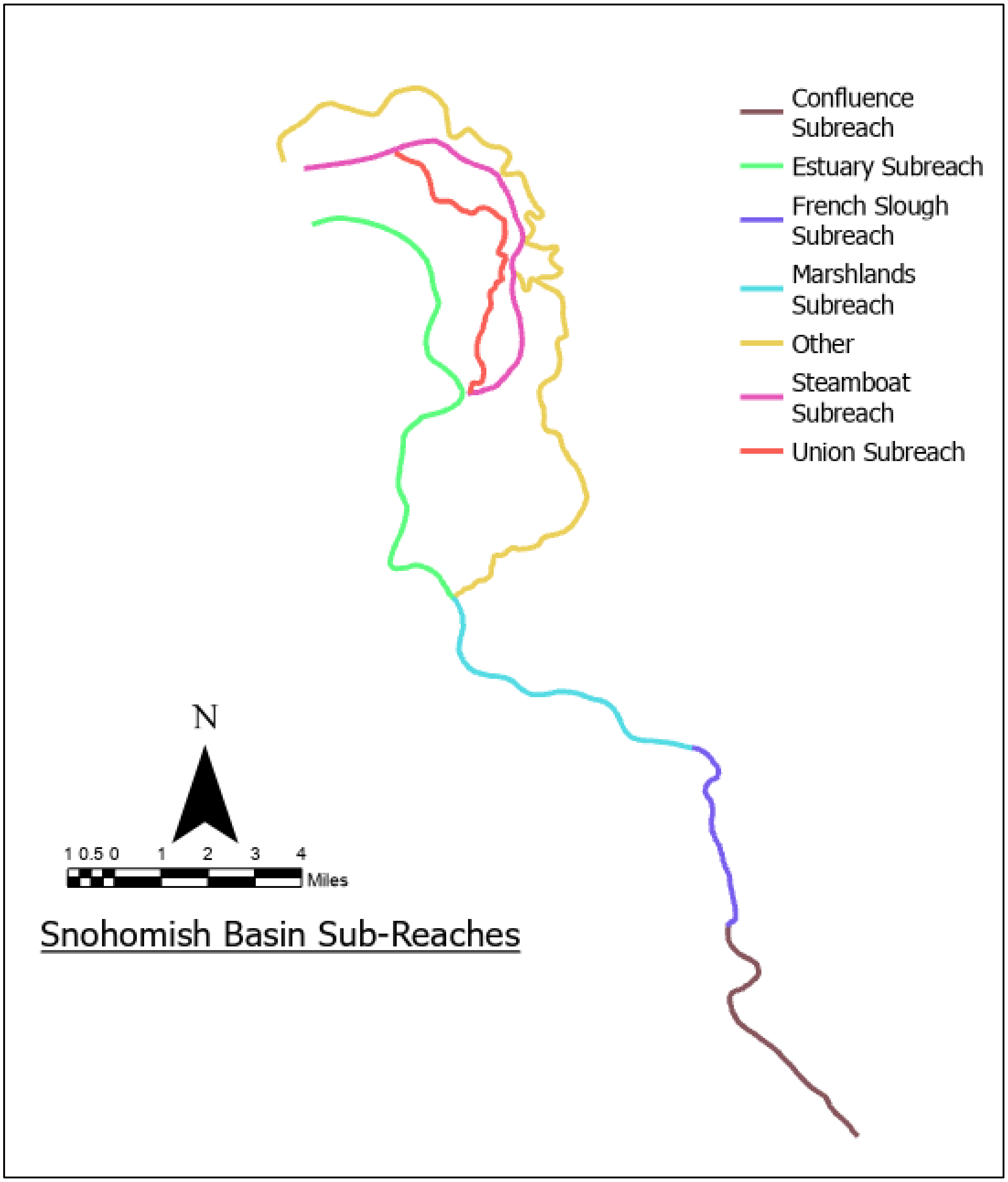


Figure 2. Snohomish Basin Subreaches

1.3 Velocity Plots

Velocity Difference Plots use the same code as the Depth Inundation Comparison Maps, only the variables are switched from depth to velocity maximums. Only the existing condition flows for the 50%, 10%, and 1% AEP are plotted.

1.4 Duration Plots

Inundation Duration plots use the same code as the Depth Inundation Comparison Maps, only the variables are switched from depth to velocity maximums. Only the existing condition flows for the December 2022 king tides and the existing conditions 1% AEP events (Scenario 10) are provided as these span the range of expected conditions.

1.5 Model accuracy discussion

The Snohomish River estuary hydraulic model is based on best available data but has several limitations that affect the results and should be considered when evaluating changes in inundation. Model accuracy is the combined error of underlying data, limitations of the model, and natural variability. Hydraulic models are typically calibrated to provide the most accurate estimate possible using available gage data, and actual flood elevations for the same condition should be expected to fluctuate around that estimate, within the accuracy of the model. While this model is calibrated to within 0.25 feet of observed gage data at Snohomish, the widespread levee overtopping and effects of levee breaching, long duration of the flood hydrograph, and variable effects of tides and storm surge result in flood elevations that are uncertain and can easily vary by well over a foot (above or below) model predictions.

Using the principles for quantifying model uncertainty presented in USACE EM 1110-2-1609 (Table 2) we roughly estimate that modeled flood elevations are very likely to be within 2 feet of observed high water marks accounting for the effects of tides, surge, antecedent conditions, data issues, model limitations, weir coefficients, roughness effects, and geomorphic variability (bedforms, effect of temperature on bedforms). Table 2 below presents a summation of known major sources of error with best professional judgement of water surface sensitivity for each factor.

Table 2. Total Standard Deviation in Stage Uncertainty EM 1110-2-1609

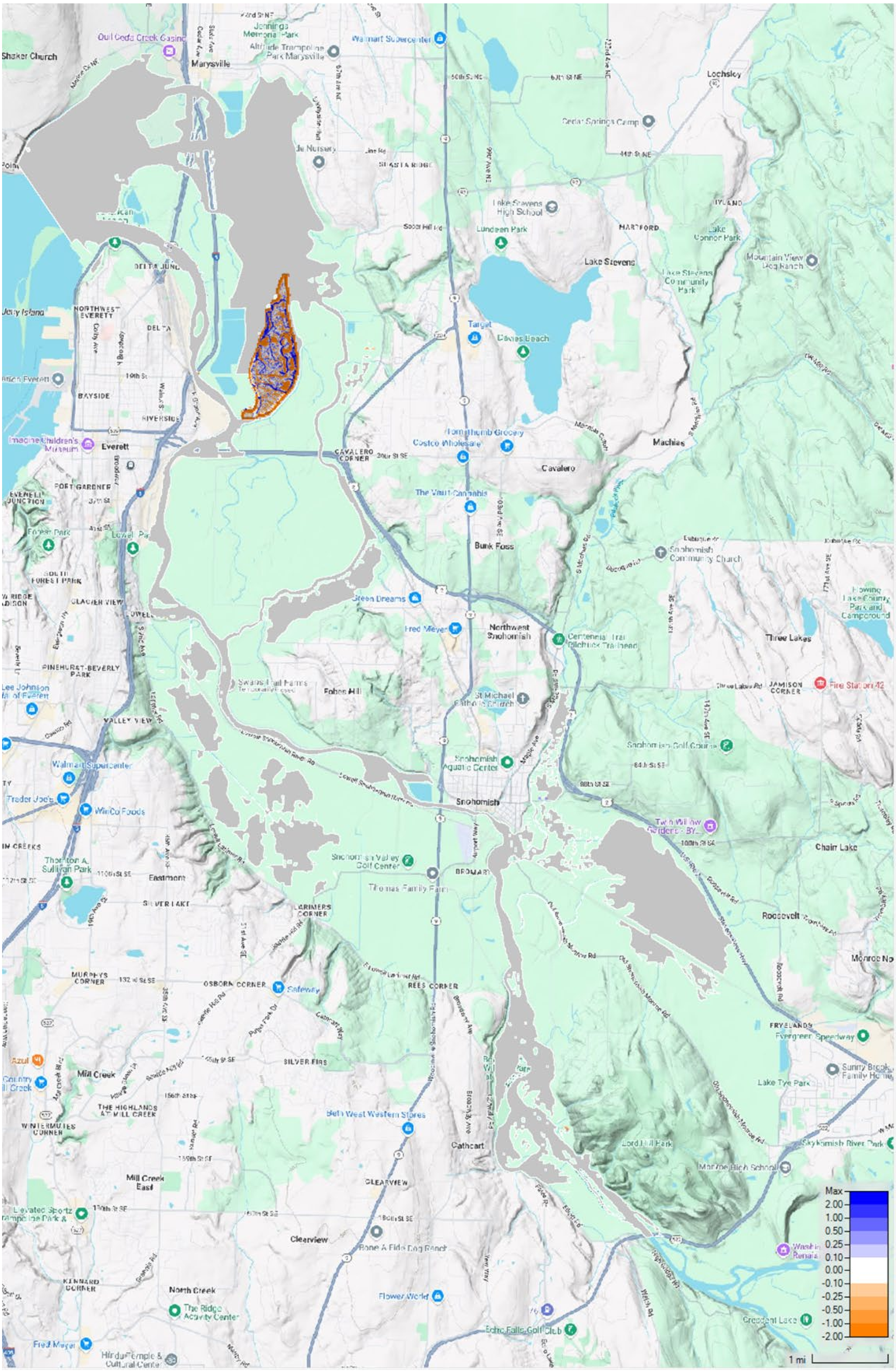
Source	**E (ft)**	**S (ft)**	S^2
Uncertainty in modeling approach			
Lidar data and bathy data confidence	1	0.250	0.06
n value sensitivity	0.5	0.125	0.02
Calibration error for HWM data	0.25	0.063	0.00
Variation in weir coeff for lateral structures	1.00	0.250	0.06
total model uncertainty	**1.52069**	**0.380**	**0.14**
Natural variability			
Settlement / breaching of levee features	2.00	0.500	0.25
tidal backwater and storm surge effects	2.00	0.500	0.25
sediment/geomorphic effects	0.50	0.125	0.02
total natural uncertainty	**2.87228**	**0.718**	**0.52**
total uncertainty	**3.25**	**0.813**	**0.66**
Stage variation with 95.4% confidence (E/2) +/- =	**1.625**	**ft**	

Results provided herein are considered conservative and will be refined in the design phase. Design phase data updates will include topographic surveys of levees and ditches near Spencer Island. This data will replace lidar data that is partly influenced by dense vegetation. Use of the actual ground elevations in the PED phase model will allow more levee overtopping to occur under existing conditions, lessening the differences between existing and proposed conditions. This is likely to reduce and possibly eliminate the need for the conveyance (channel improvement) near Spencer Island to prevent worsening of induced flooding on developed portions of Smith Island.

2. Depth Comparison Maps

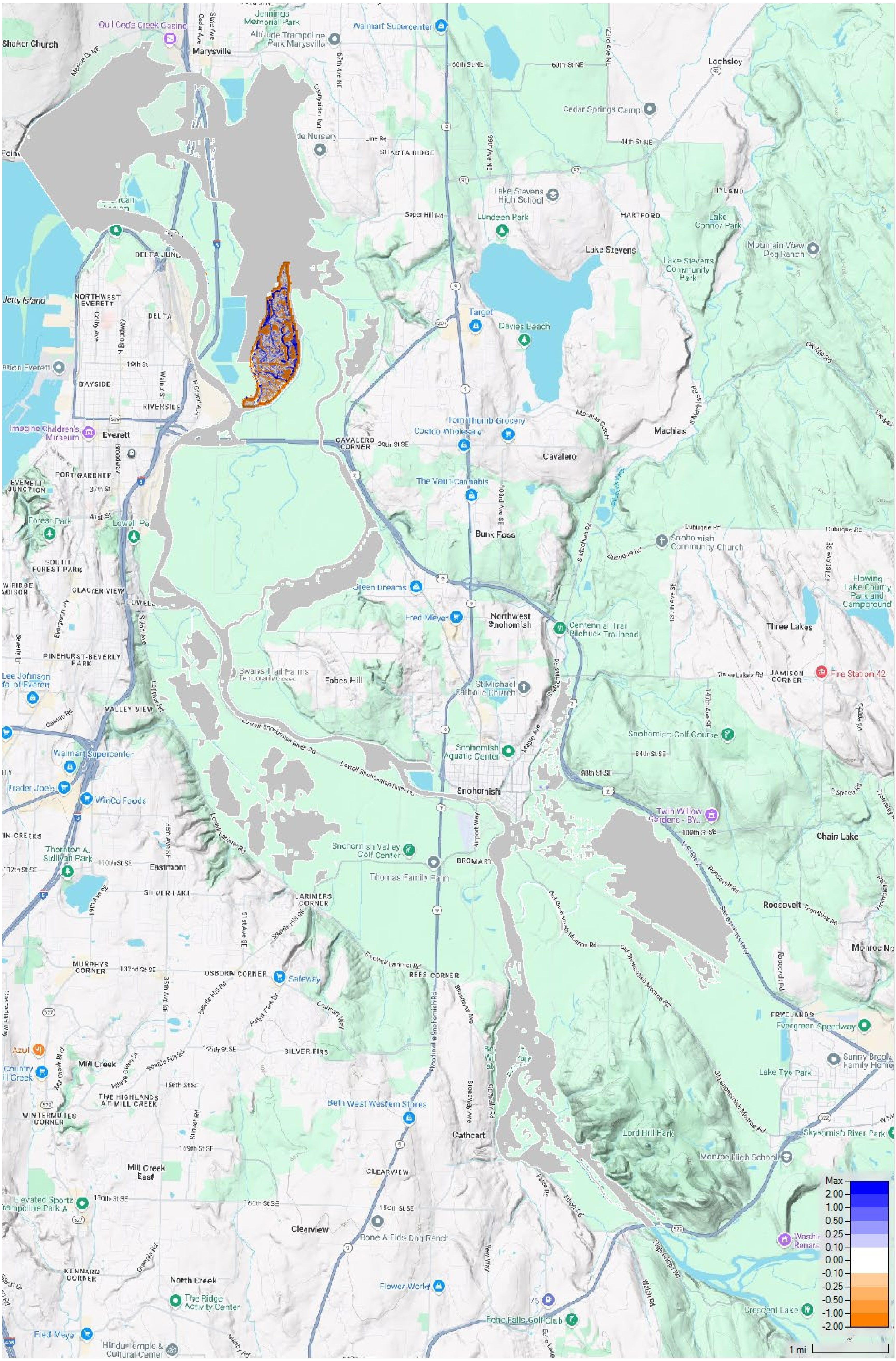
2.1 Scenario 1

Figure 3. Scenario 1 Depth Comparison. 99% AEP tide, 99% AEP river flow.



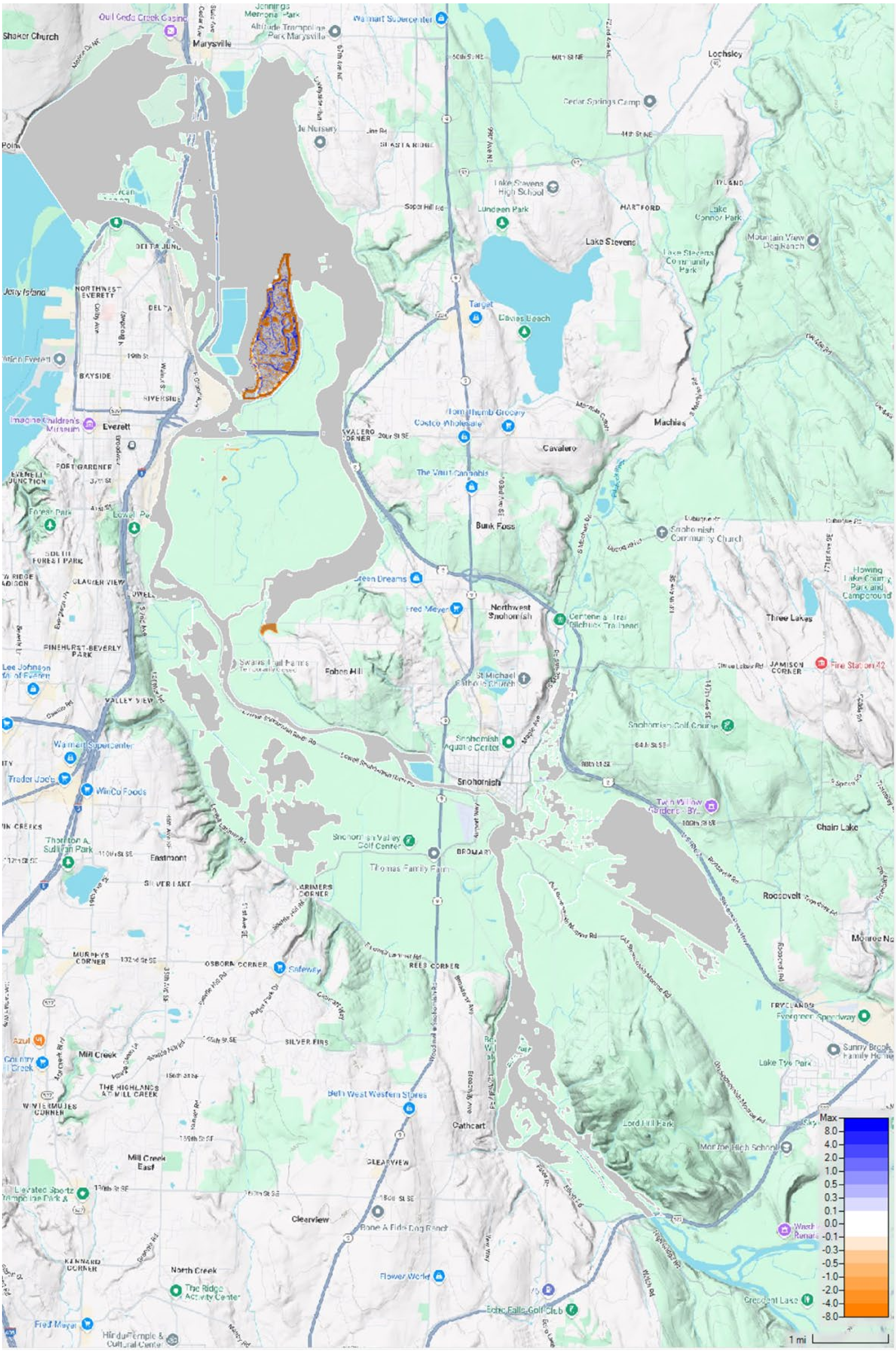
2.2 Scenario 2

Figure 4. Scenario 2 Depth Comparison. 50% AEP tide, 99% AEP river flow.



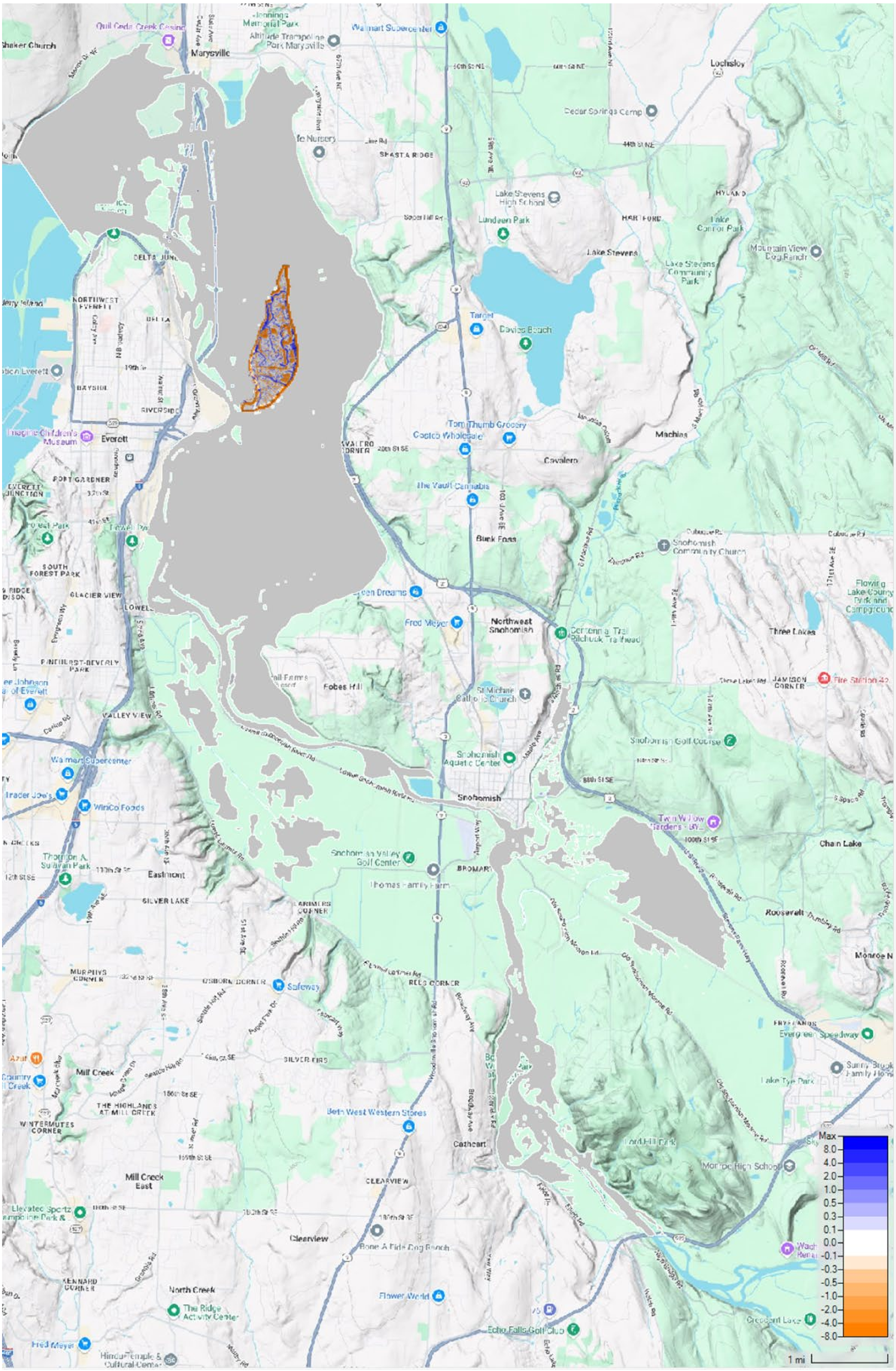
2.3 Scenario 3

Figure 5. Scenario 3 Depth Comparison. 10% AEP tide, 99% AEP river flow.



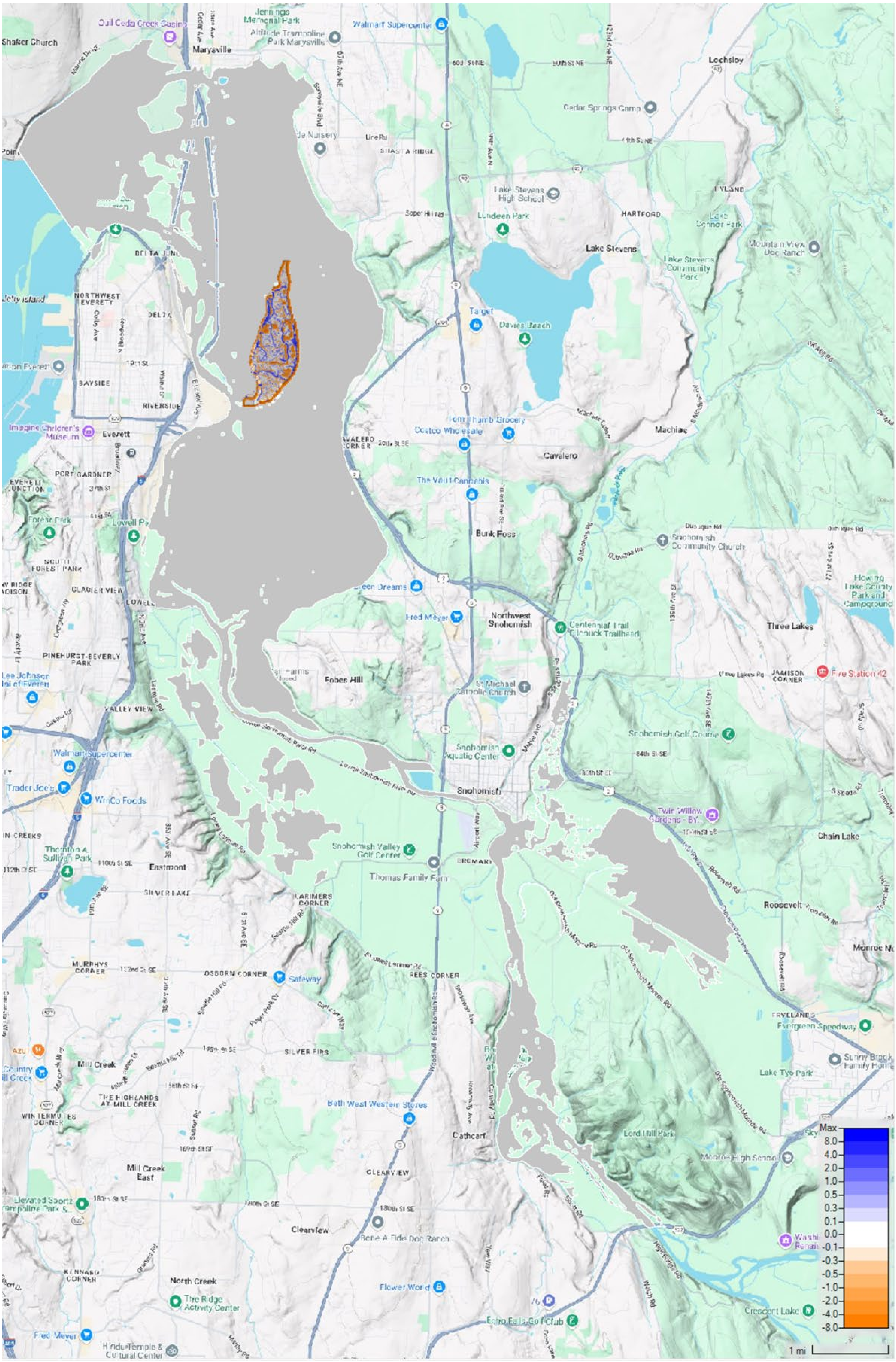
2.4 Scenario 4

Figure 6. Scenario 4 Depth Comparison. 2% AEP tide, 99% AEP river flow.



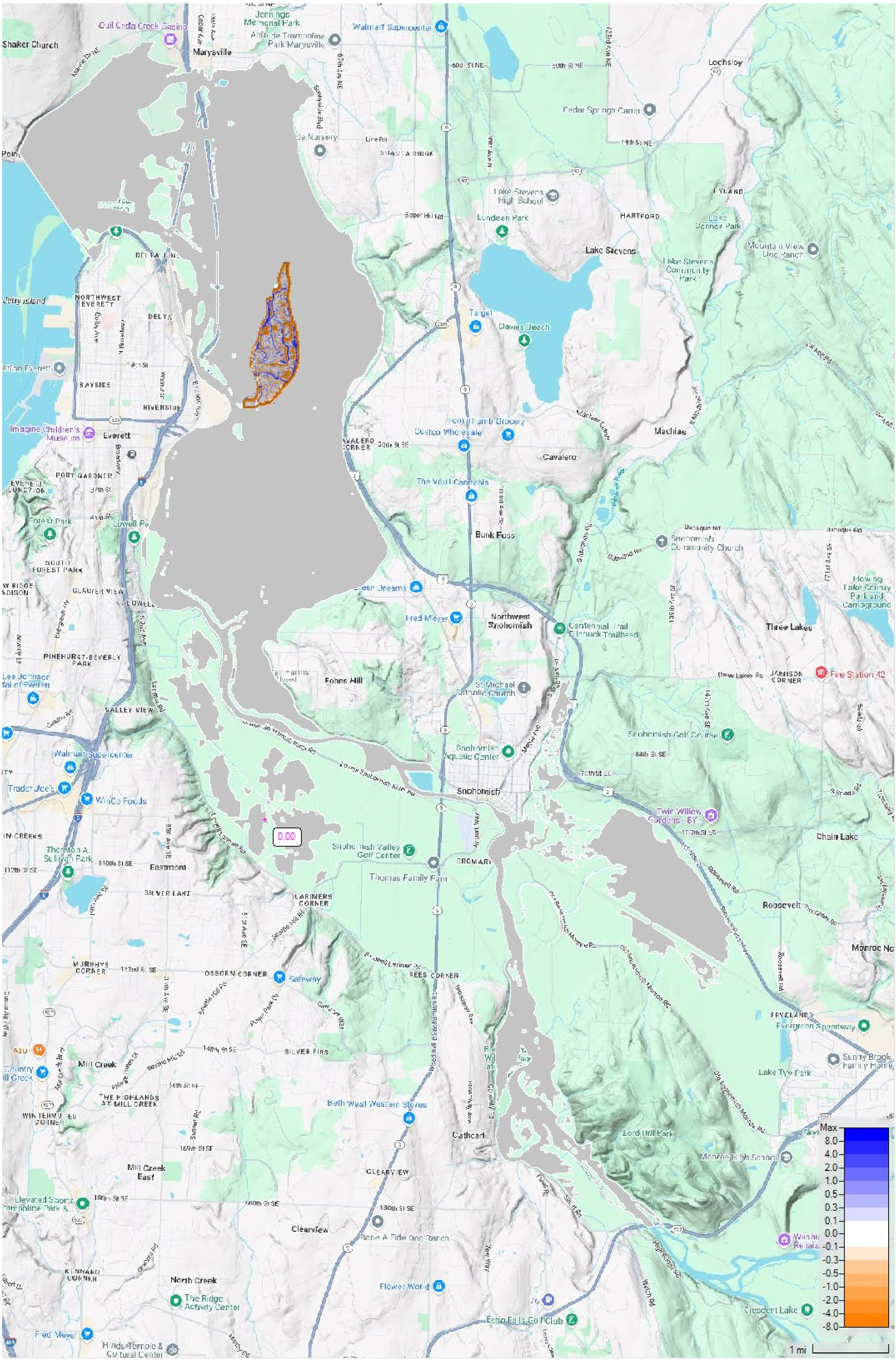
2.5 Scenario 5

Figure 7. Scenario 5 Depth Comparison. 1% AEP tide, 99% AEP river flow.



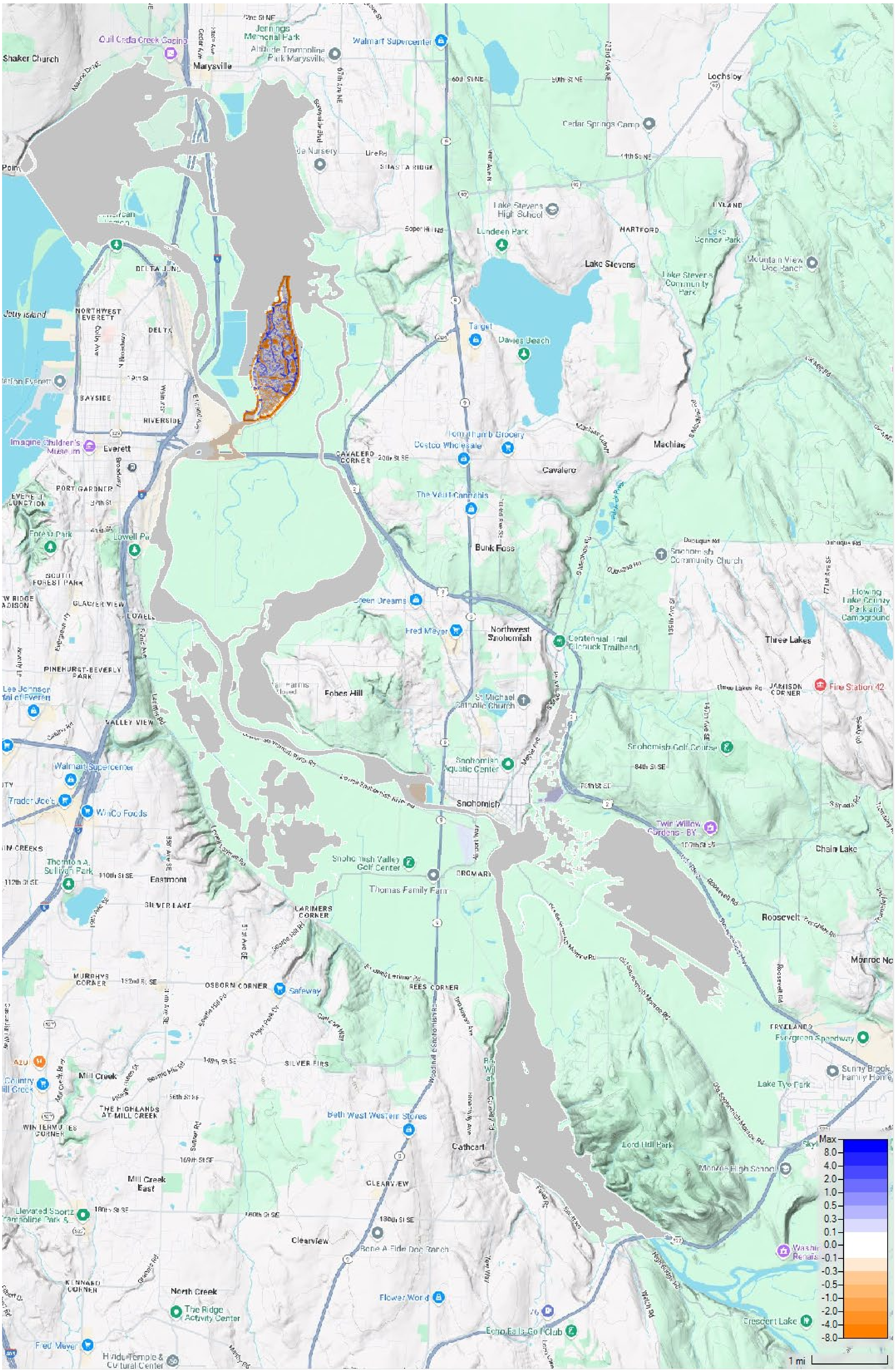
2.6 Scenario 6

Figure 8. Scenario 6 Depth Comparison. 0.2% AEP tide, 99% AEP river flow.



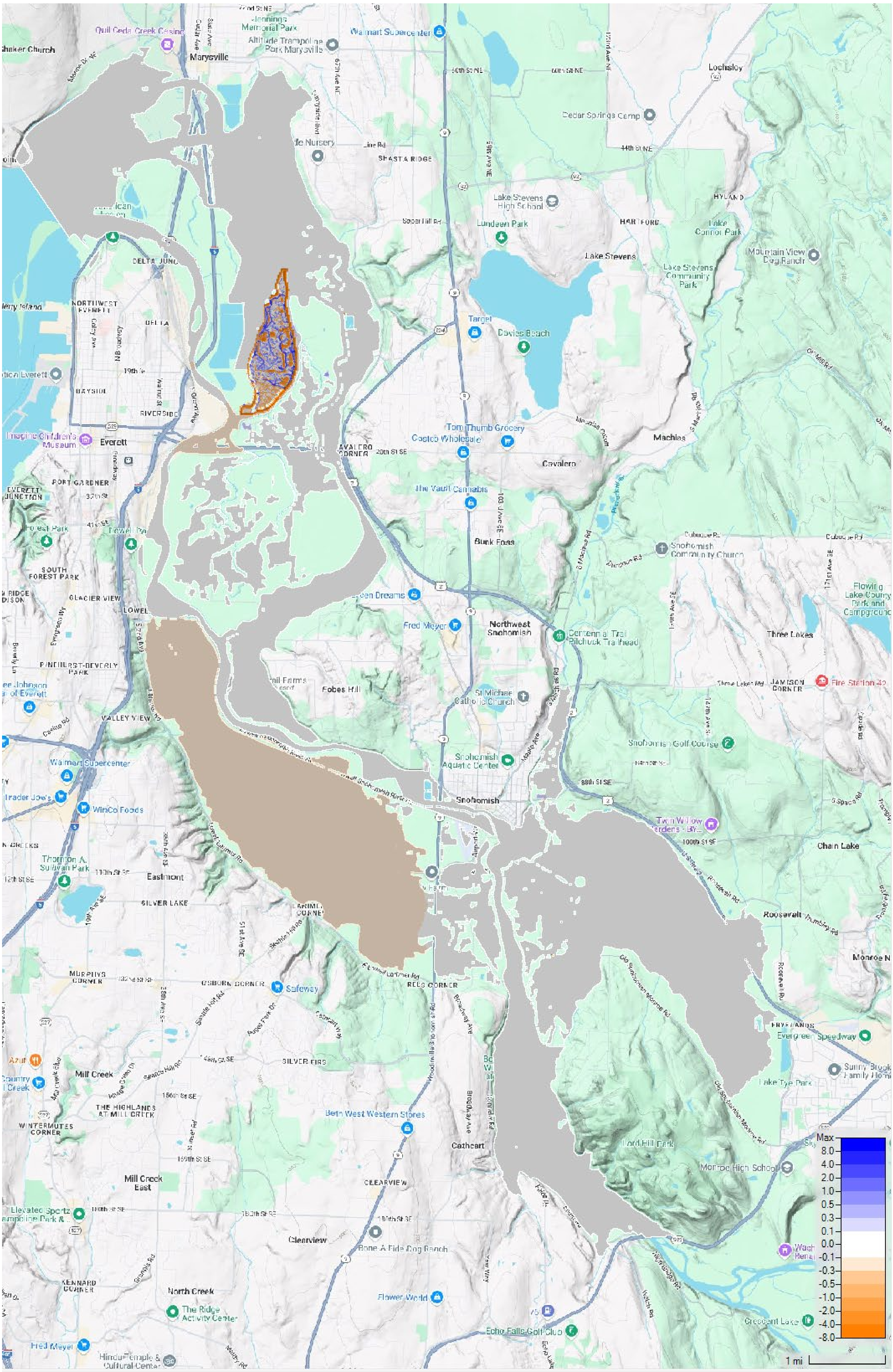
2.7 Scenario 7

Figure 9. Scenario 7 Depth Comparison. MHHW + 1 ft tide, 50% AEP river flow.



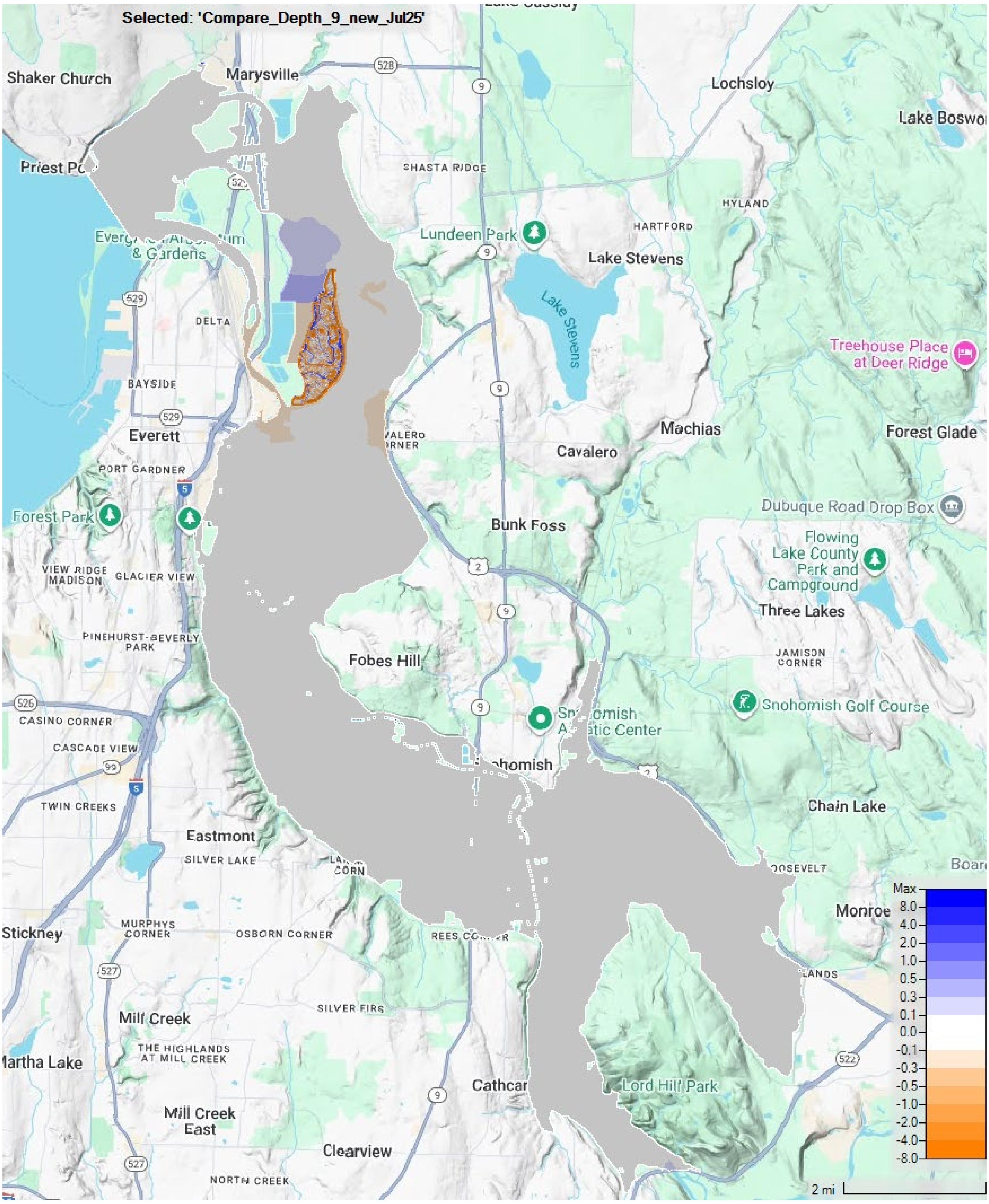
2.8 Scenario 8

Figure 10. Scenario 8 Depth Comparison. MHHW + 1 ft tide, 10% AEP river flow.



2.9 Scenario 9

Figure 11. Scenario 9 Depth Comparison. MHHW + 1 ft tide, 2% AEP river flow.



2.10 Scenario 10

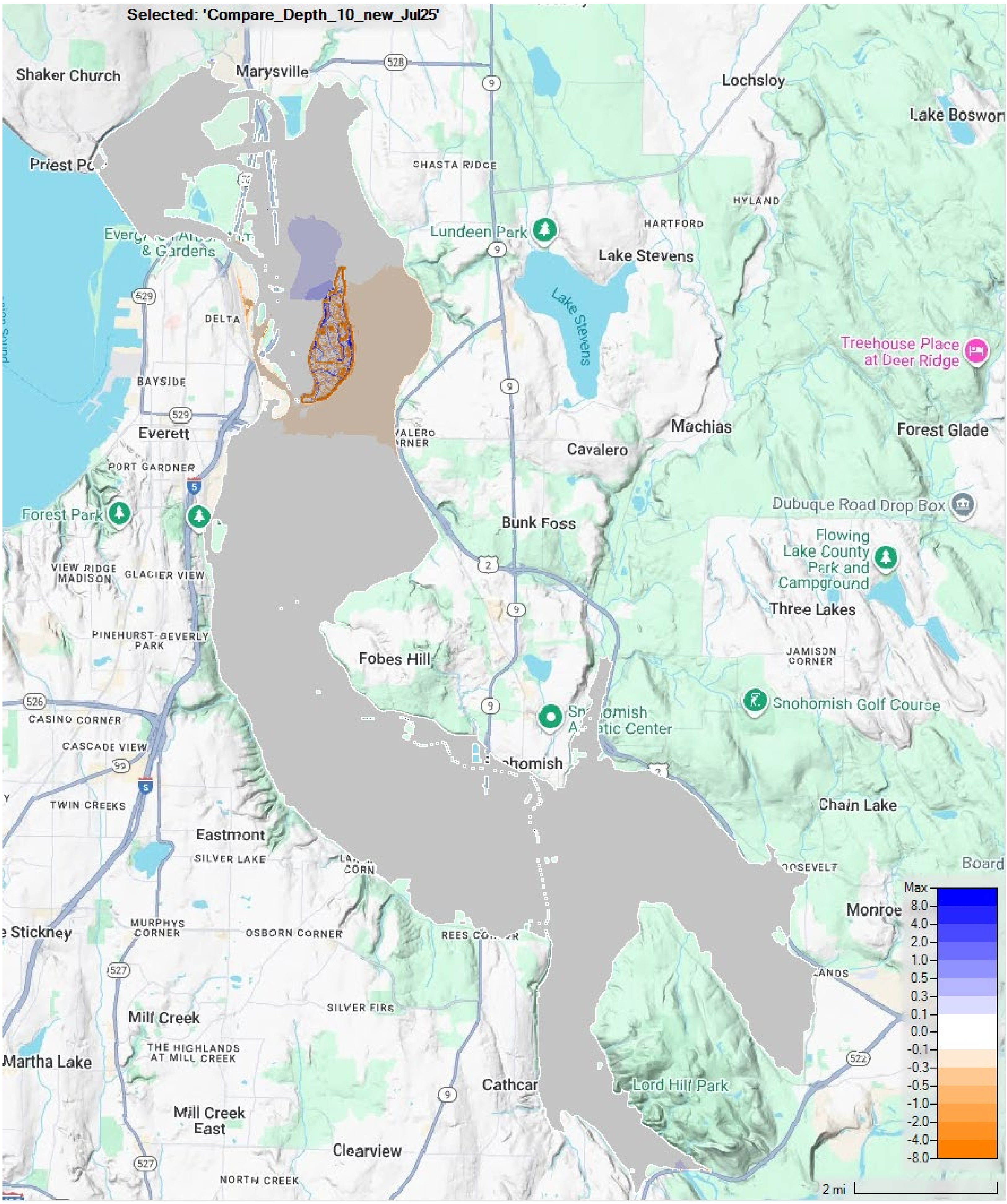


Figure 12. Scenario 10 Depth Comparison. MHHW + 1 ft tide, 1% AEP river flow.

2.11 Scenario 11

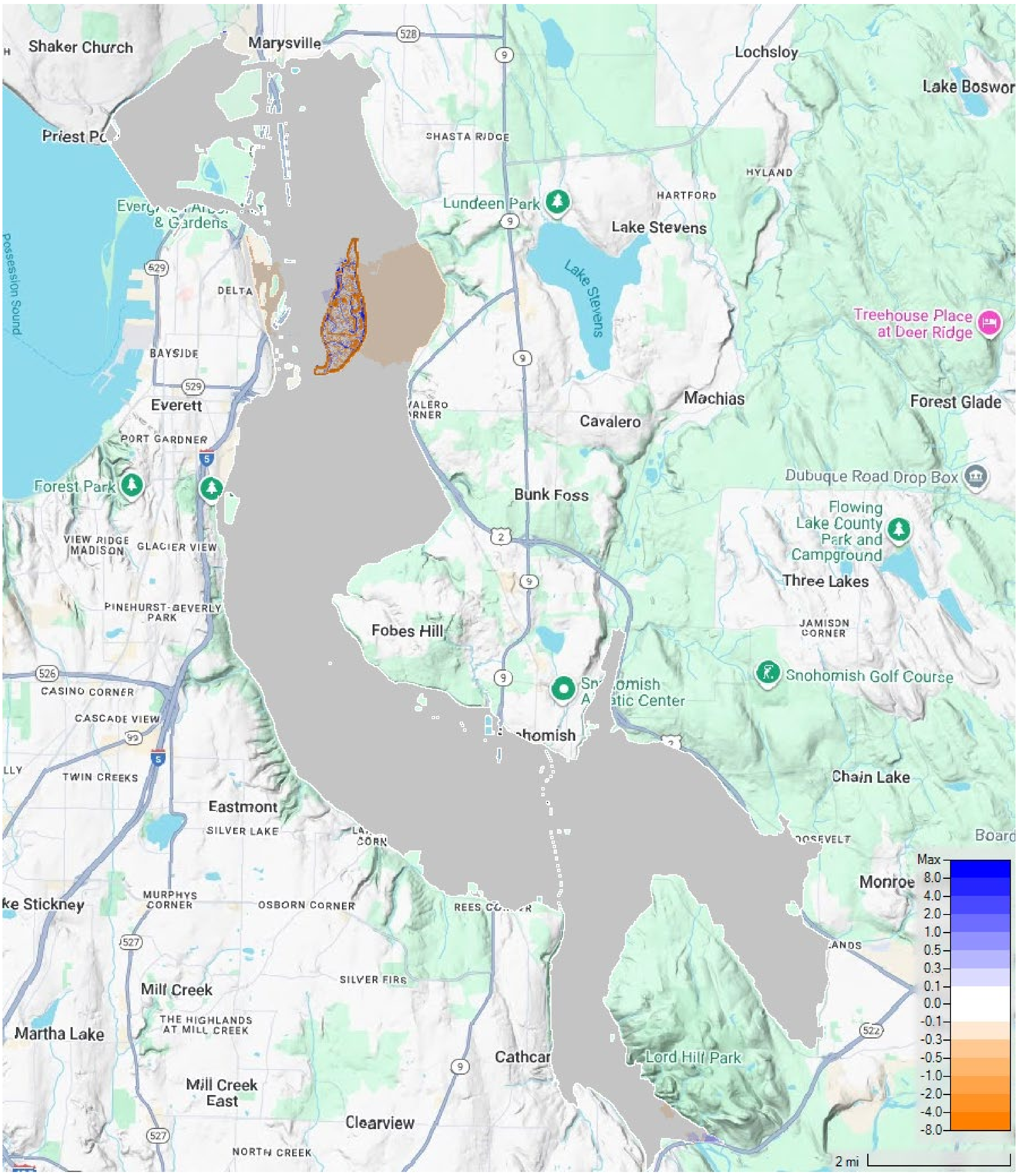


Figure 13. Scenario 11 Depth Comparison. MHHW + 1 ft tide, 0.2% AEP river flow.

2.12 Scenario 12

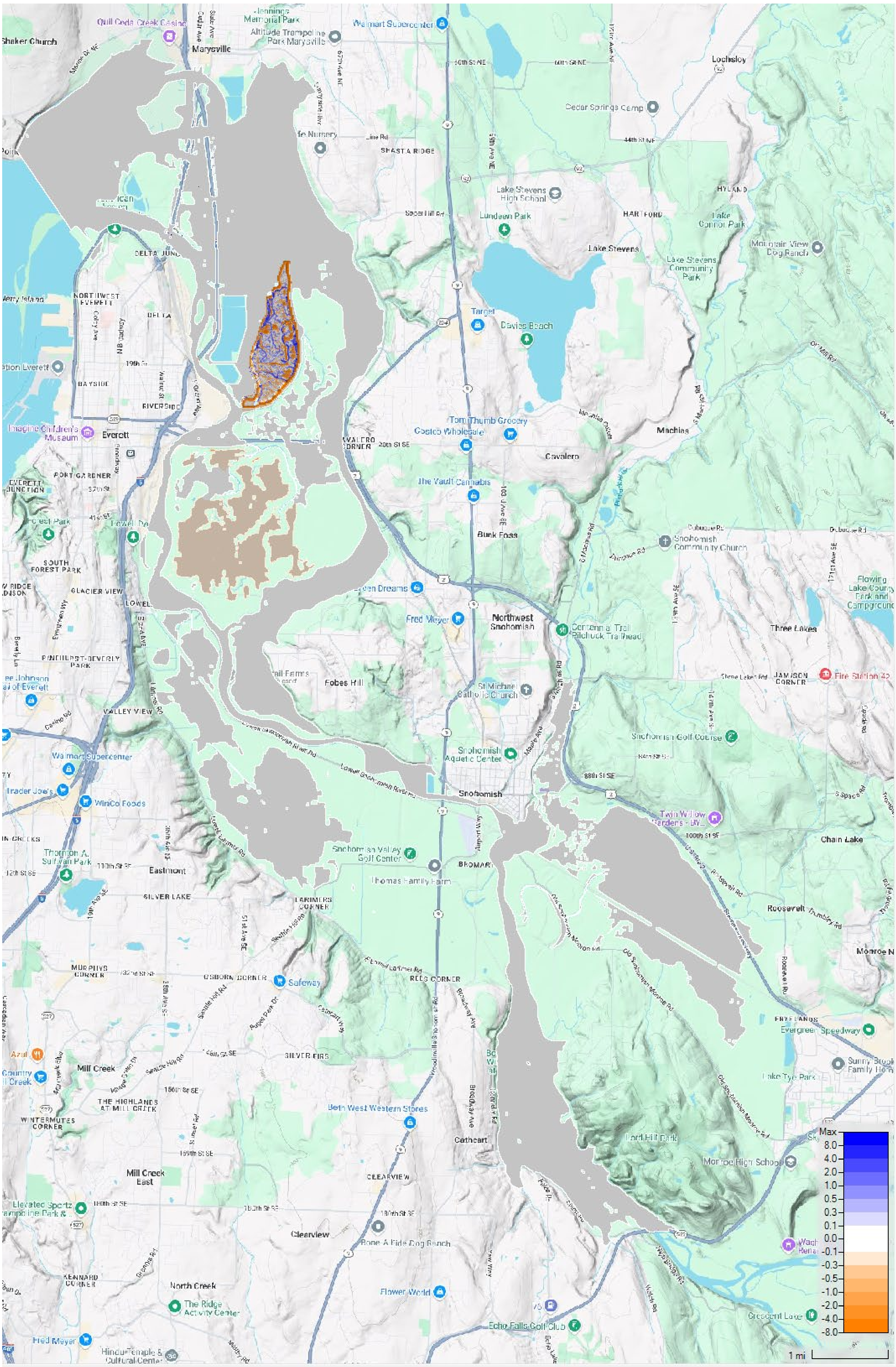


Figure 14. Scenario 12 Depth Comparison. Projected 2080 MHHW + 1 ft tide, projected 2080 50% AEP river flow.

2.13 Scenario 13

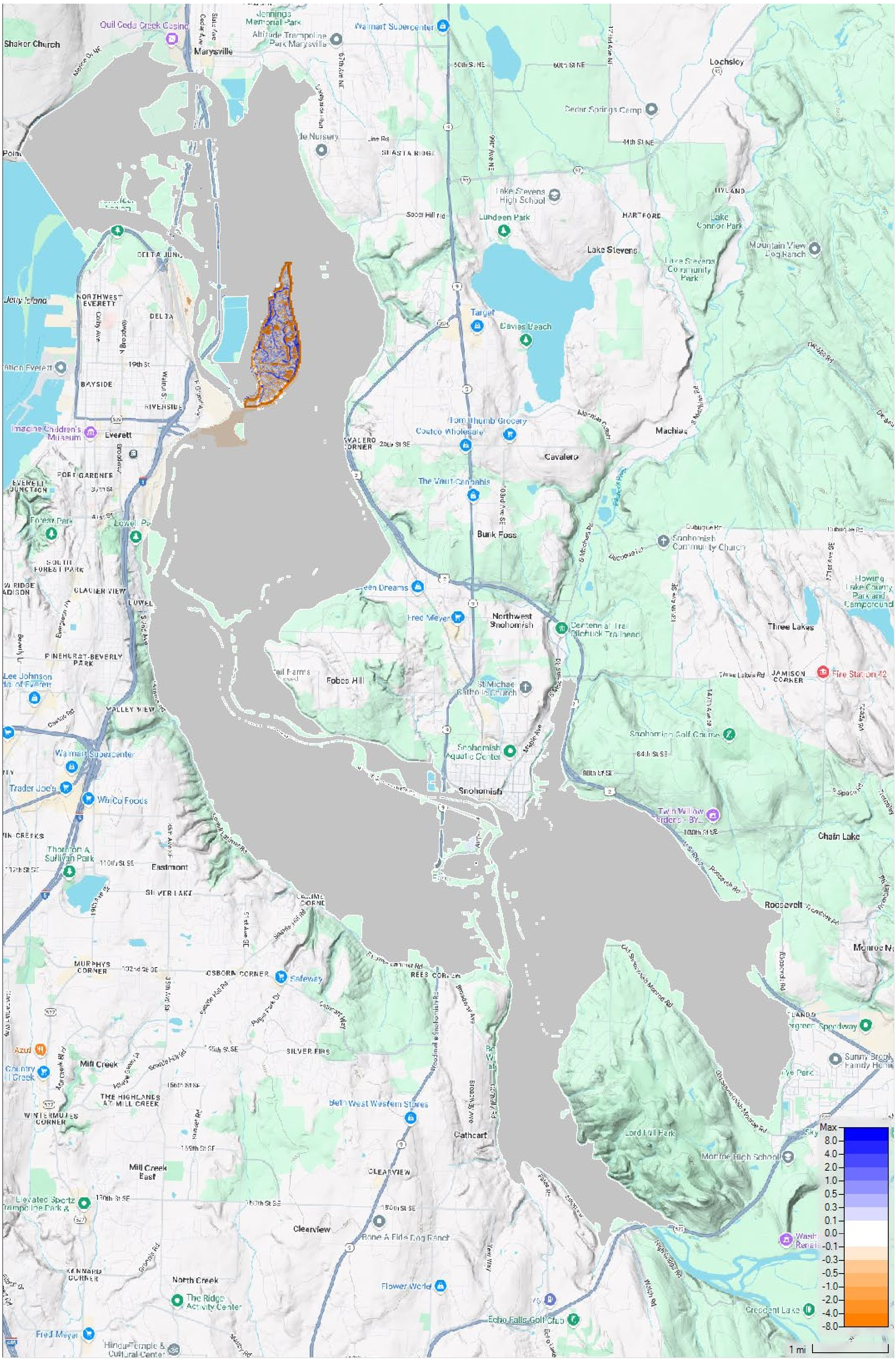
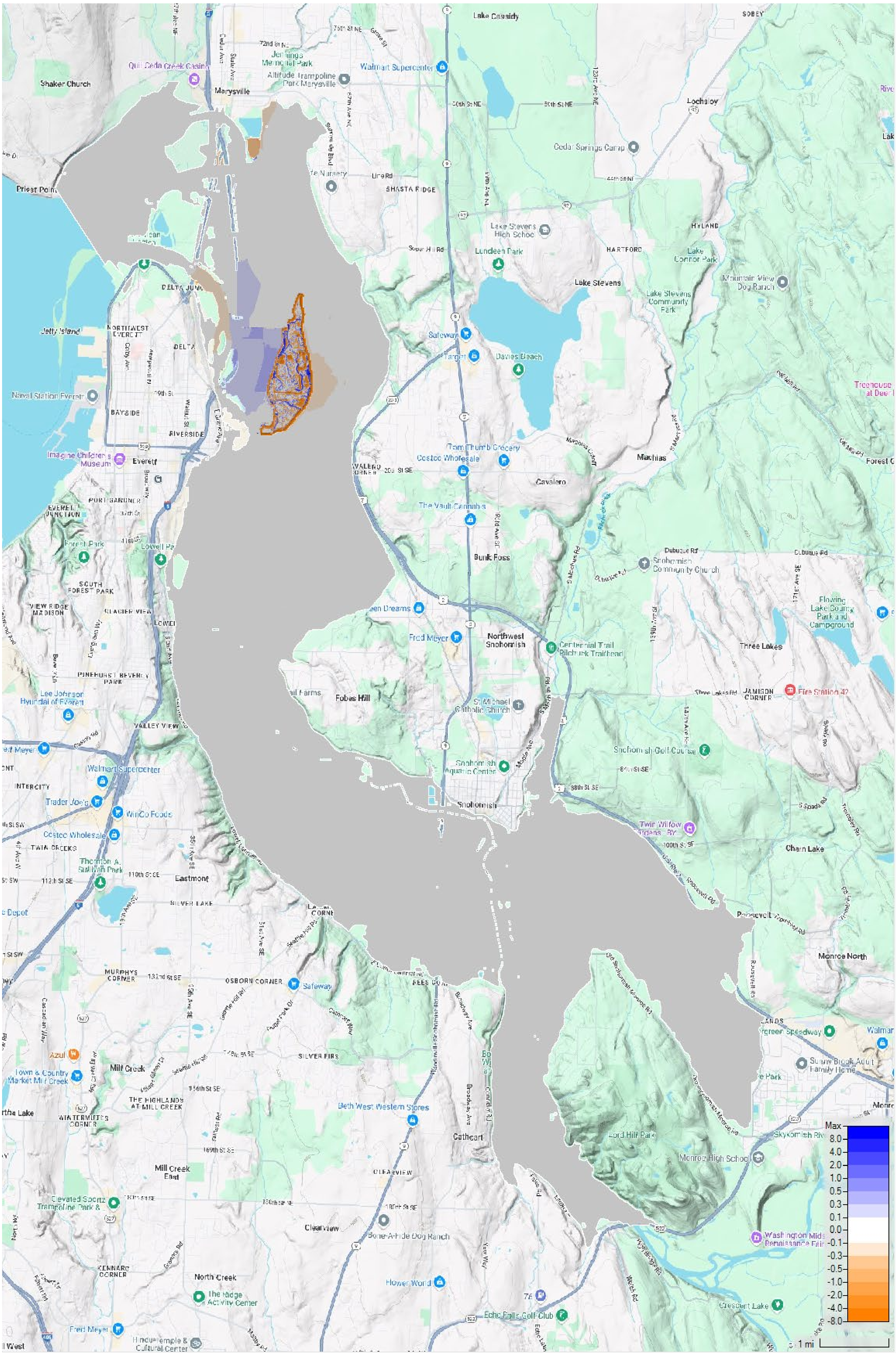


Figure 15. Scenario 13 Depth Comparison. Projected 2080 MHHW + 1 ft tide, projected 2080 2% AEP river flow.

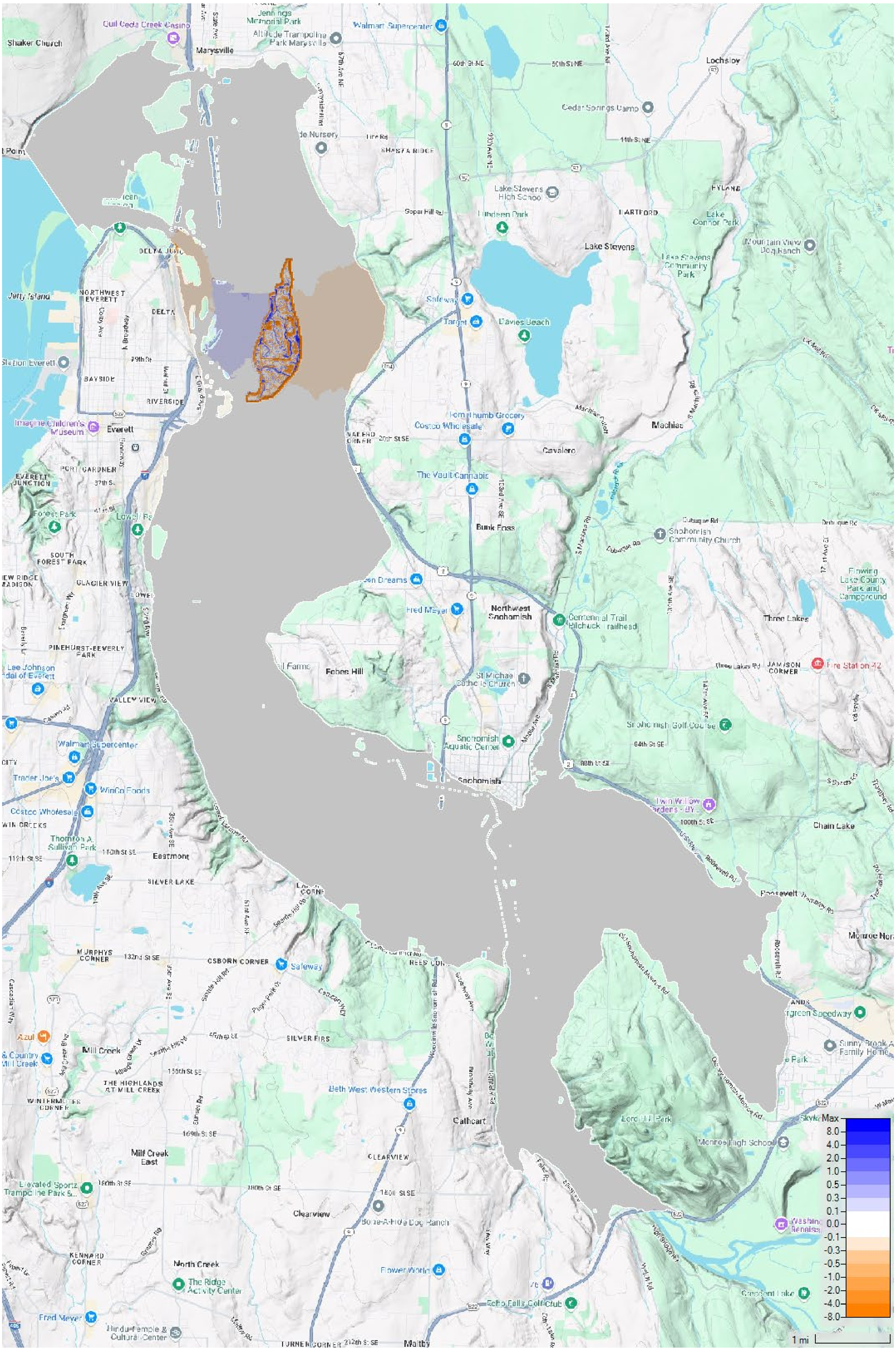
2.14 Scenario 14

Figure 16. Scenario 14 Depth Comparison. Projected 2080 MHHW + 1 ft tide, projected 2080 1% AEP river flow.



2.15 Scenario 15

Figure 17. Scenario 15 Depth Comparison. Projected 2080 MHHW + 1 ft tide, projected 2080 0.2% AEP river flow.



3. Water Surface Profile Plots

3.1 Tidal Conditions

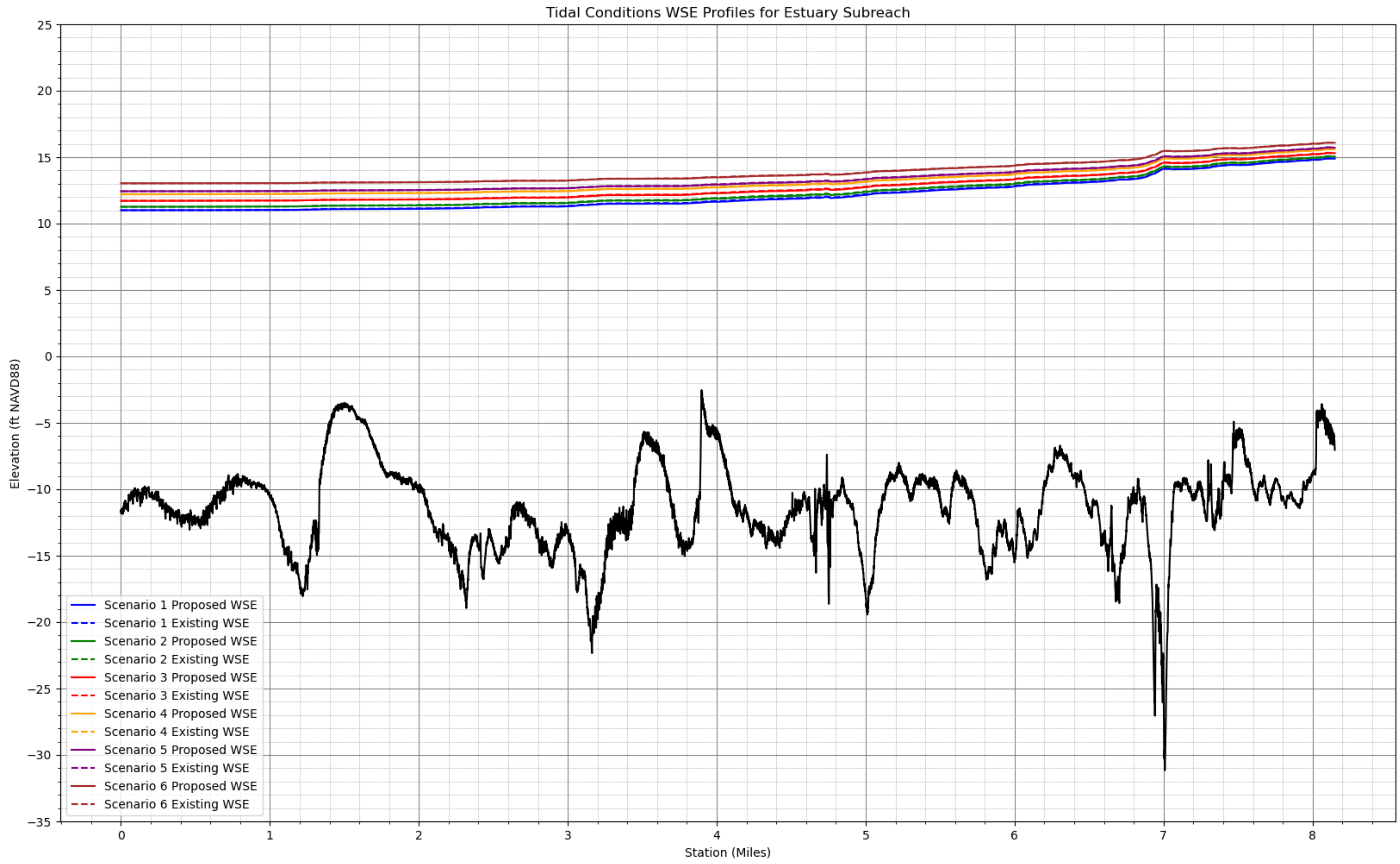


Figure 19. Tidal Conditions WSE at Union Slough Subreach

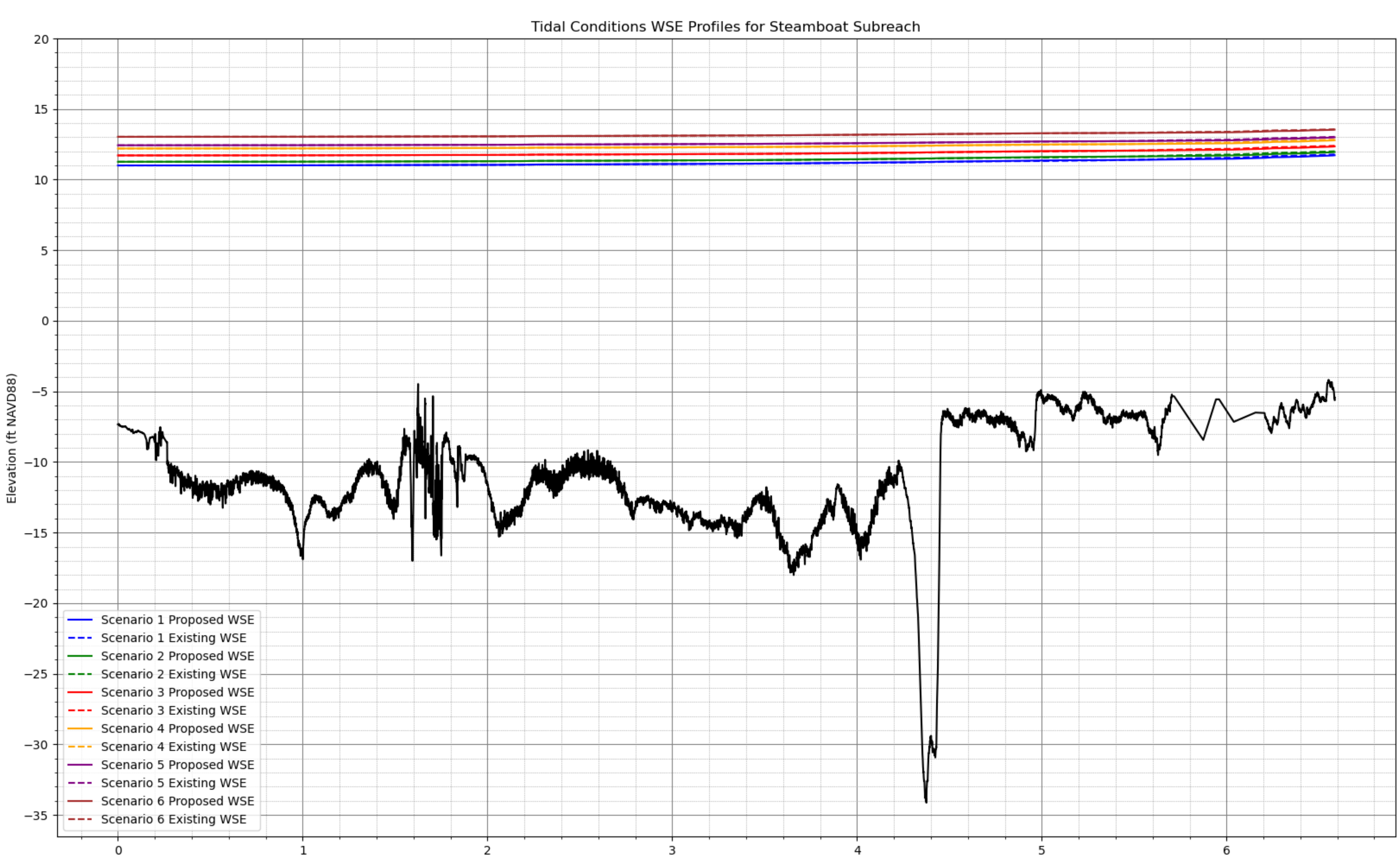


Figure 18. Tidal Conditions WSE at Steamboat Slough Subreach

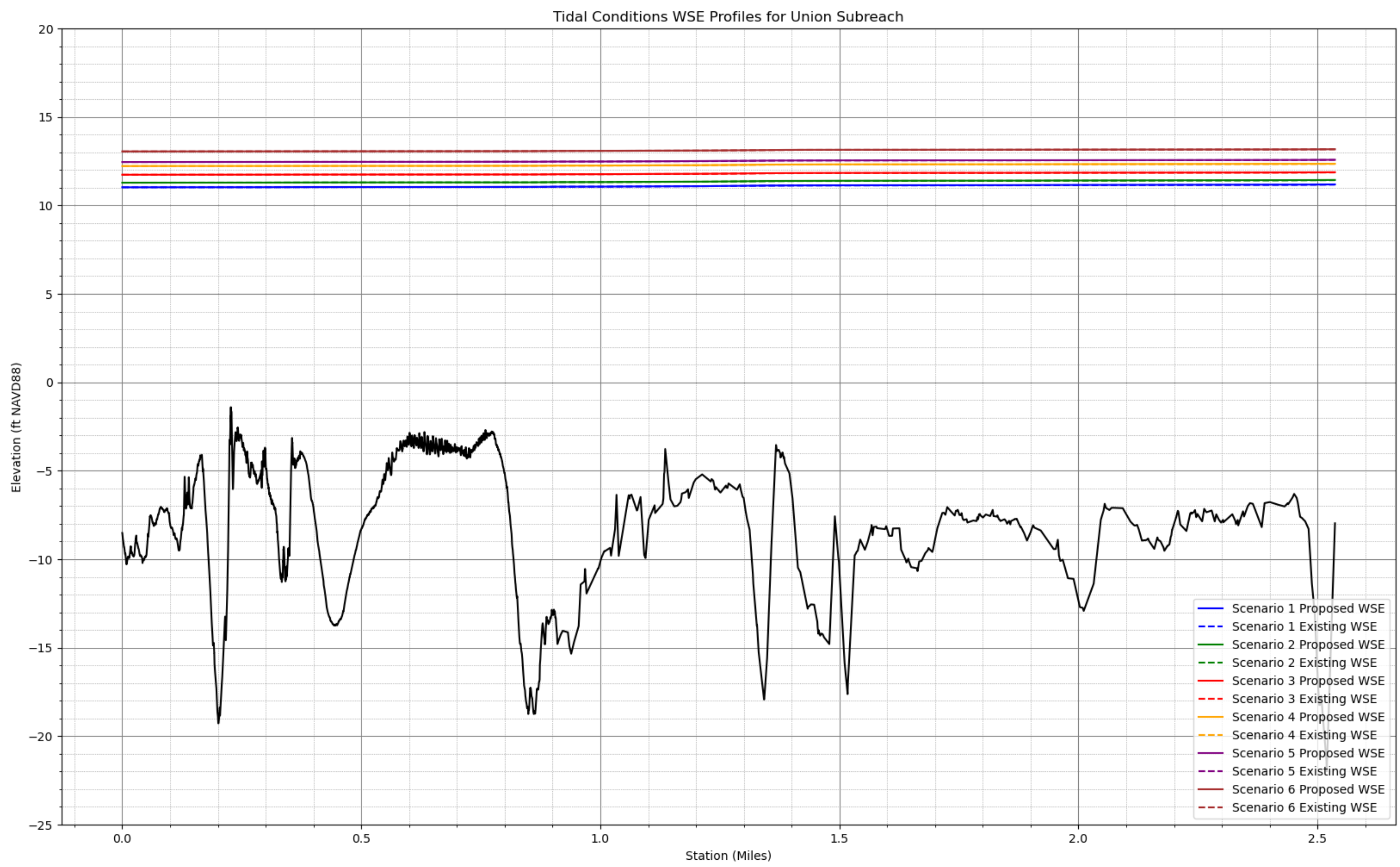


Figure 20. Tidal Conditions WSE in Estuary Subreach

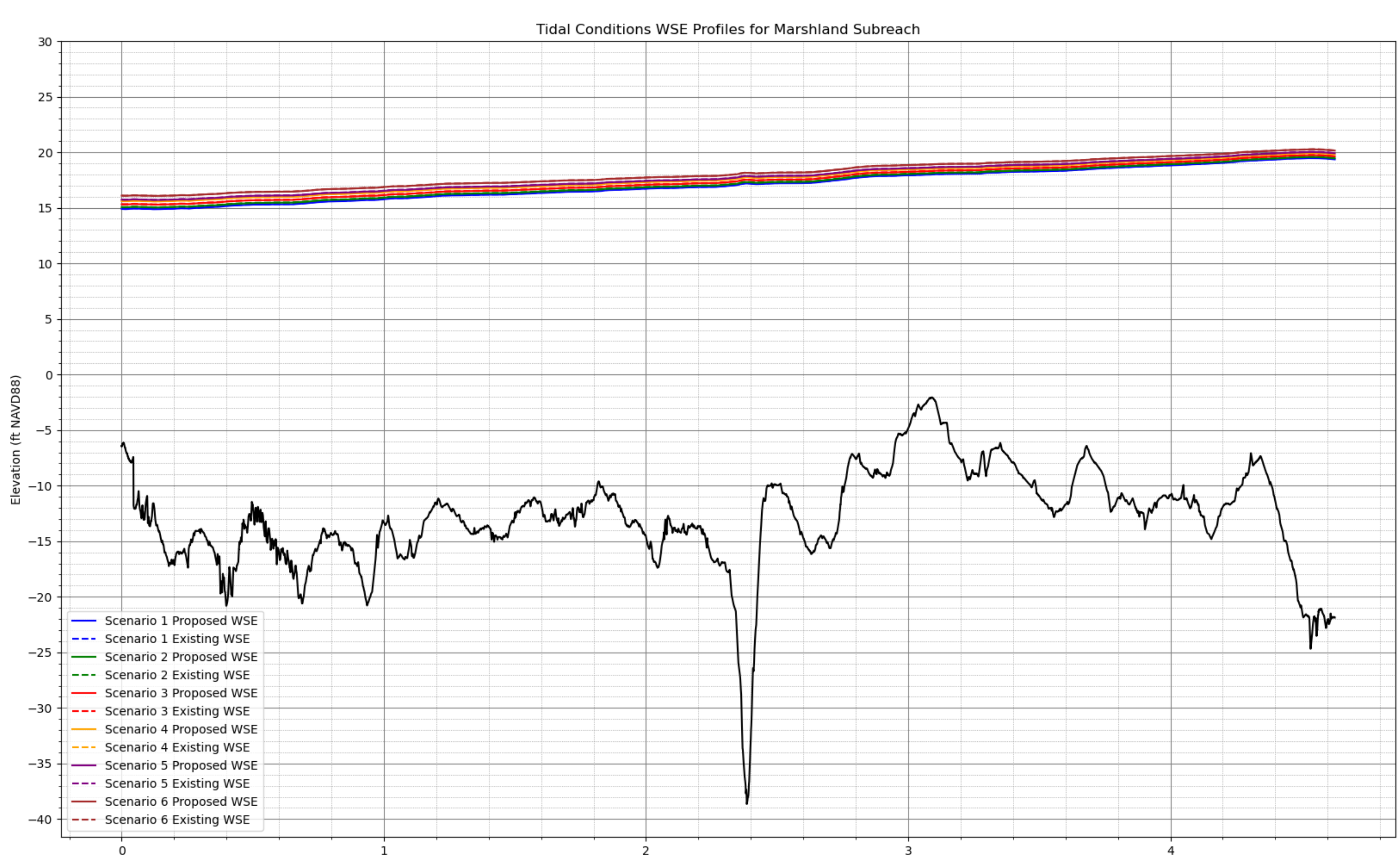


Figure 21. Tidal Conditions WSE in Marshland Subreach

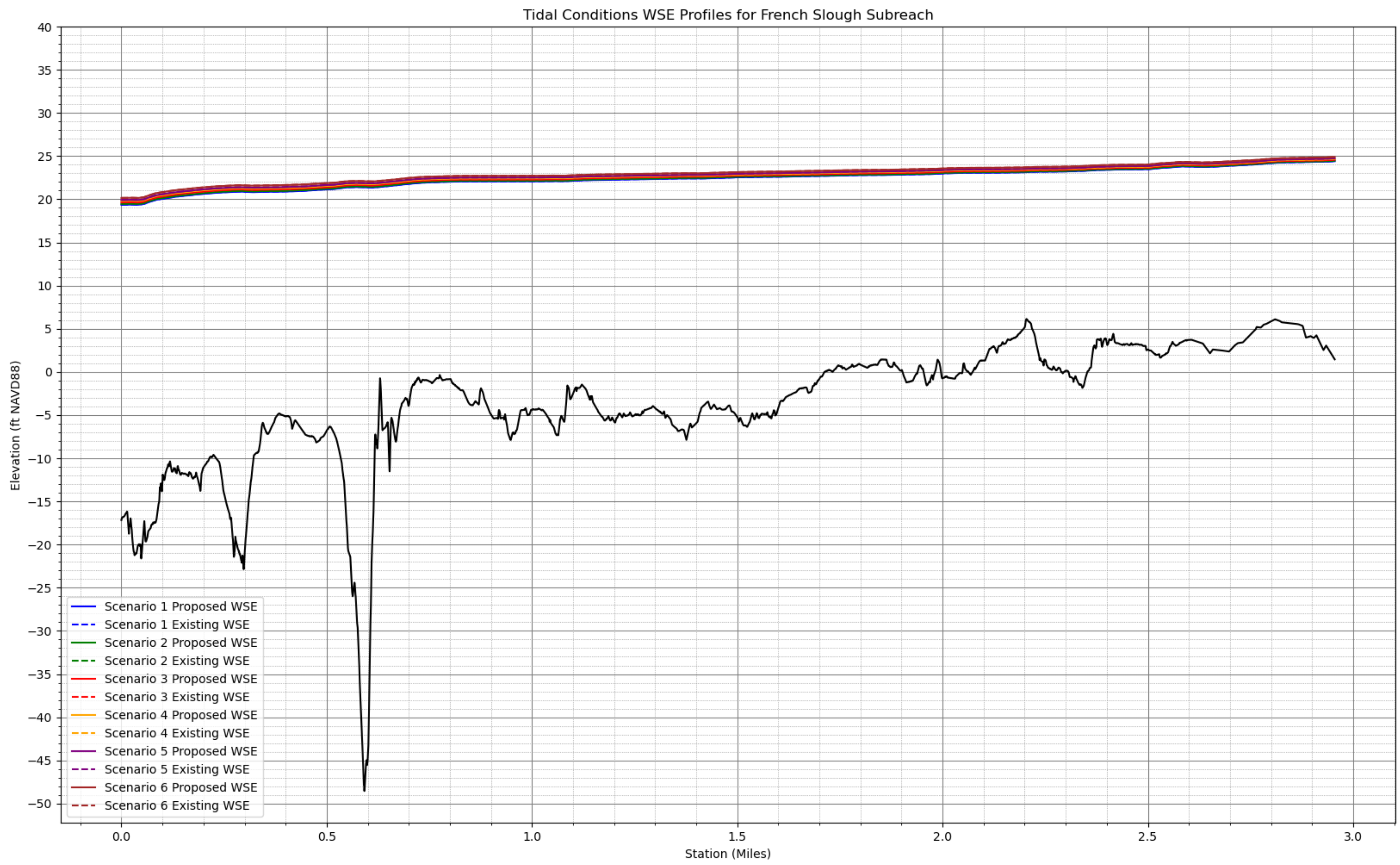


Figure 22. Tidal Conditions WSE at French Slough Subreach

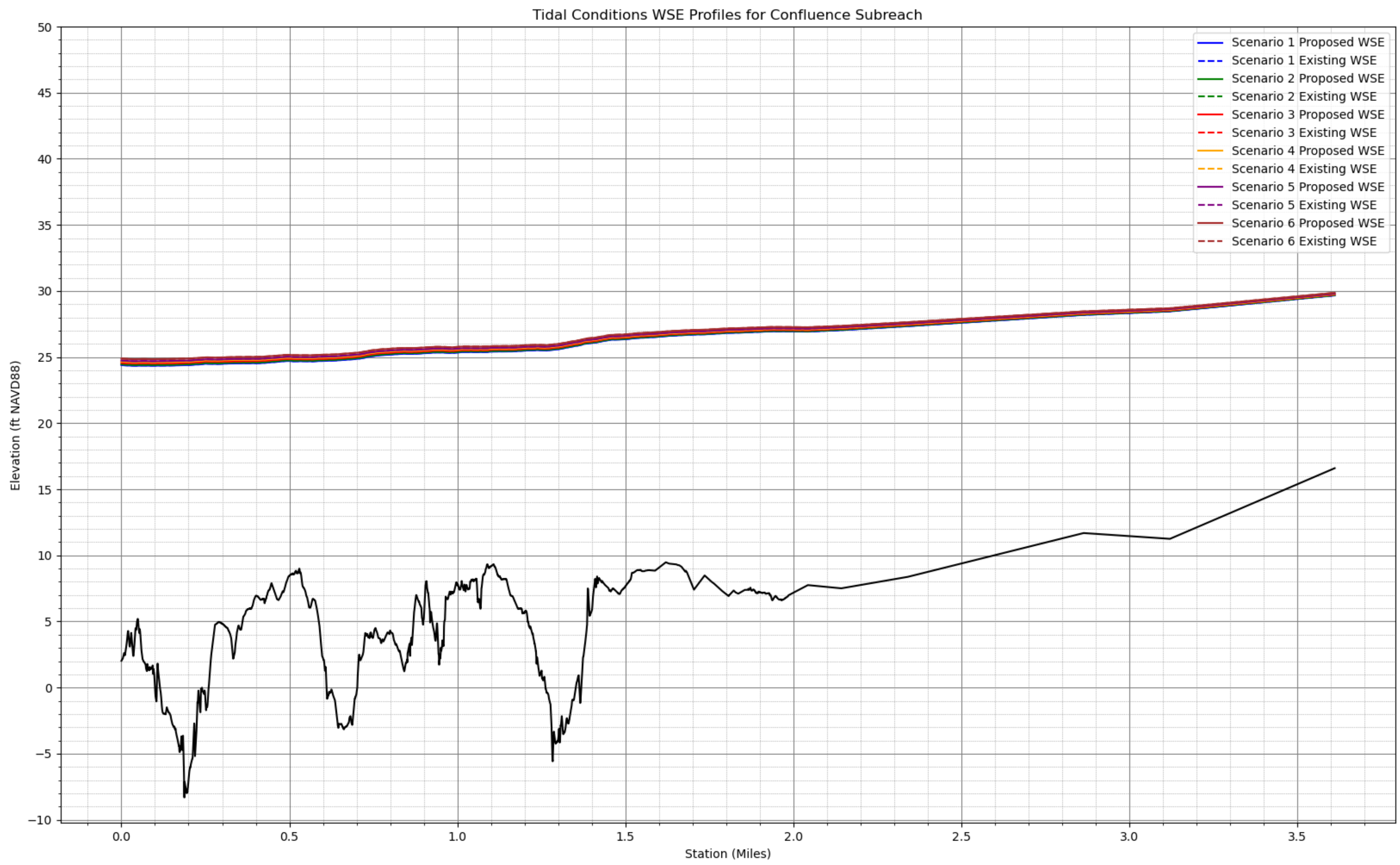


Figure 23. Tidal Conditions WSE at Confluence Subreach

3.2 Existing and Future Flow Conditions

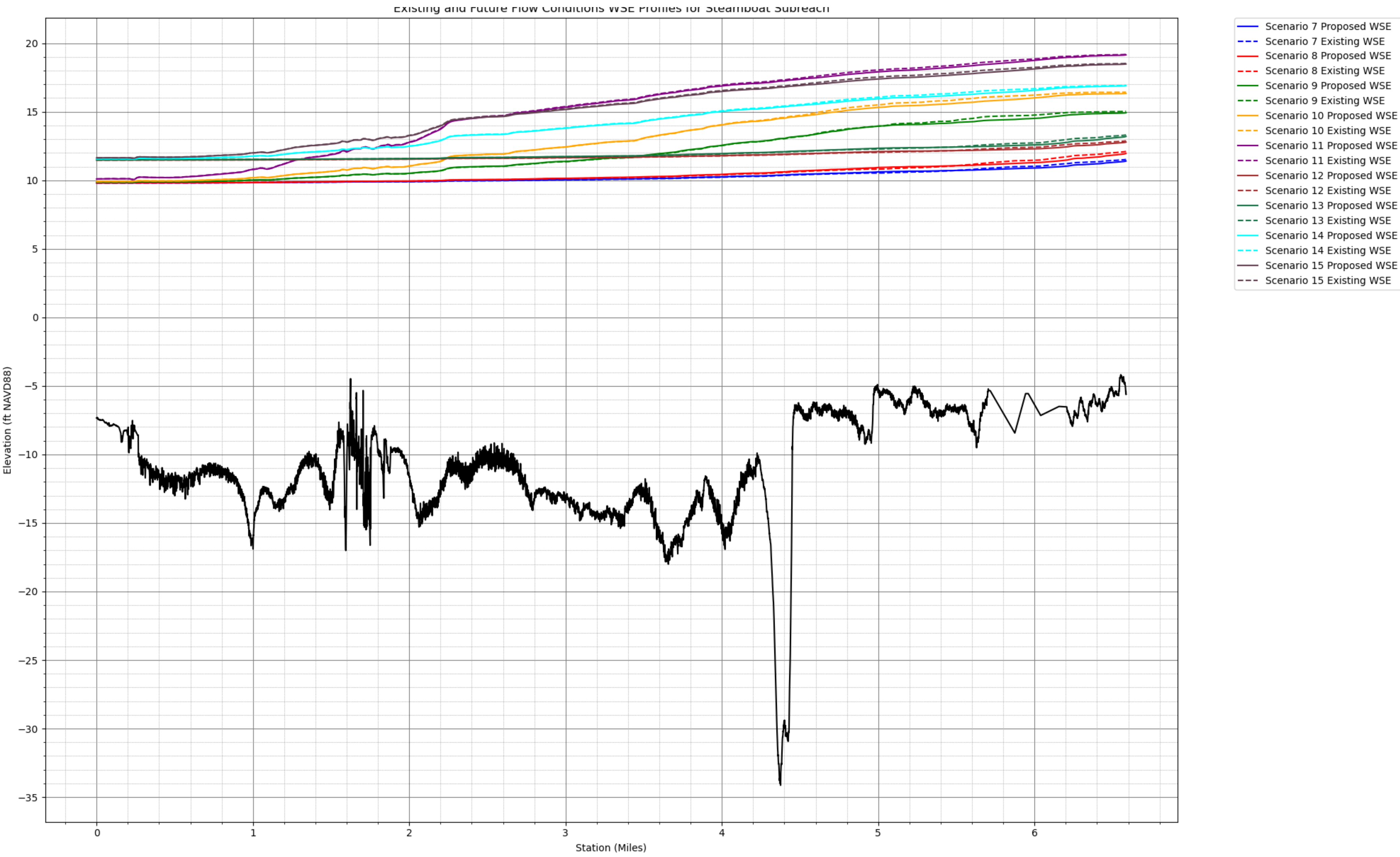


Figure 24. Flow Conditions WSE at Steamboat Slough Subreach

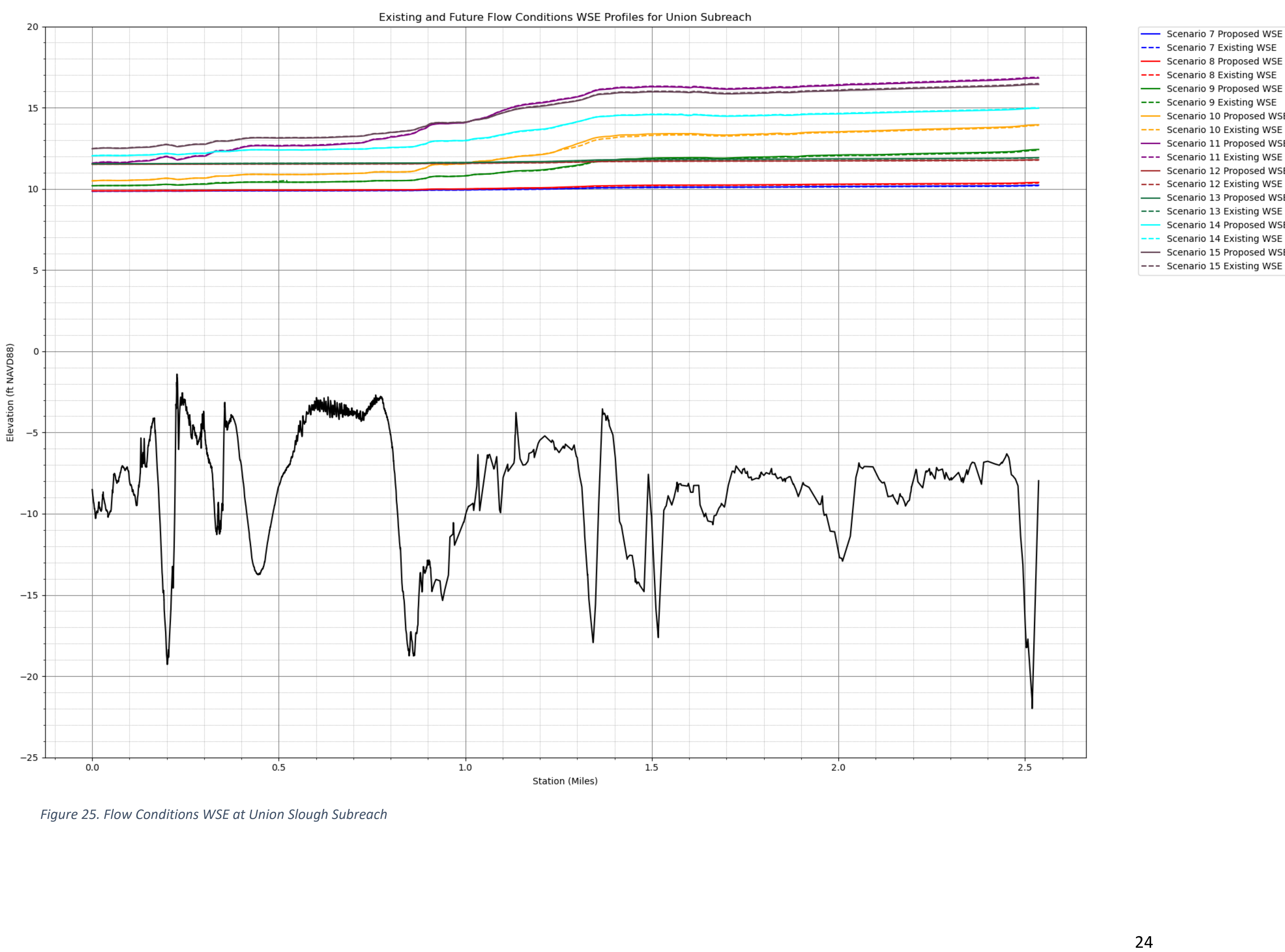


Figure 25. Flow Conditions WSE at Union Slough Subreach

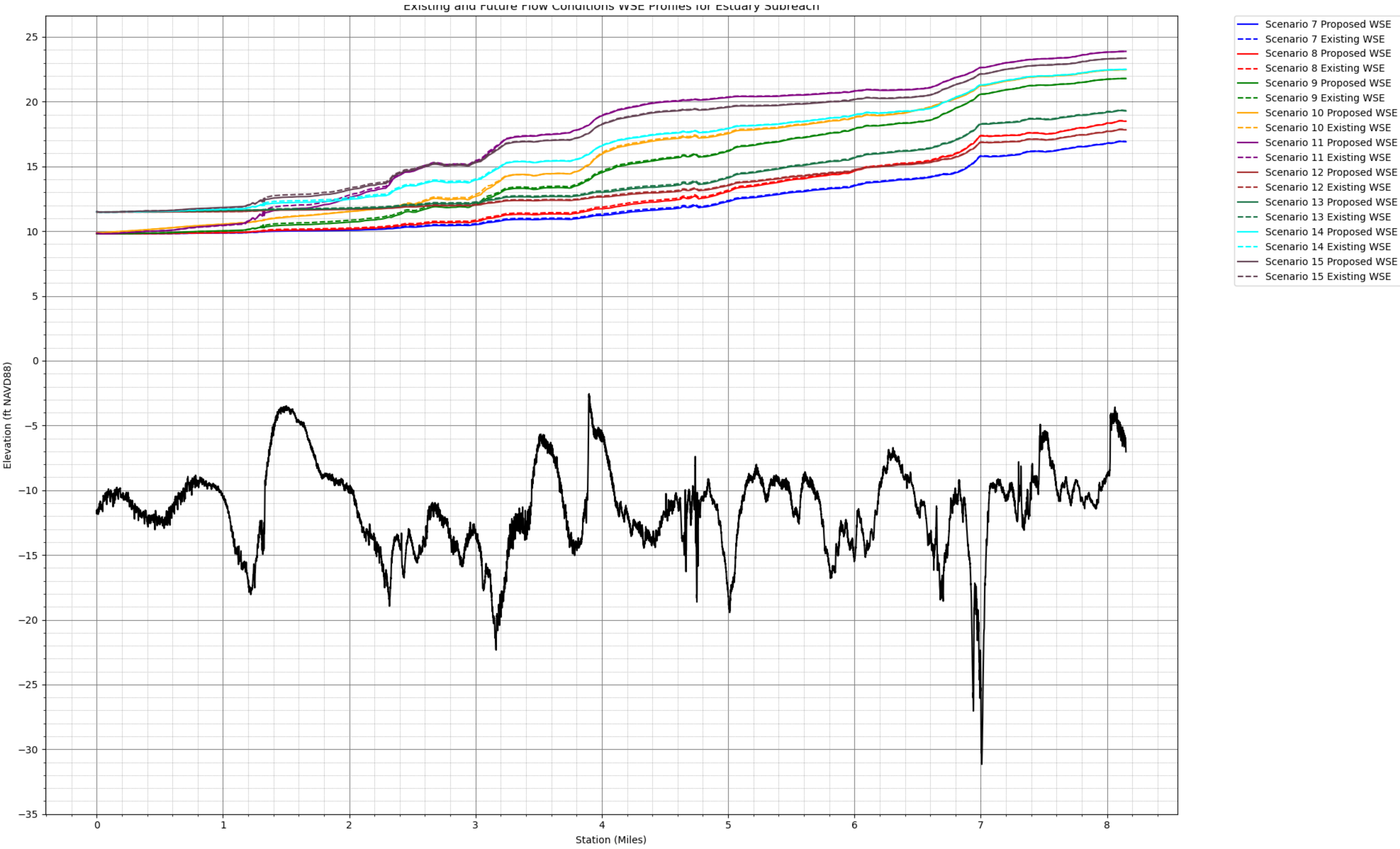


Figure 26. Flow Conditions WSE at Estuary Subreach

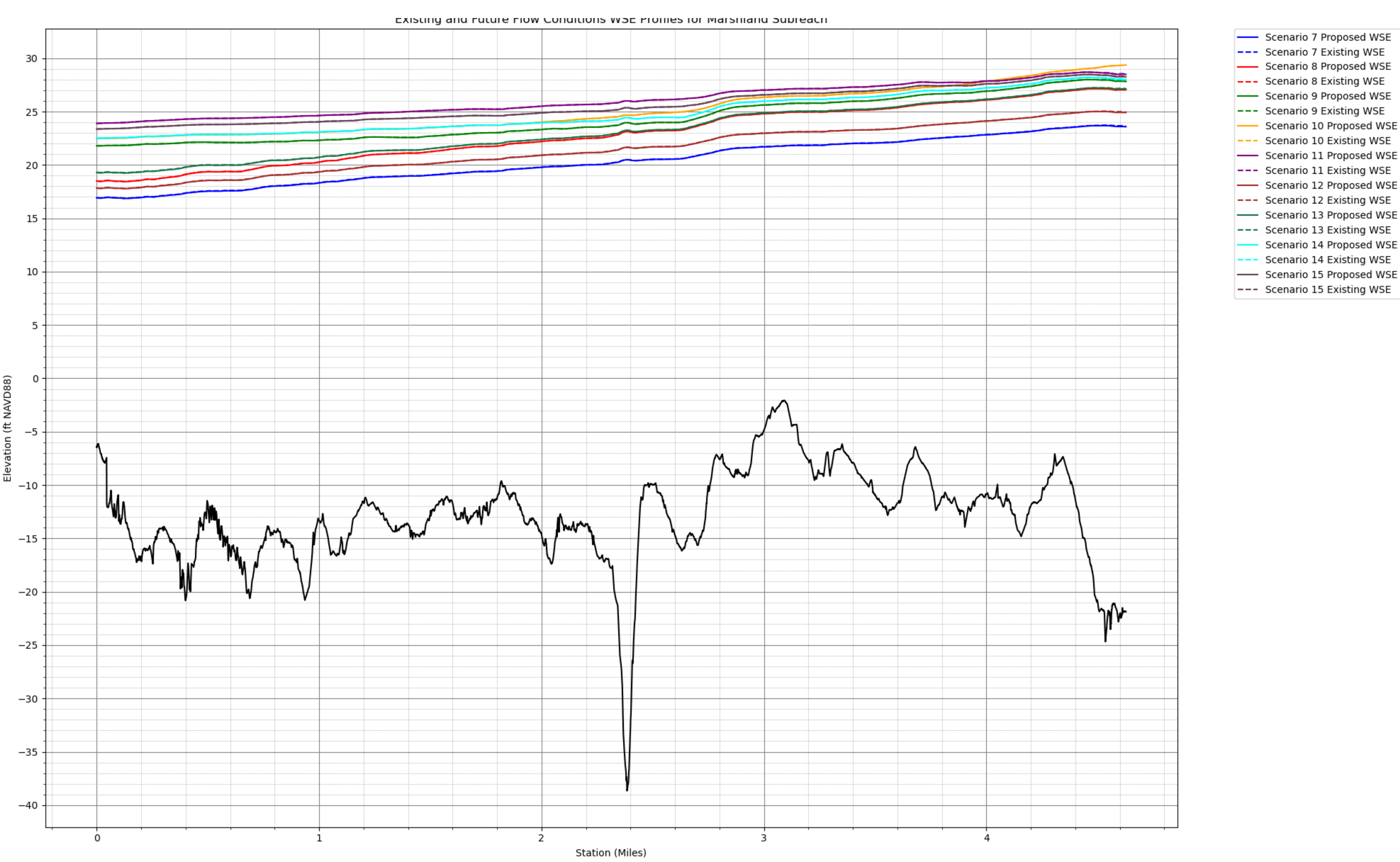


Figure 27. Flow Conditions WSE at Marshland Subreach

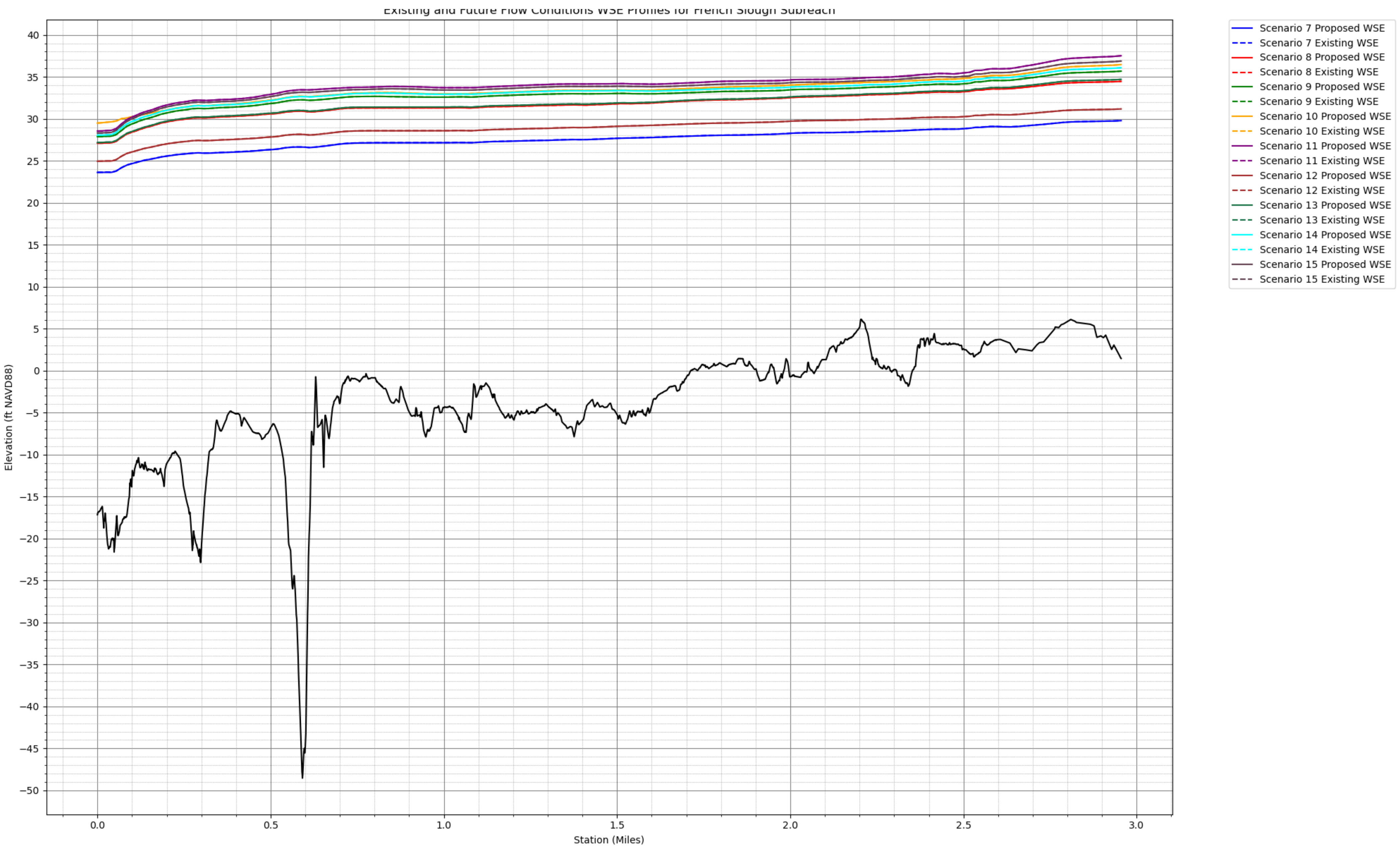


Figure 29. Flow Conditions WSE for French Slough Subreach

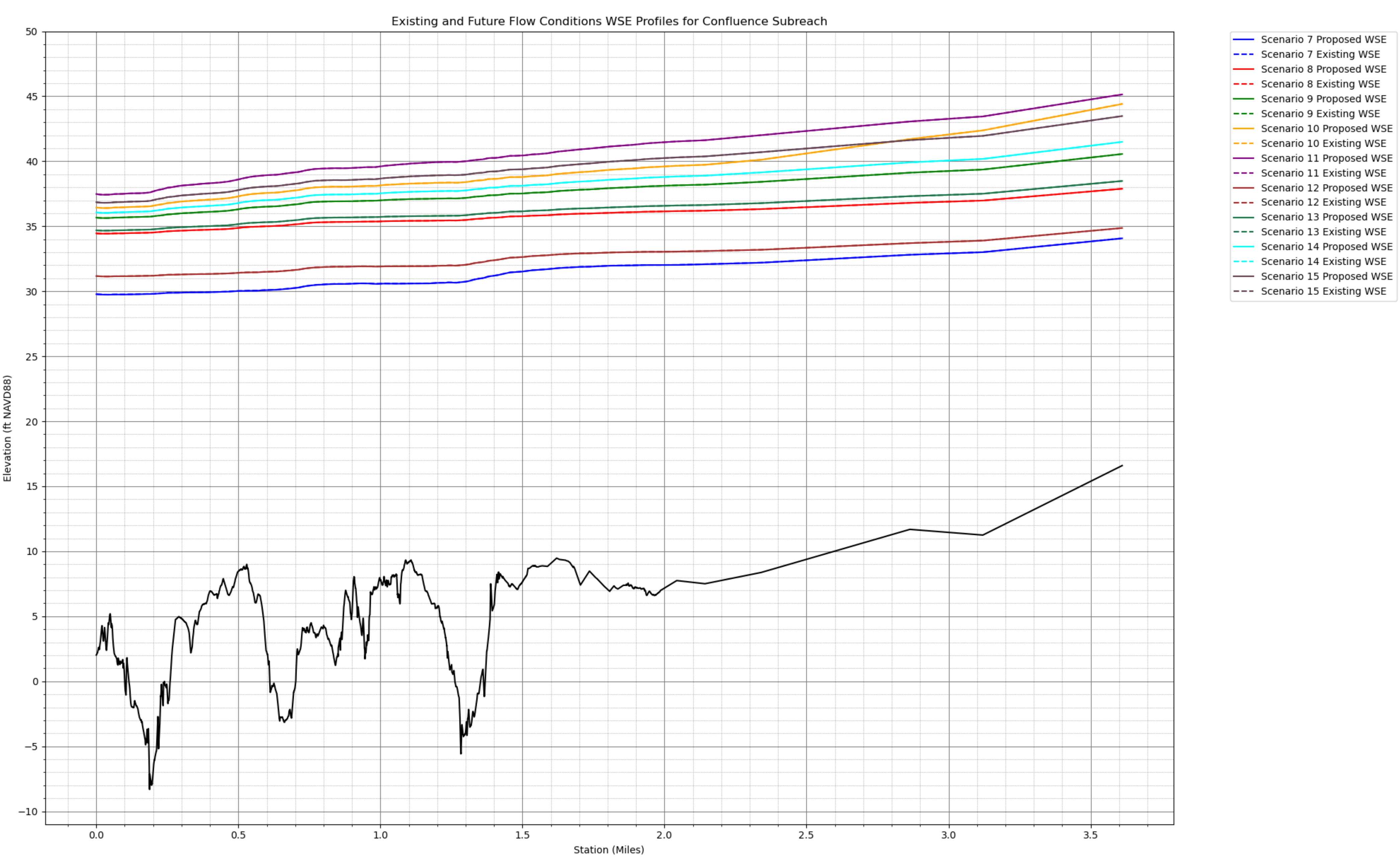


Figure 28. Flow Conditions WSE for Confluence Subreach

3.2 Proposed vs Existing Plots

3.2.1 Estuary Subreach

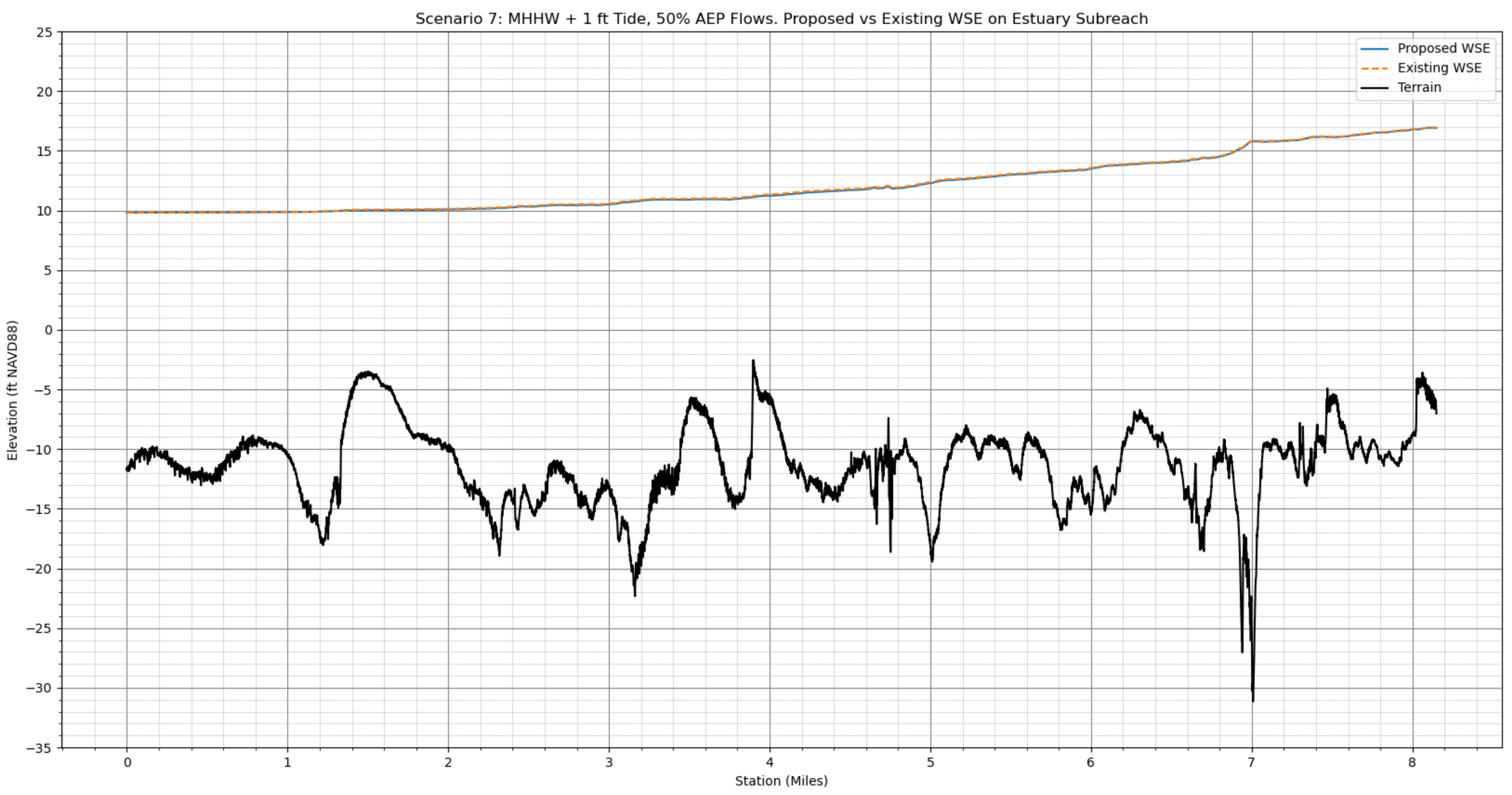


Figure 30. 50% AEP Existing Flow Conditions at Estuary Subreach

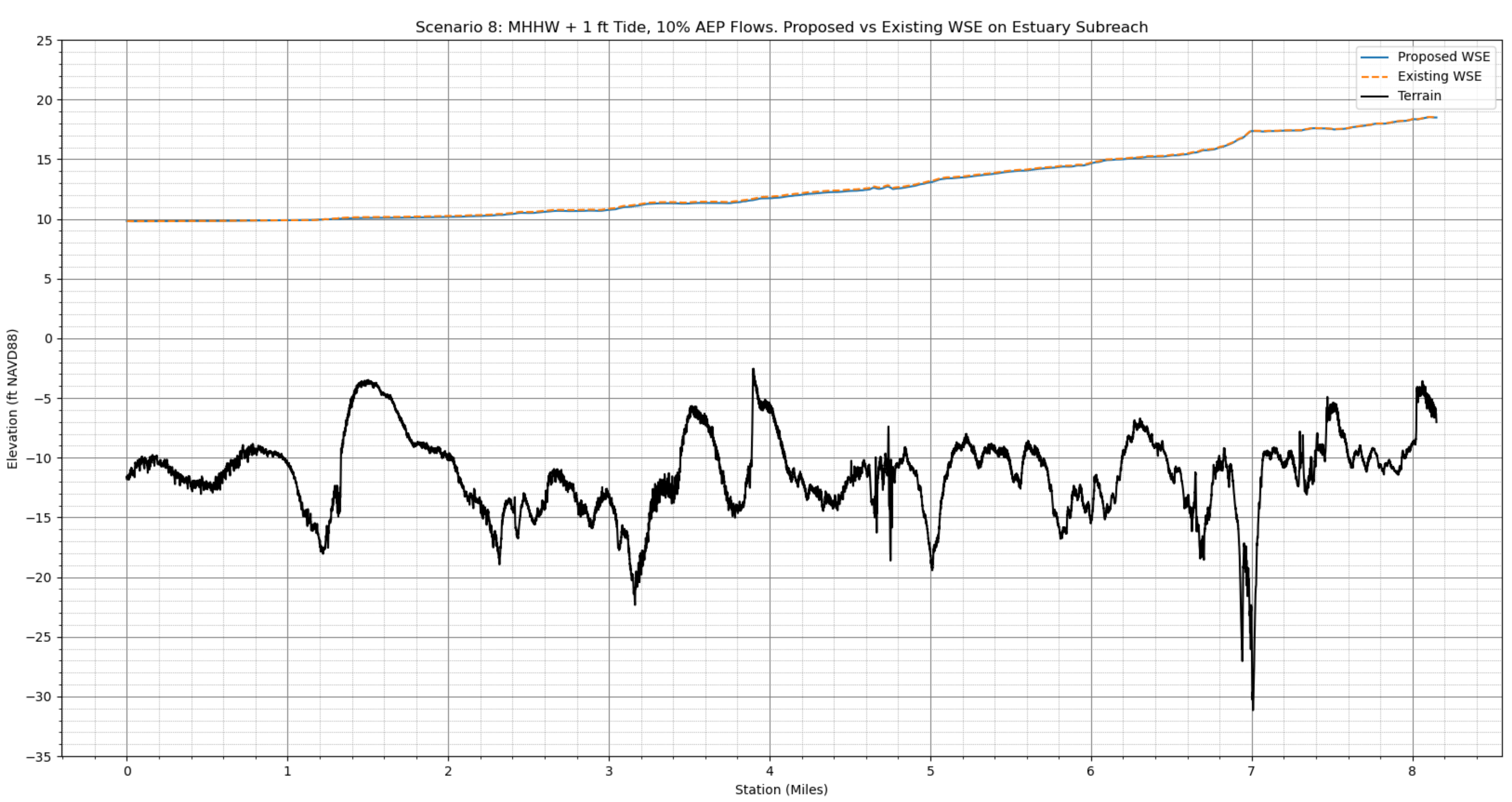


Figure 31. 50% AEP 2080 Flow Conditions at Estuary Subreach

Figure 32. 10% AEP Existing Flow Conditions at Estuary Subreach

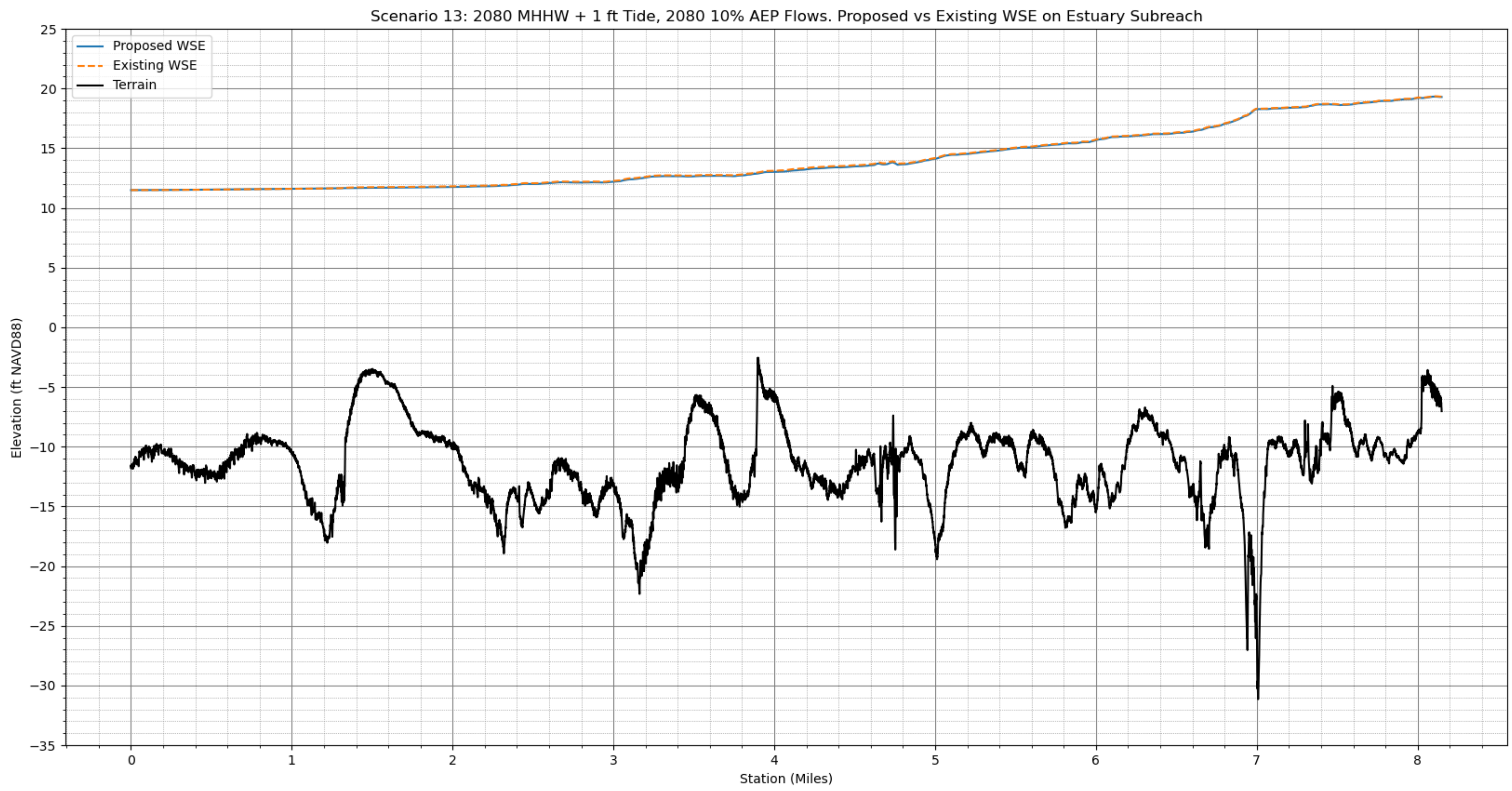


Figure 33. 10% AEP 2080 Flow Conditions at Estuary Subreach

Figure 34. 1% AEP Existing Flow Conditions at Estuary Subreach

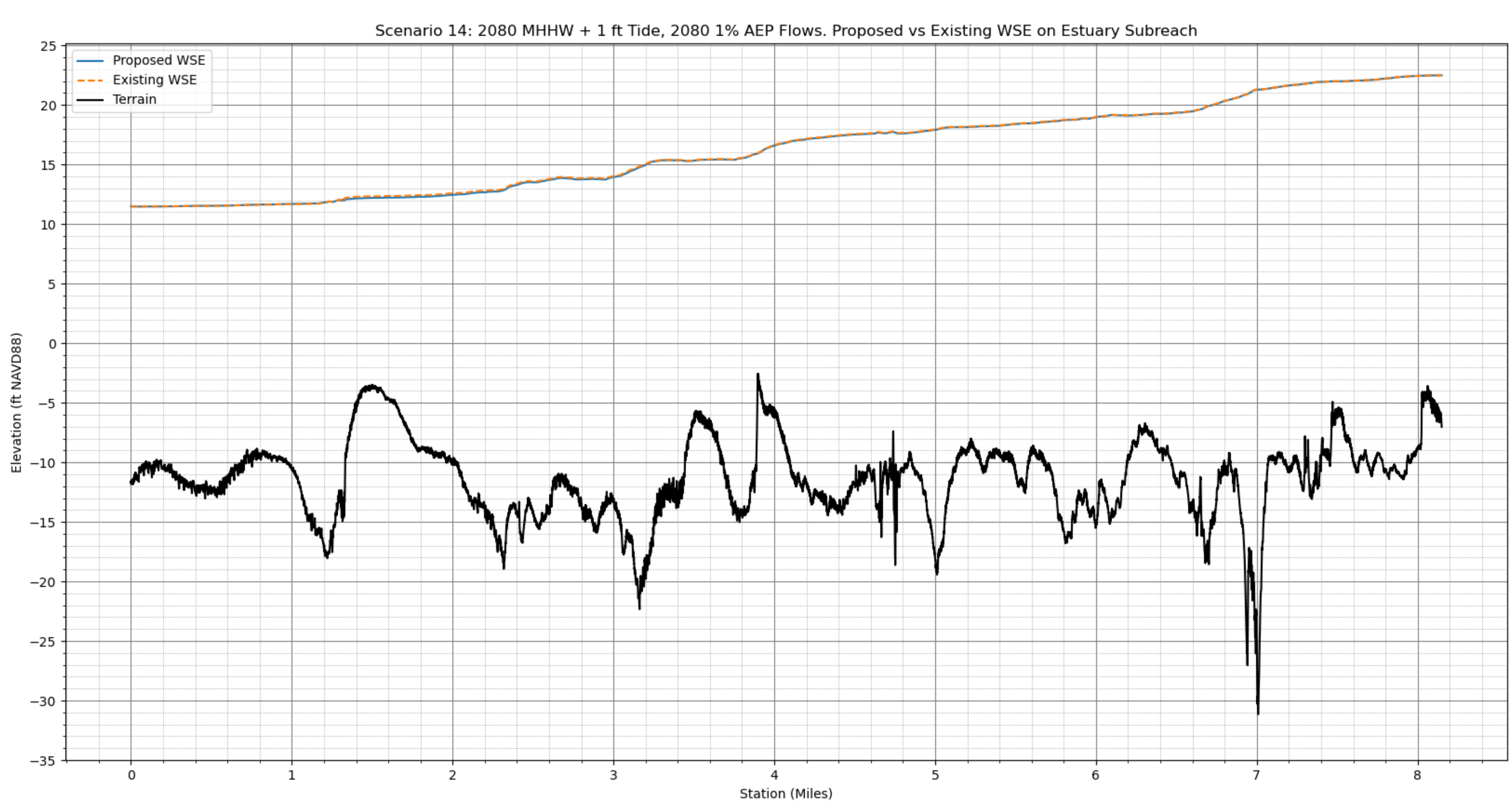


Figure 35. 1% AEP 2080 Flow Conditions at Estuary Subreach

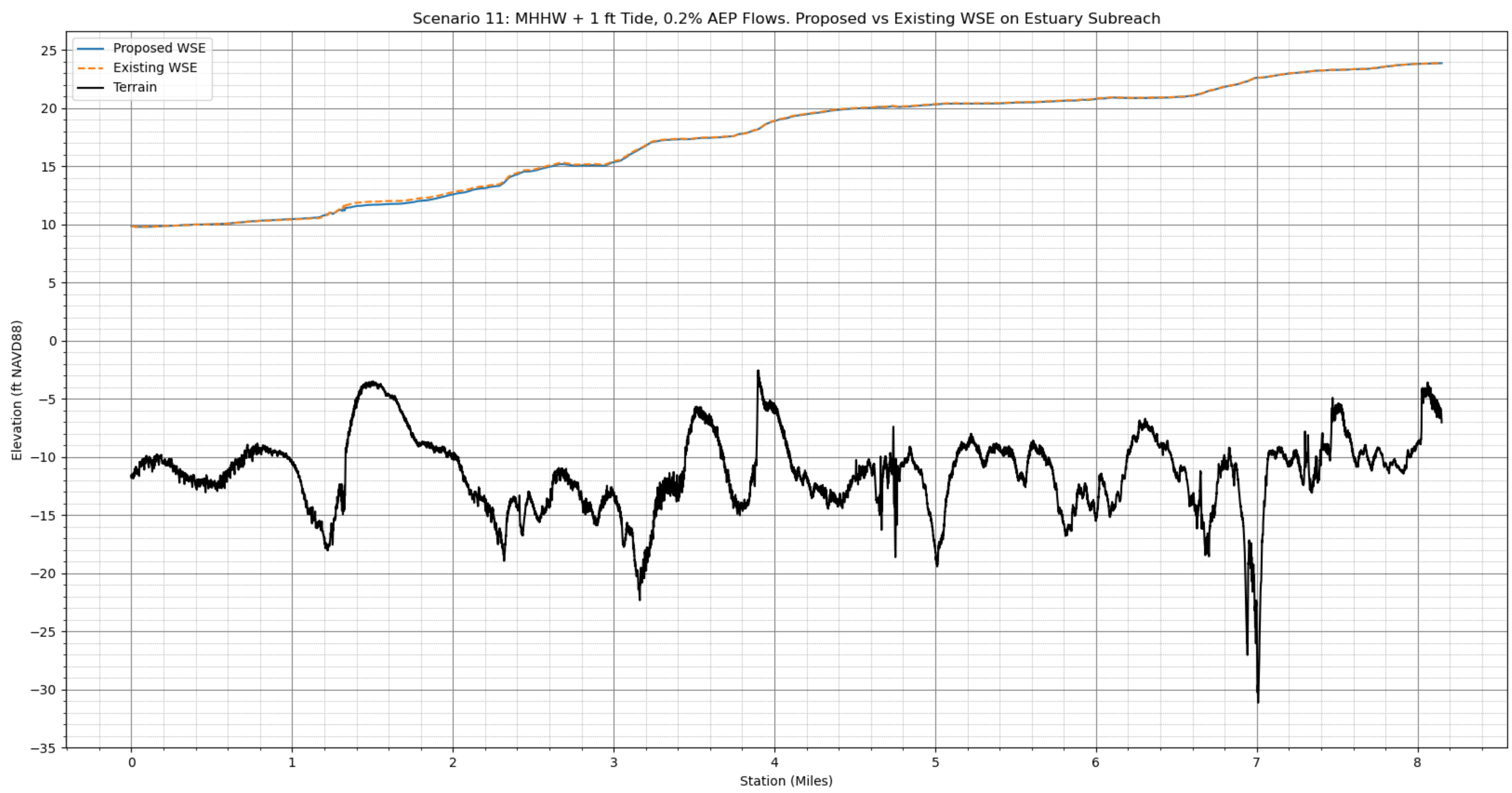


Figure 36. 0.2% AEP Existing Flow Conditions at Estuary Subreach

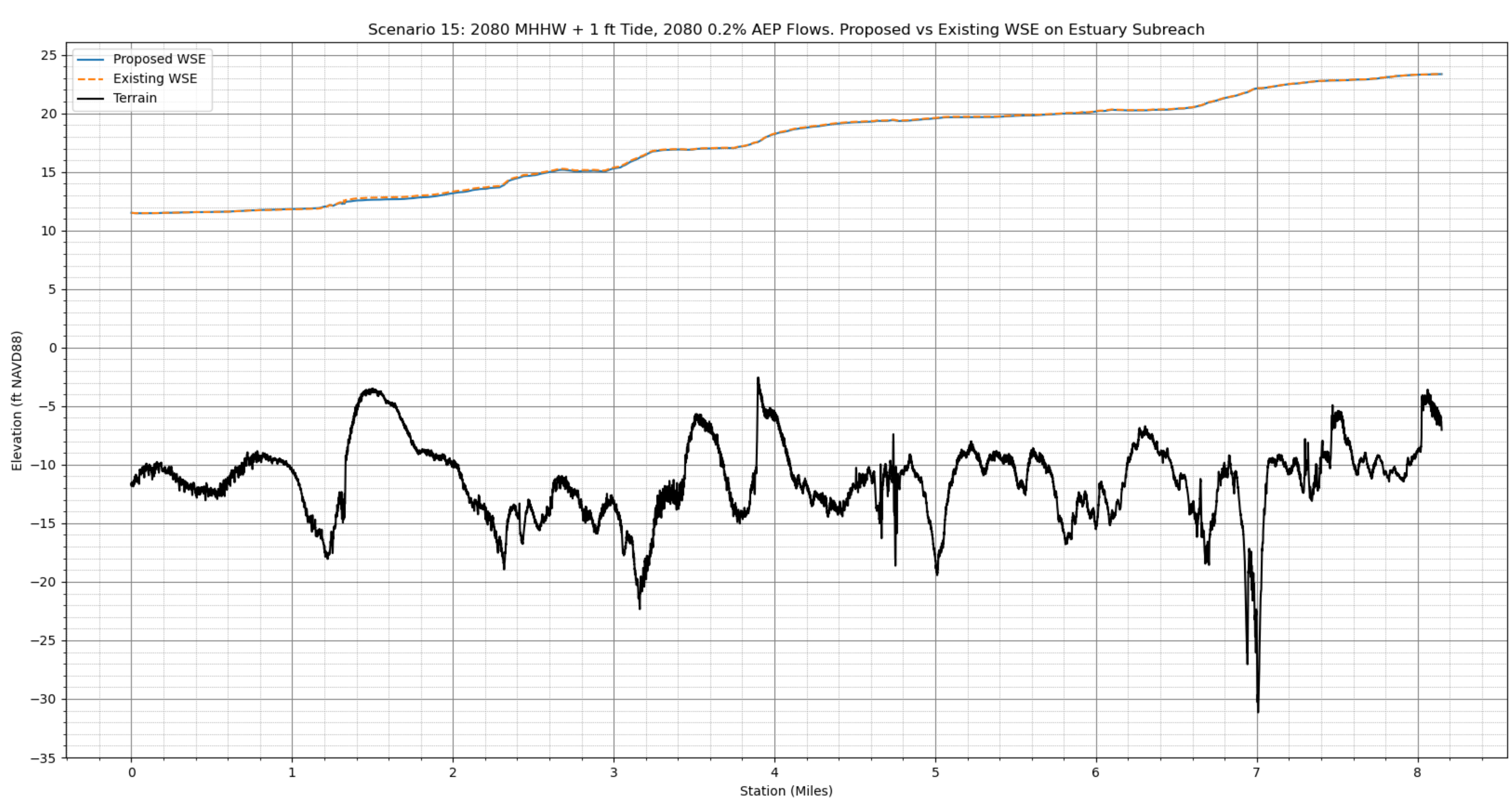


Figure 37. 0.2% AEP 2080 Flow Conditions at Estuary Subreach

3.3.2 Steamboat Subreach

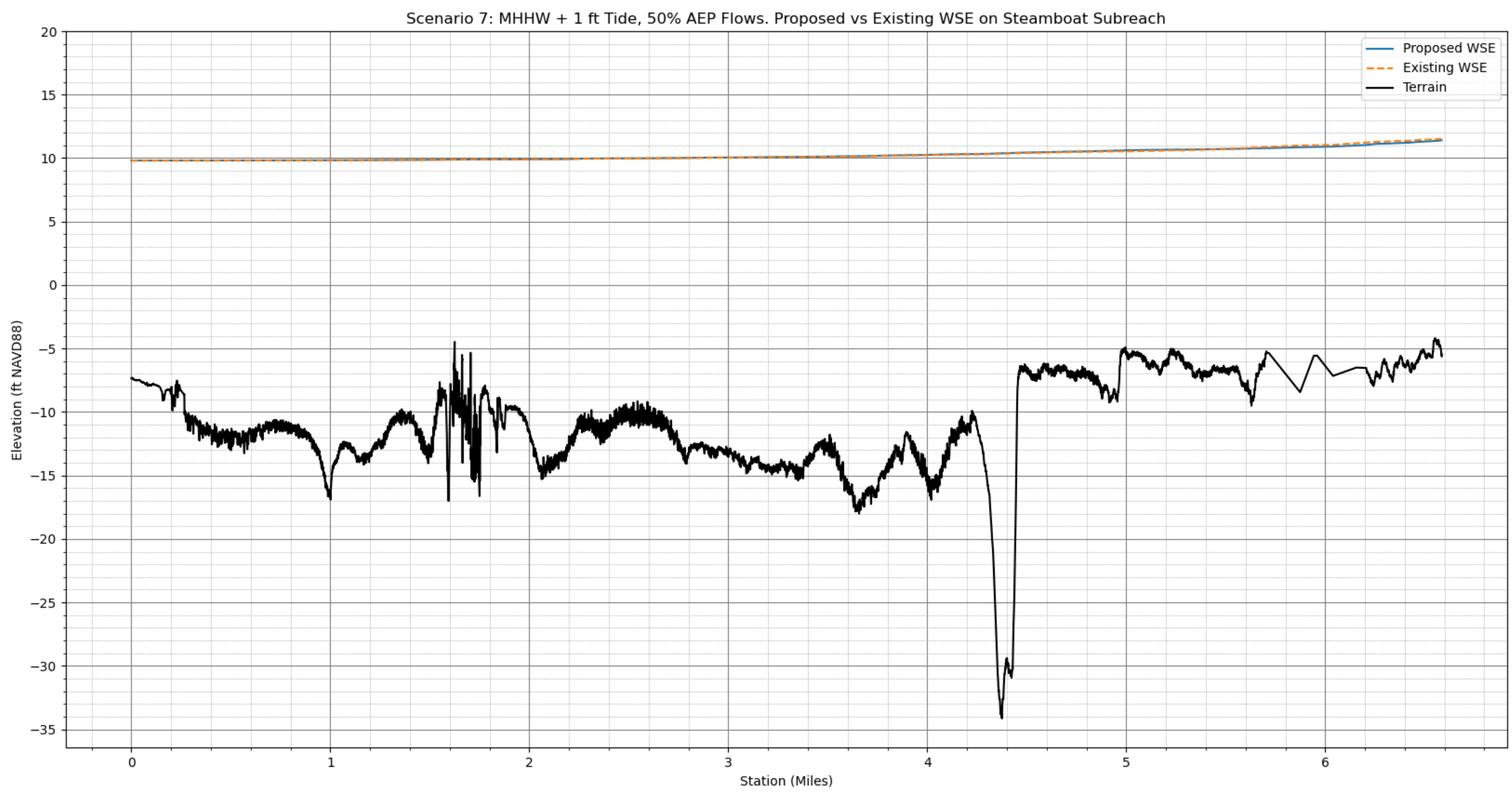


Figure 38. 50% AEP Existing Flow Conditions at Steamboat Slough Subreach

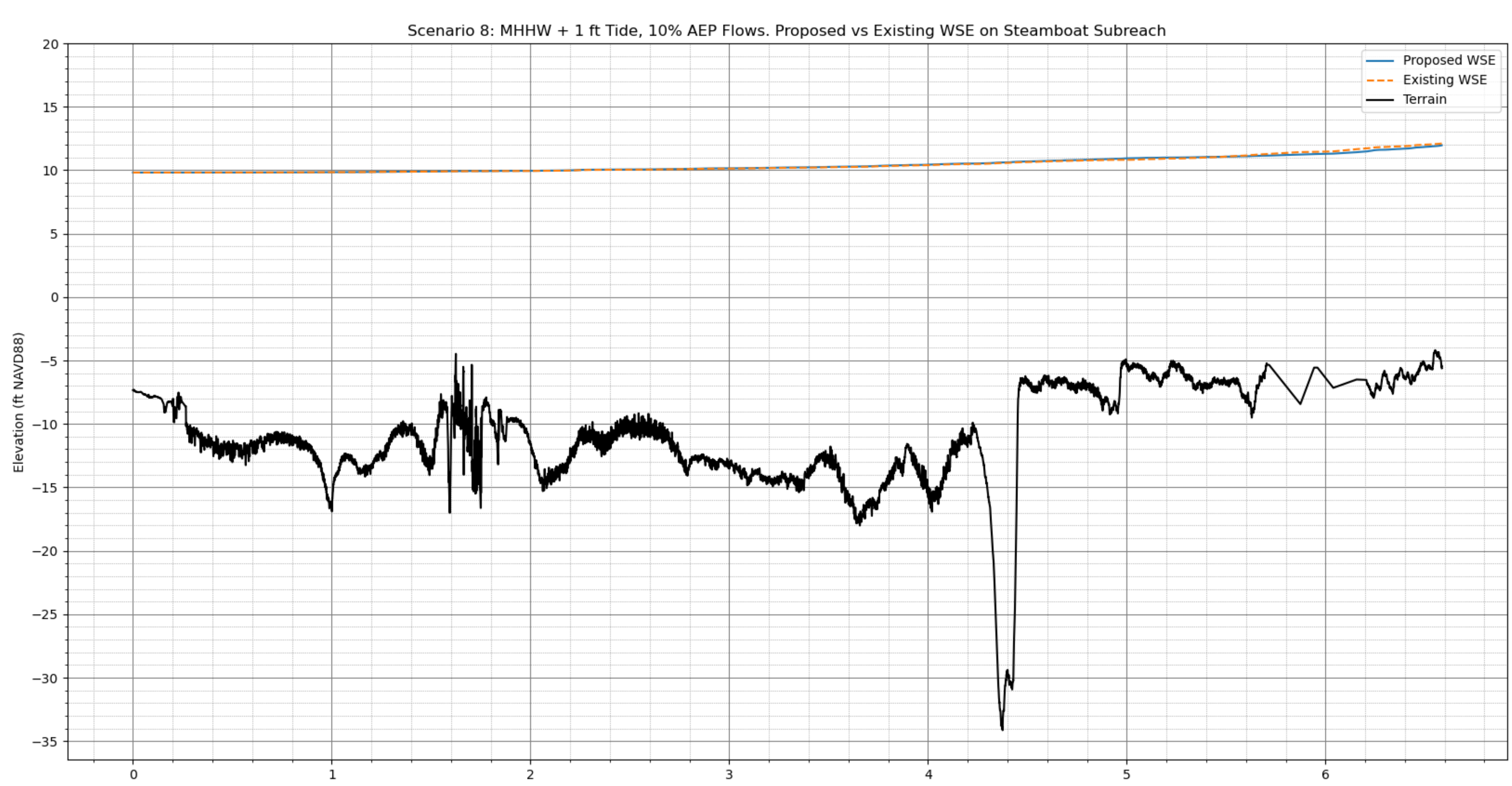


Figure 39. 50% AEP 2080 Flow Conditions at Steamboat Slough Subreach
Figure 40. 10% AEP Existing Flow Conditions at Steamboat Slough Subreach

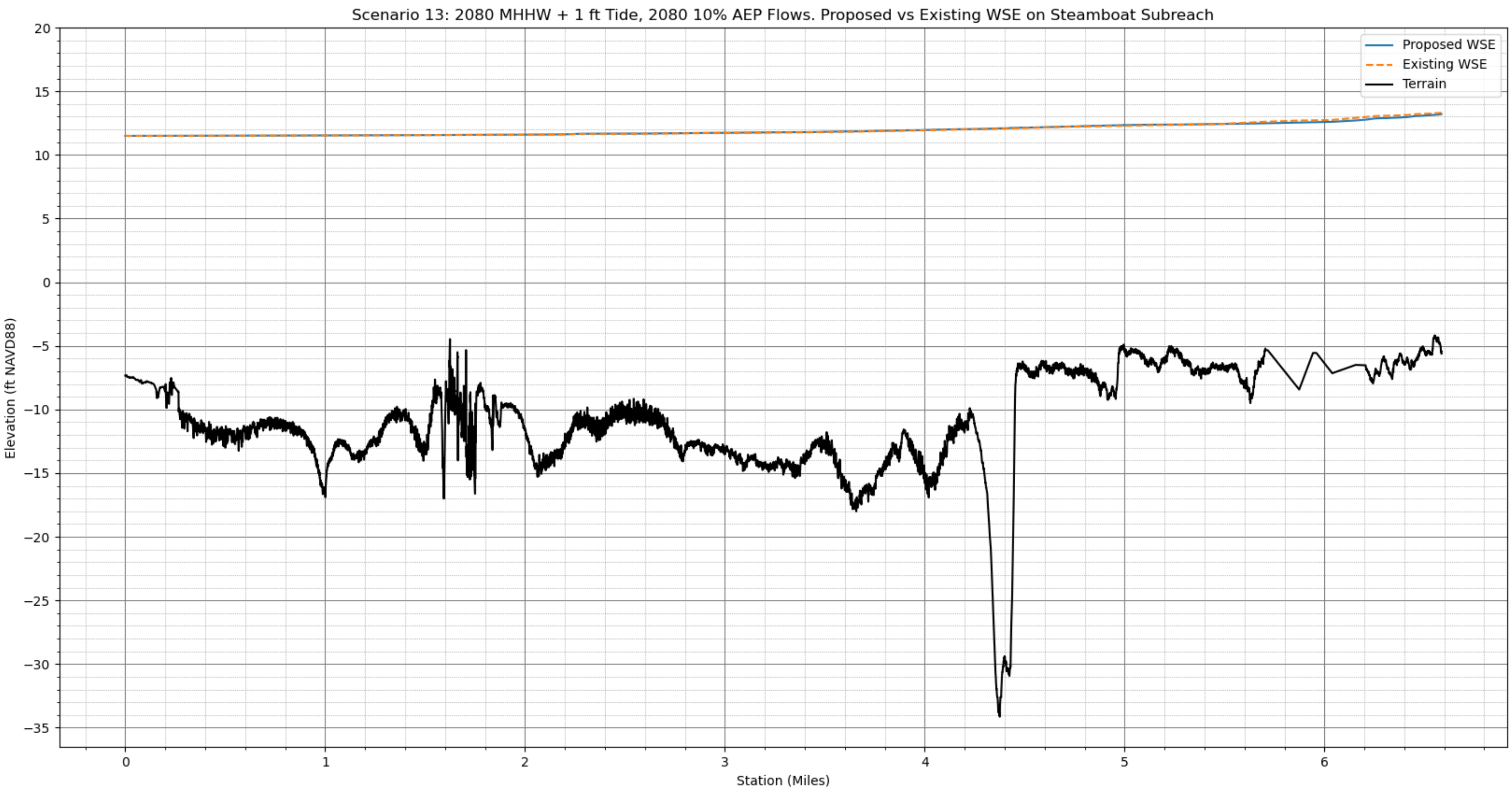


Figure 42. 1% AEP Existing Flow Conditions at Steamboat Slough Subreach

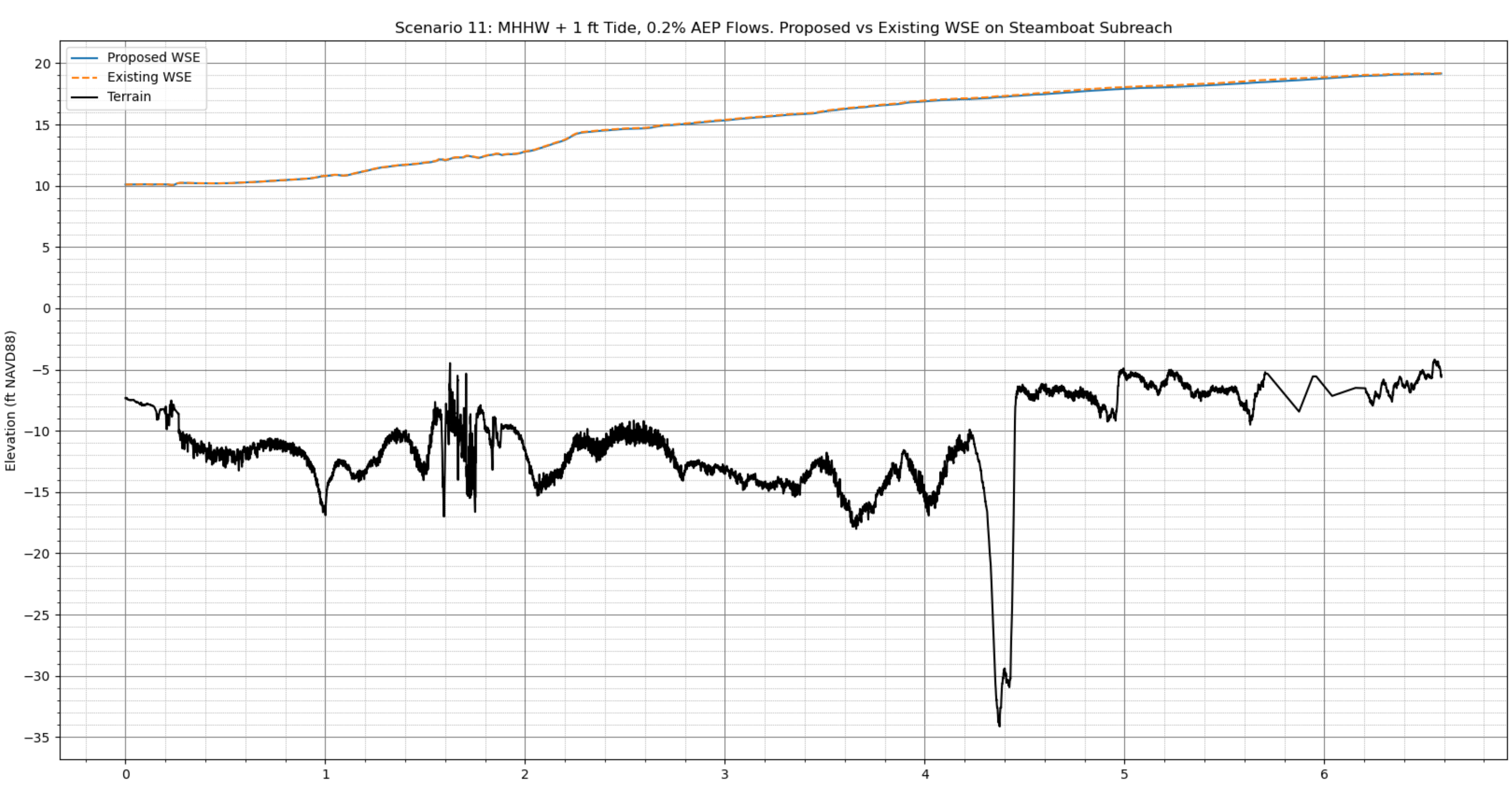


Figure 44. 0.2% AEP Existing Flow Conditions at Steamboat Slough Subreach

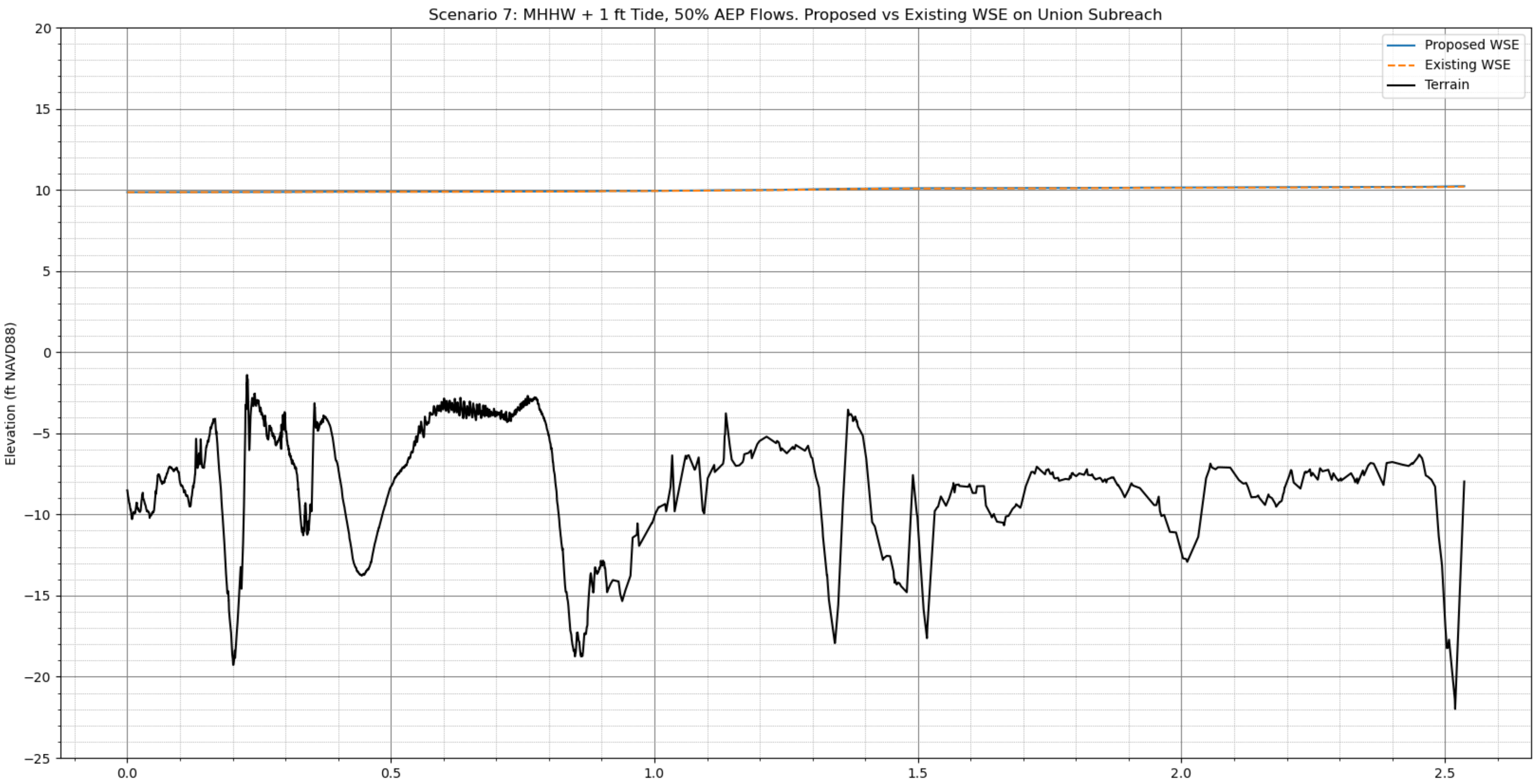


Figure 45. 0.2% AEP 2080 Flow Conditions at Steamboat Slough Subreach

3.3.3 Union Slough Subreach

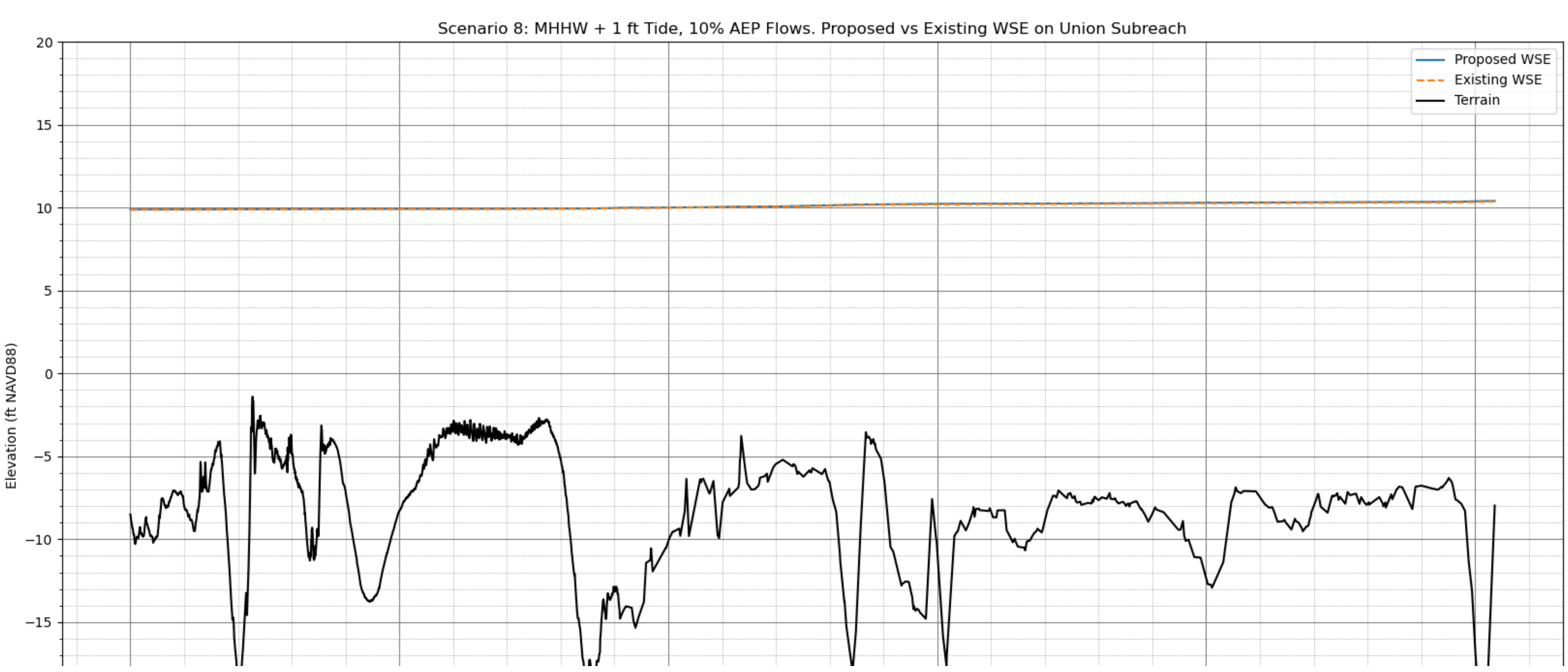
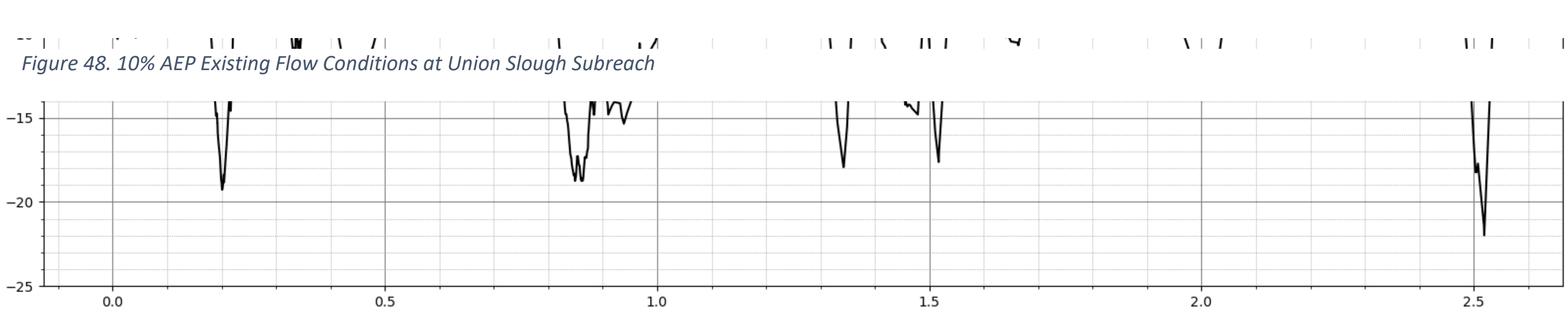


Figure 46. 50% AEP Existing Flow Conditions at Union Slough Subreach

Figure 47. 50% AEP 2080 Flow Conditions at Union Slough Subreach

Figure 48. 10% AEP Existing Flow Conditions at Union Slough Subreach



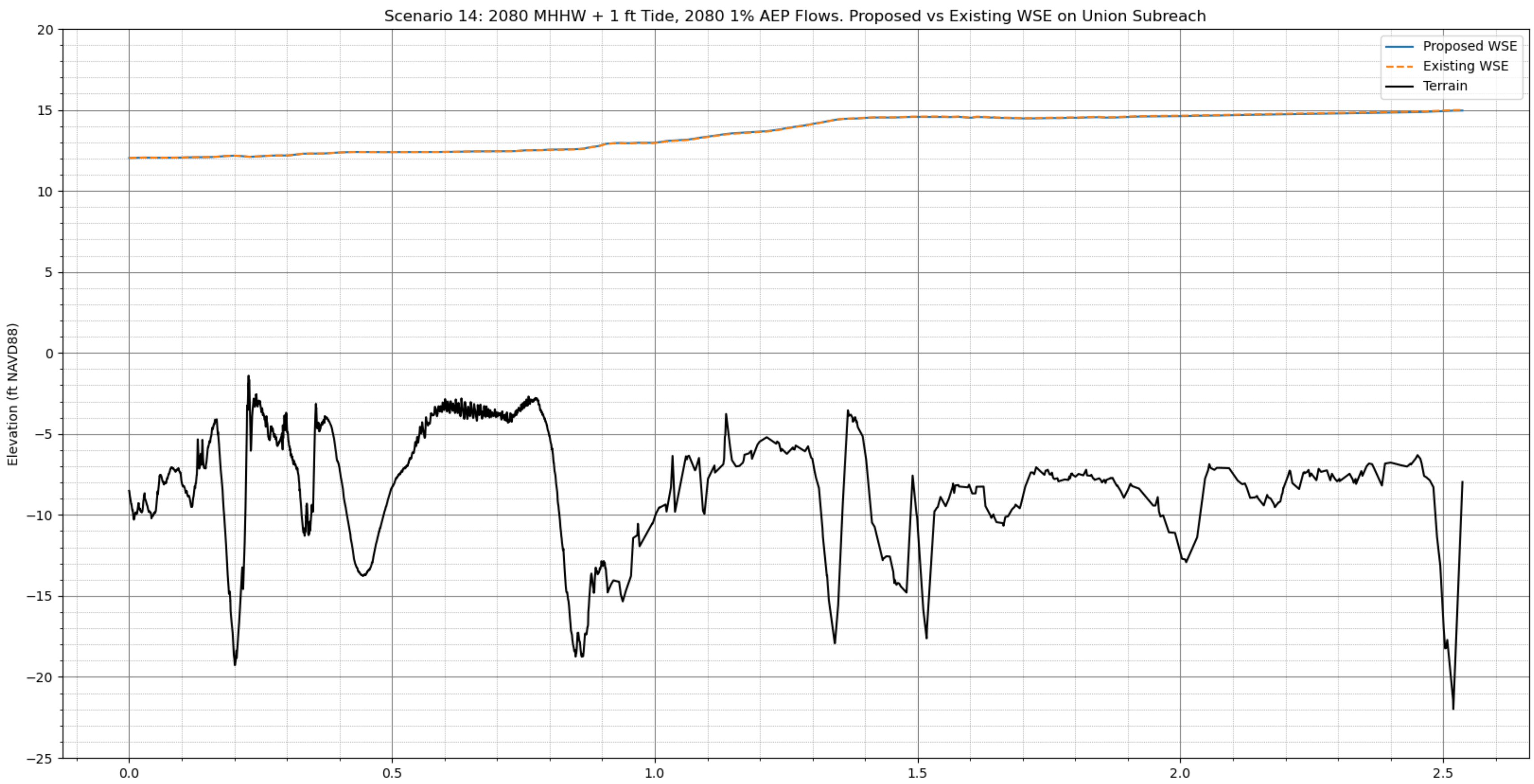


Figure 50. 1% AEP Existing Flow Conditions at Union Slough Subreach

Figure 51. 1% AEP 2080 Flow Conditions at Union Slough Subreach

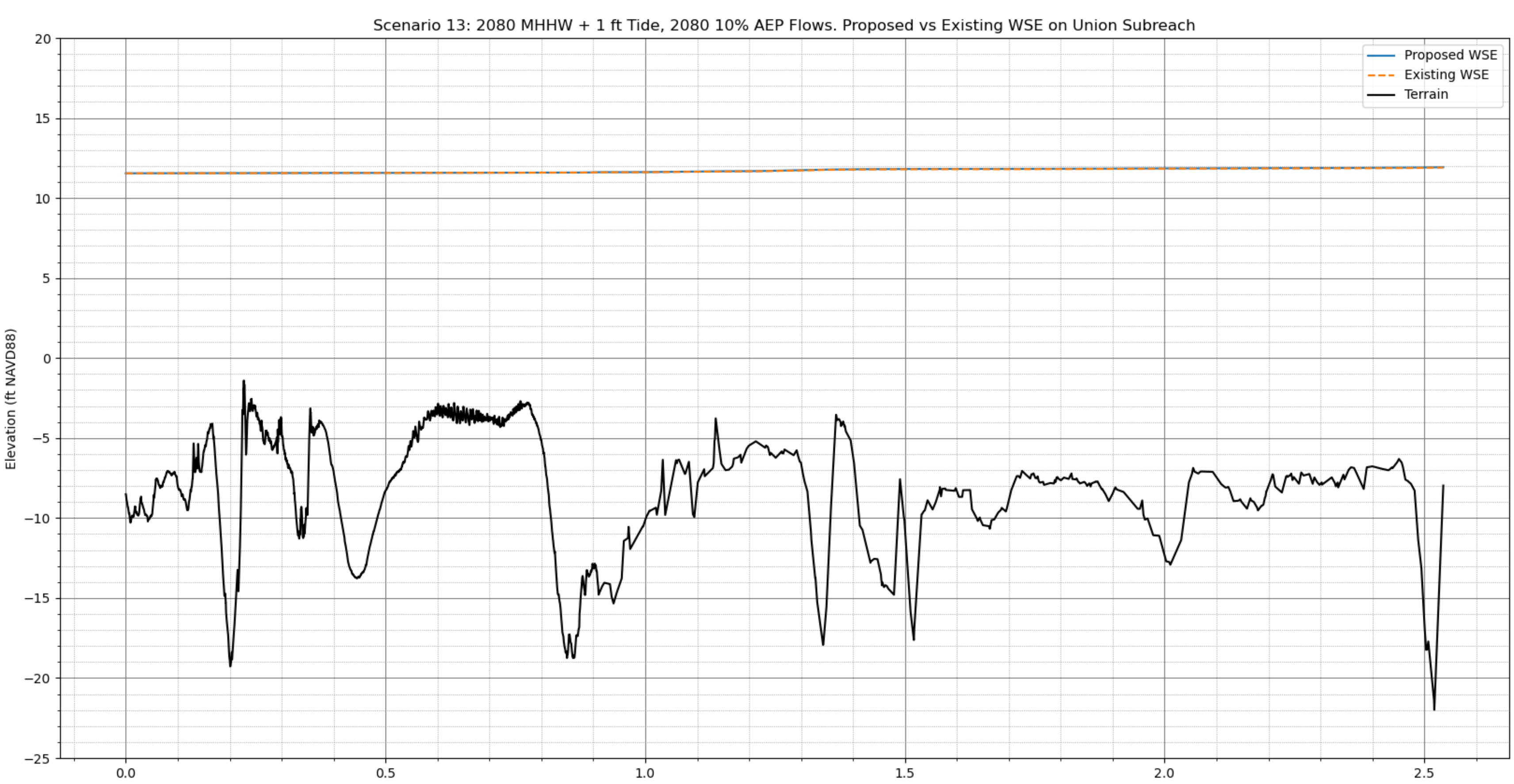


Figure 49. 10% AEP 2080 Flow Conditions at Union Slough Subreach

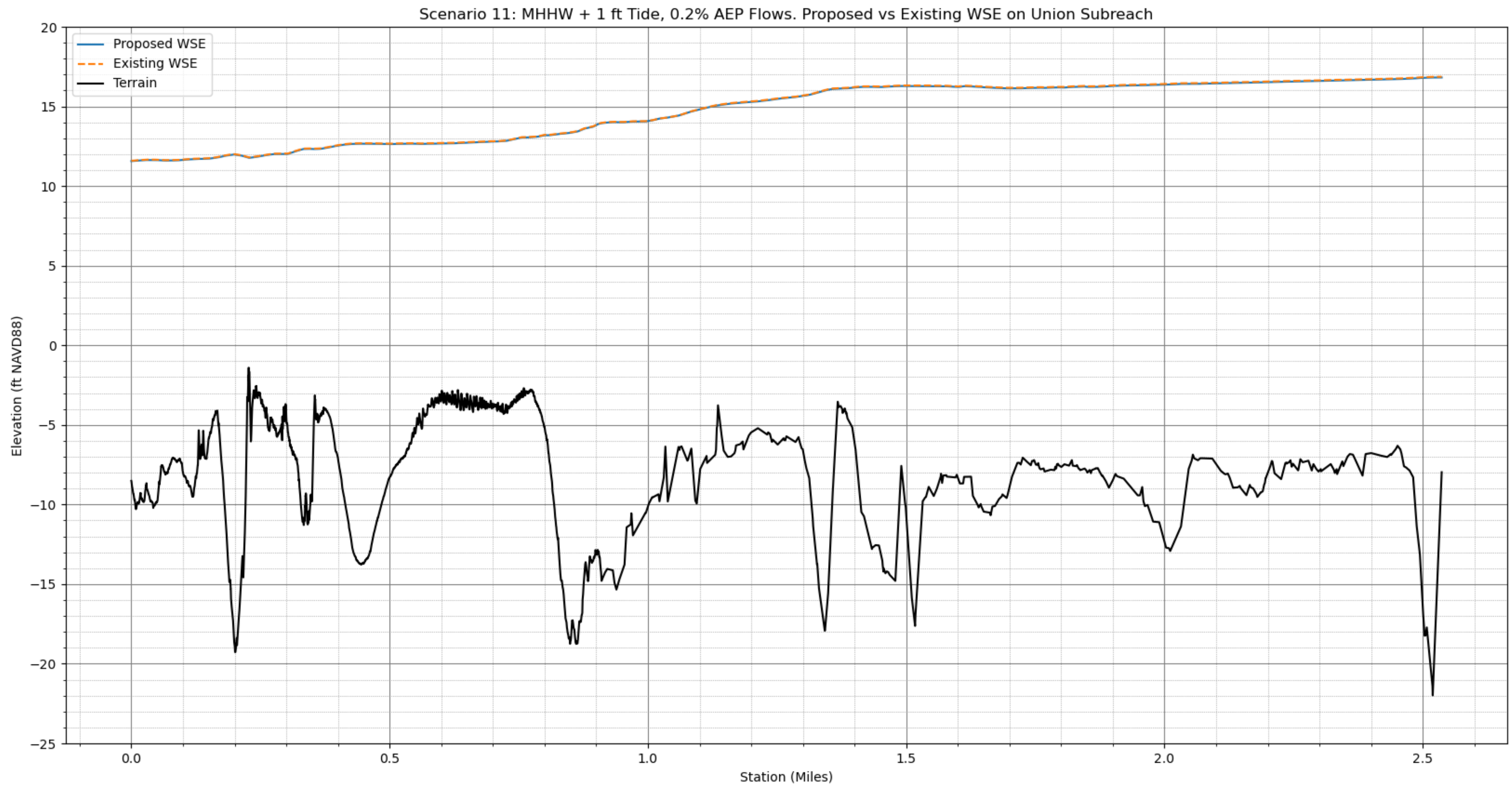


Figure 52. 0.2% AEP Existing Flow Conditions at Union Slough Subreach

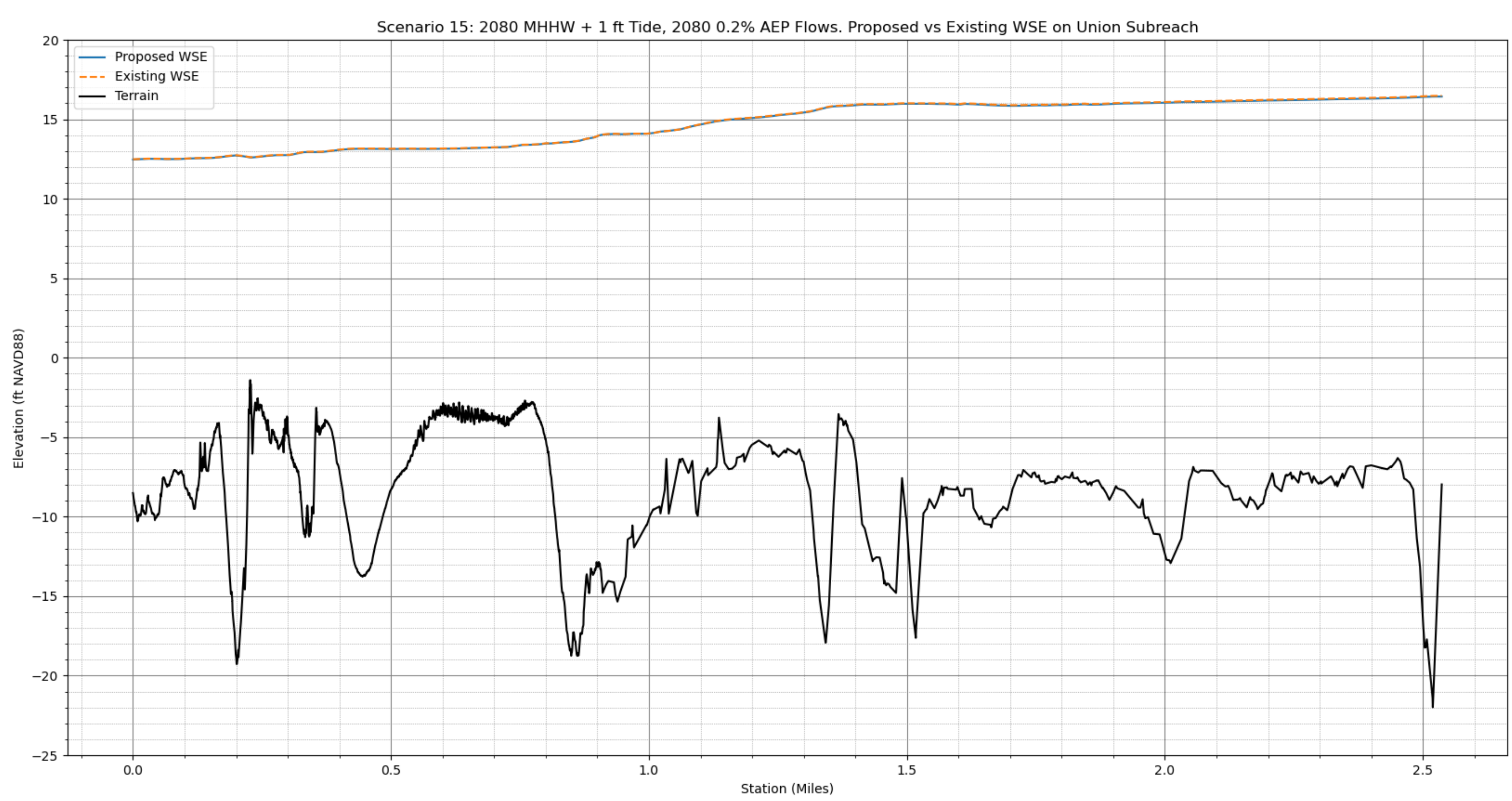


Figure 53. 0.2% AEP 2080 Flow Conditions at Union Slough Subreach

4. Velocity Plots

4.1 50% AEP Existing Flows (Scenario 7)

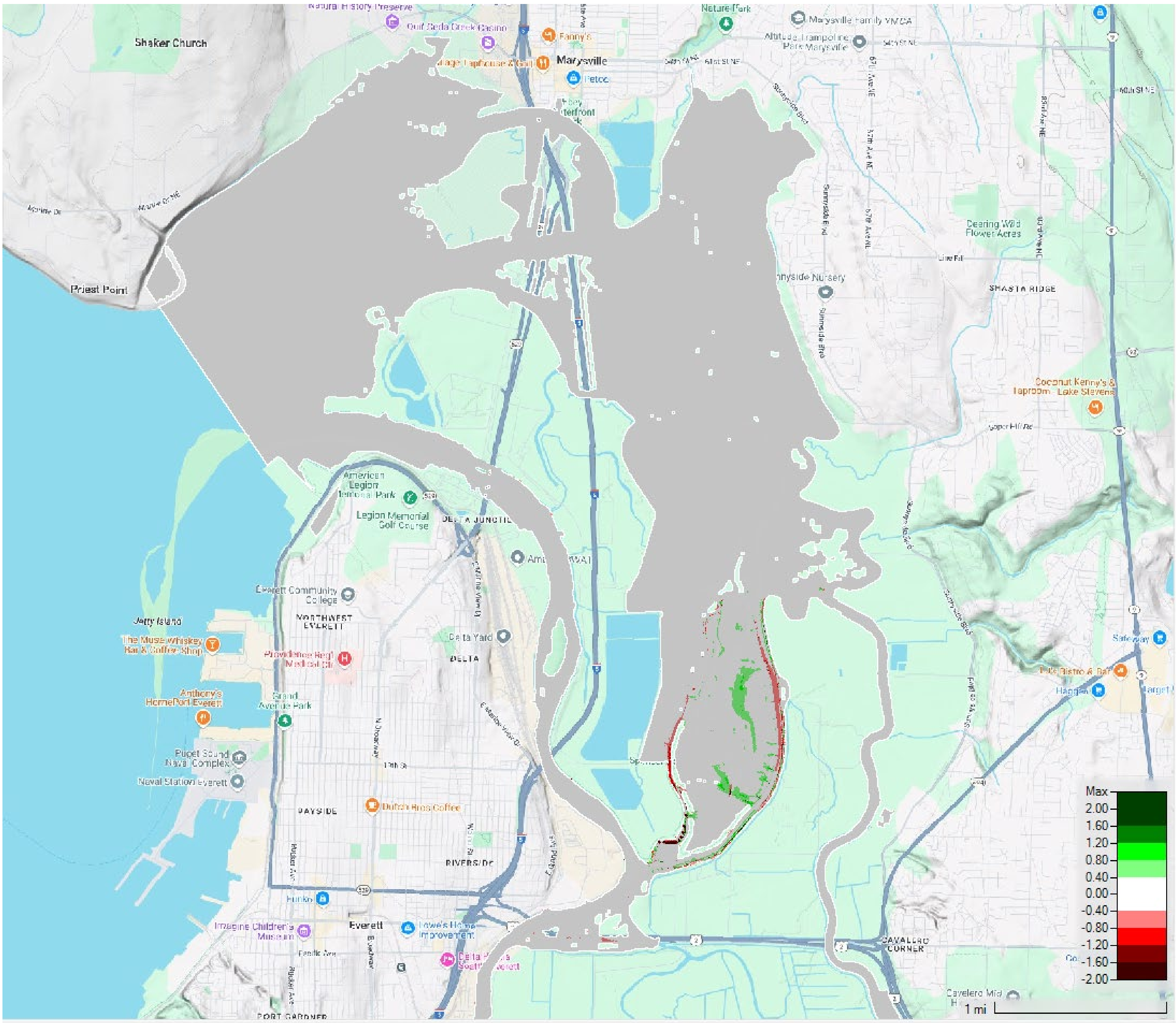


Figure 54. Velocity Difference Plot: MHHW + 1 ft Tidal Condition, 50% AEP Flows

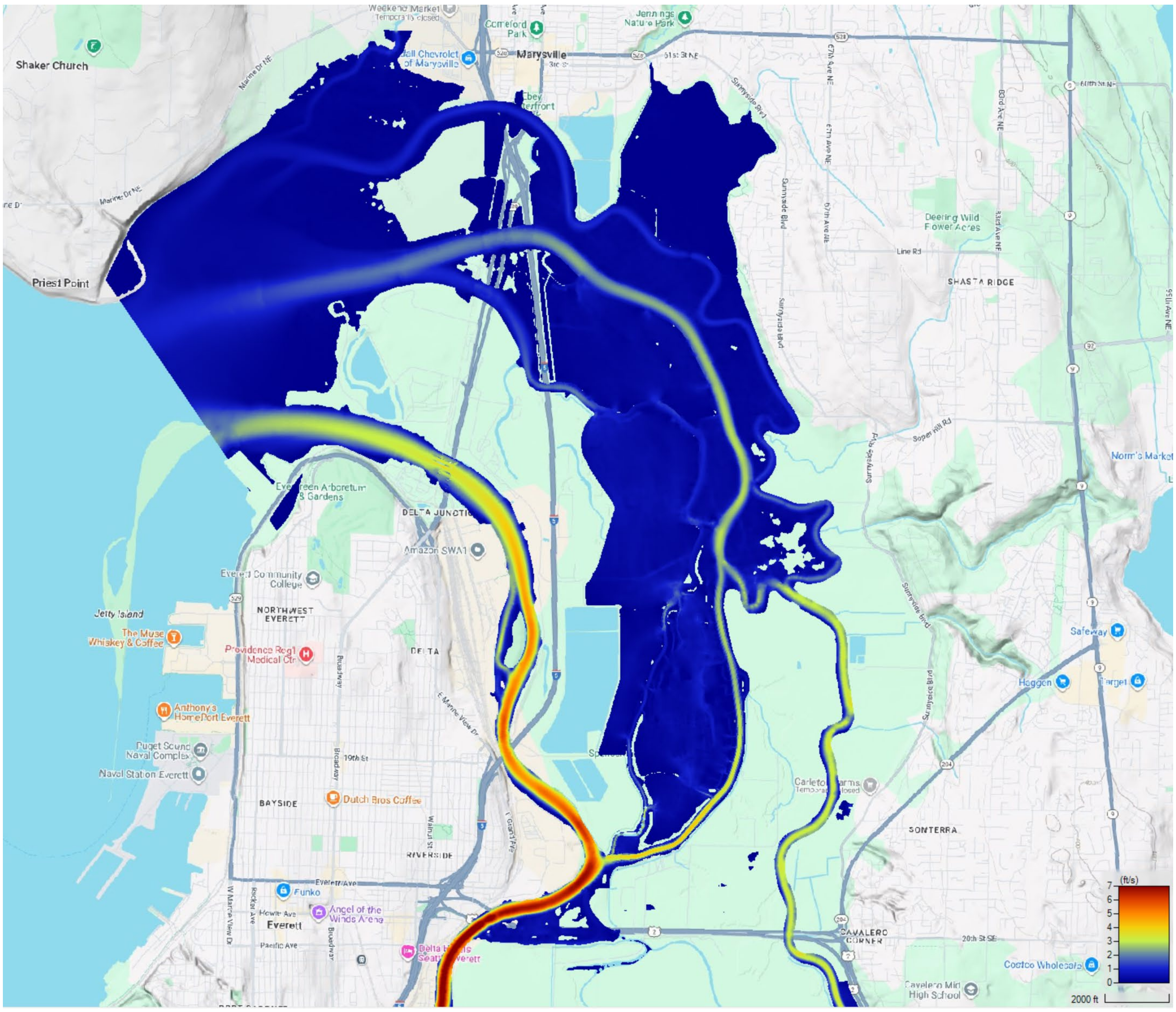


Figure 55. Proposed Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 50% AEP Flows

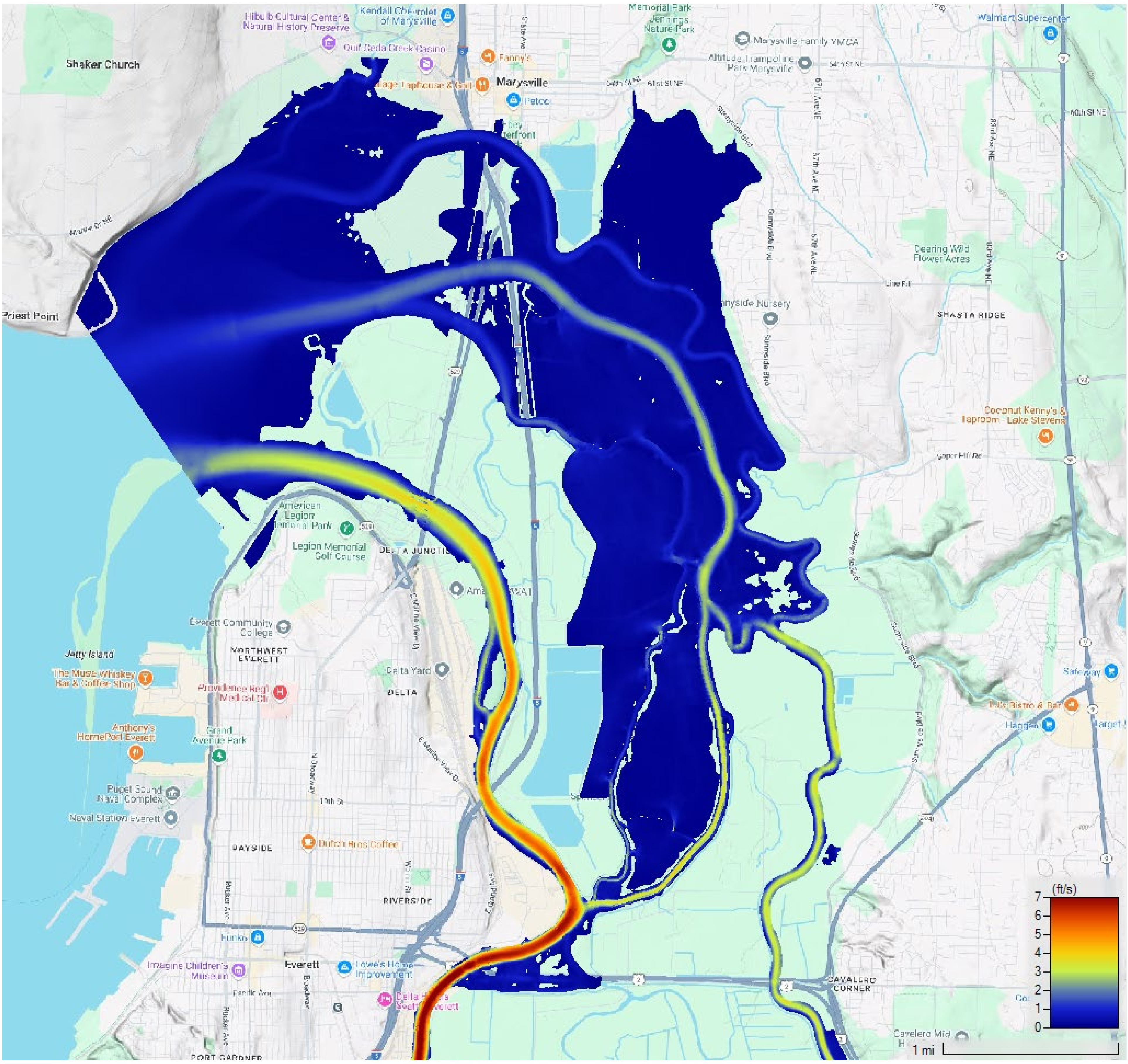


Figure 56. Existing Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 50% AEP Flows

4.2 10% AEP Existing Flows (Scenario 8)

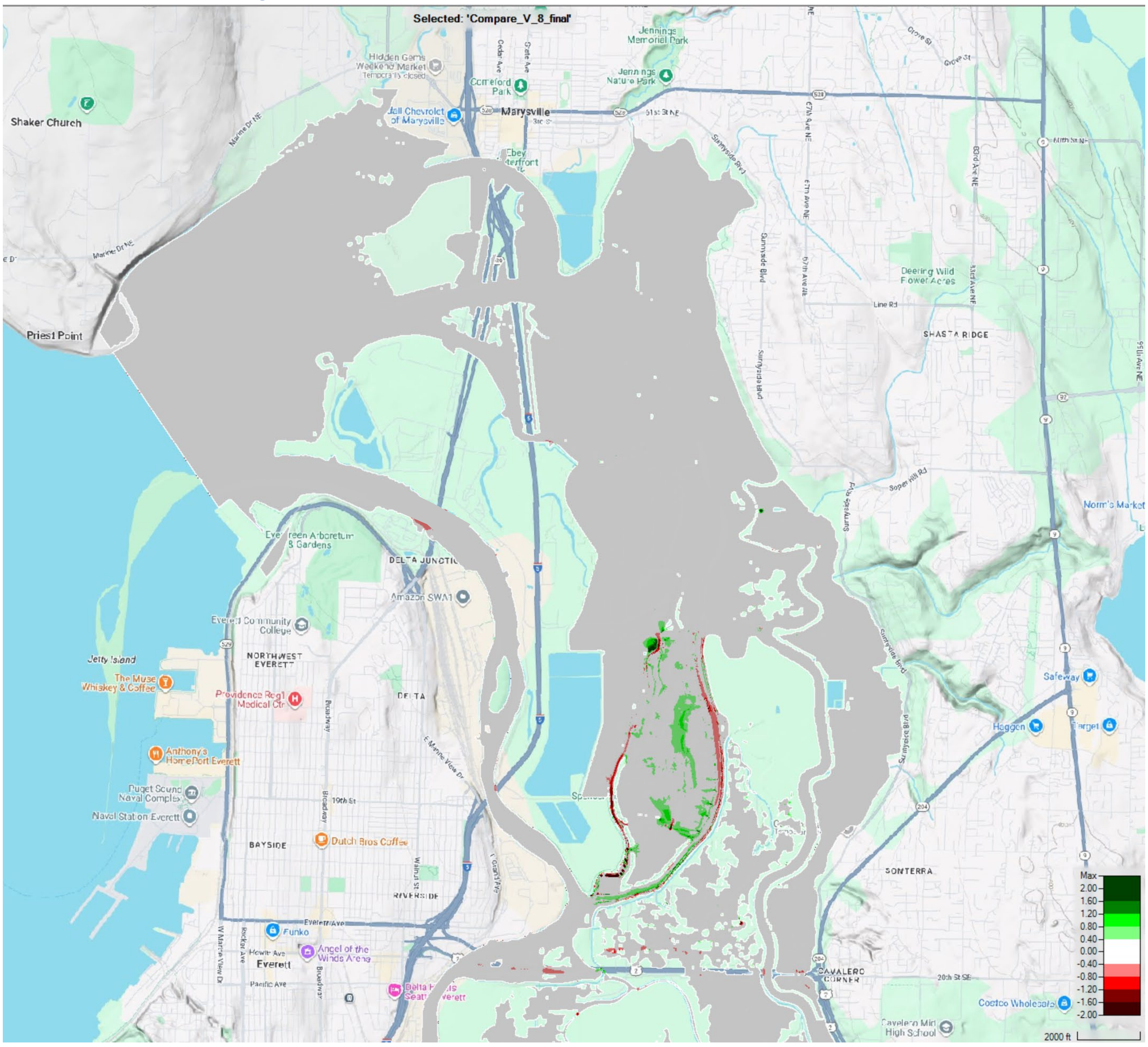


Figure 57. Velocity Difference Plot: MHHW + 1 ft Tidal Condition, 10% AEP Flows

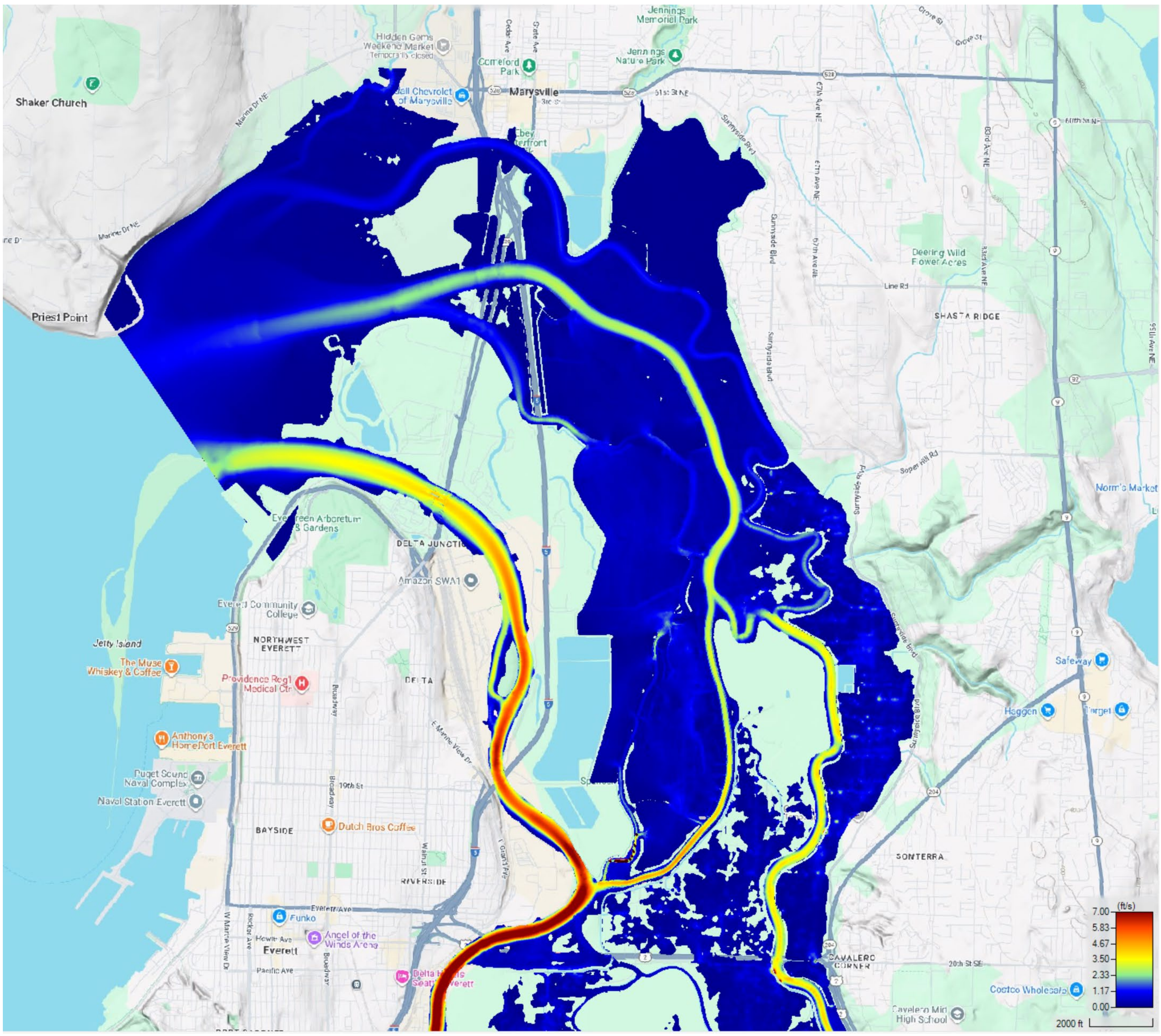


Figure 58. Proposed Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 10% AEP Flows

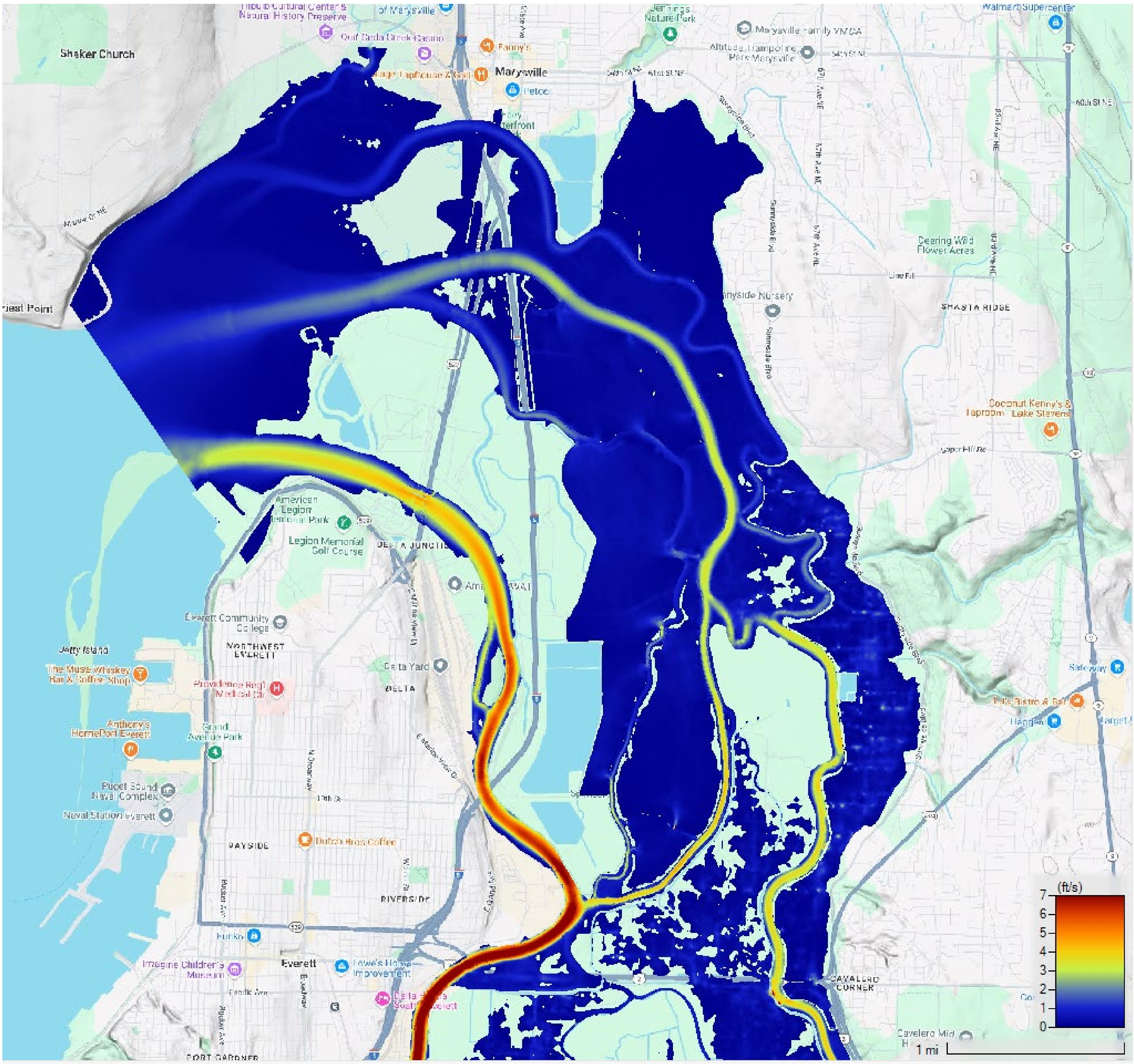


Figure 59. Existing Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 10% AEP Flows

4.3 2% AEP Existing Flows (Scenario 9)

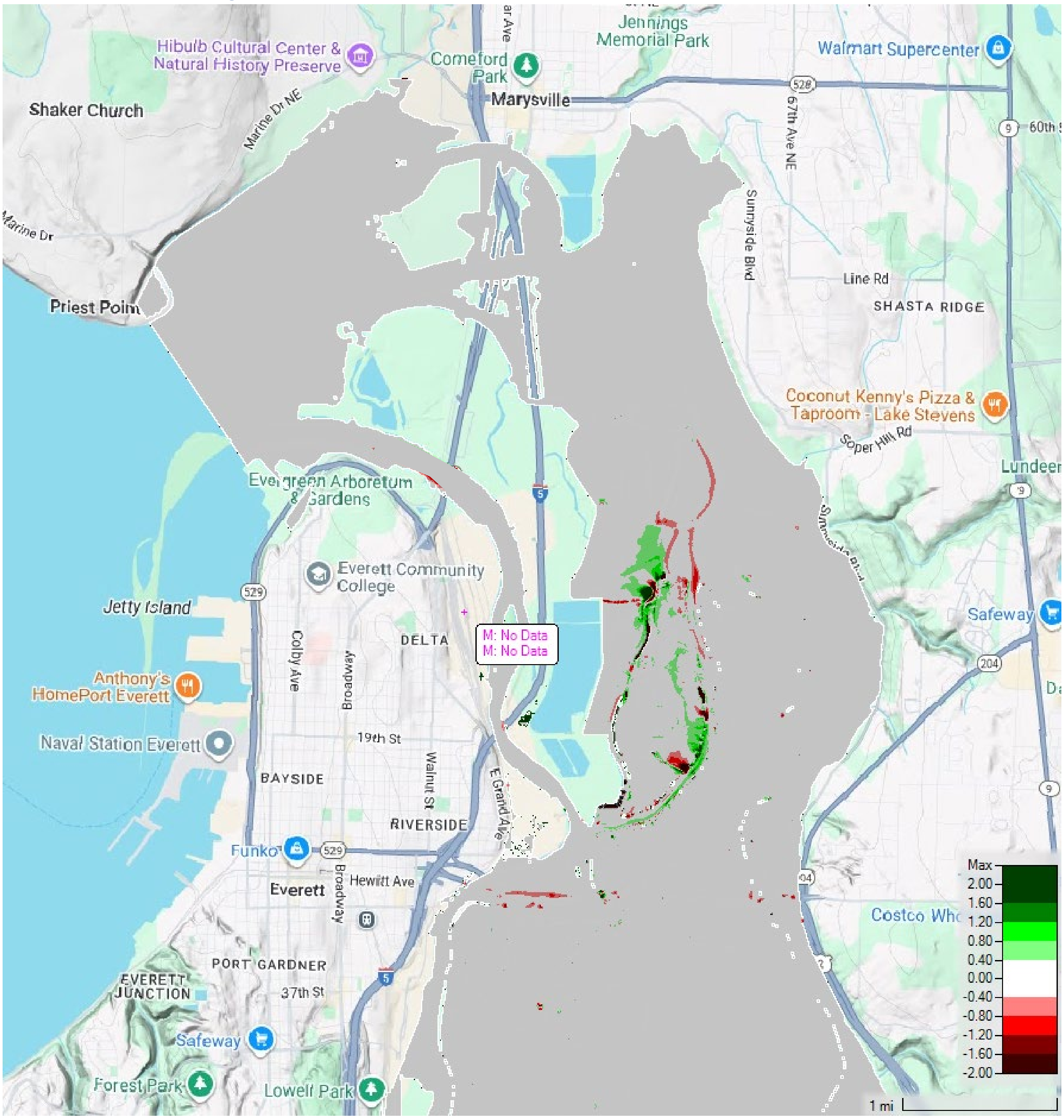


Figure 60. Velocity Difference Plot: MHHW + 1 ft Tidal Condition, 2% AEP Flows

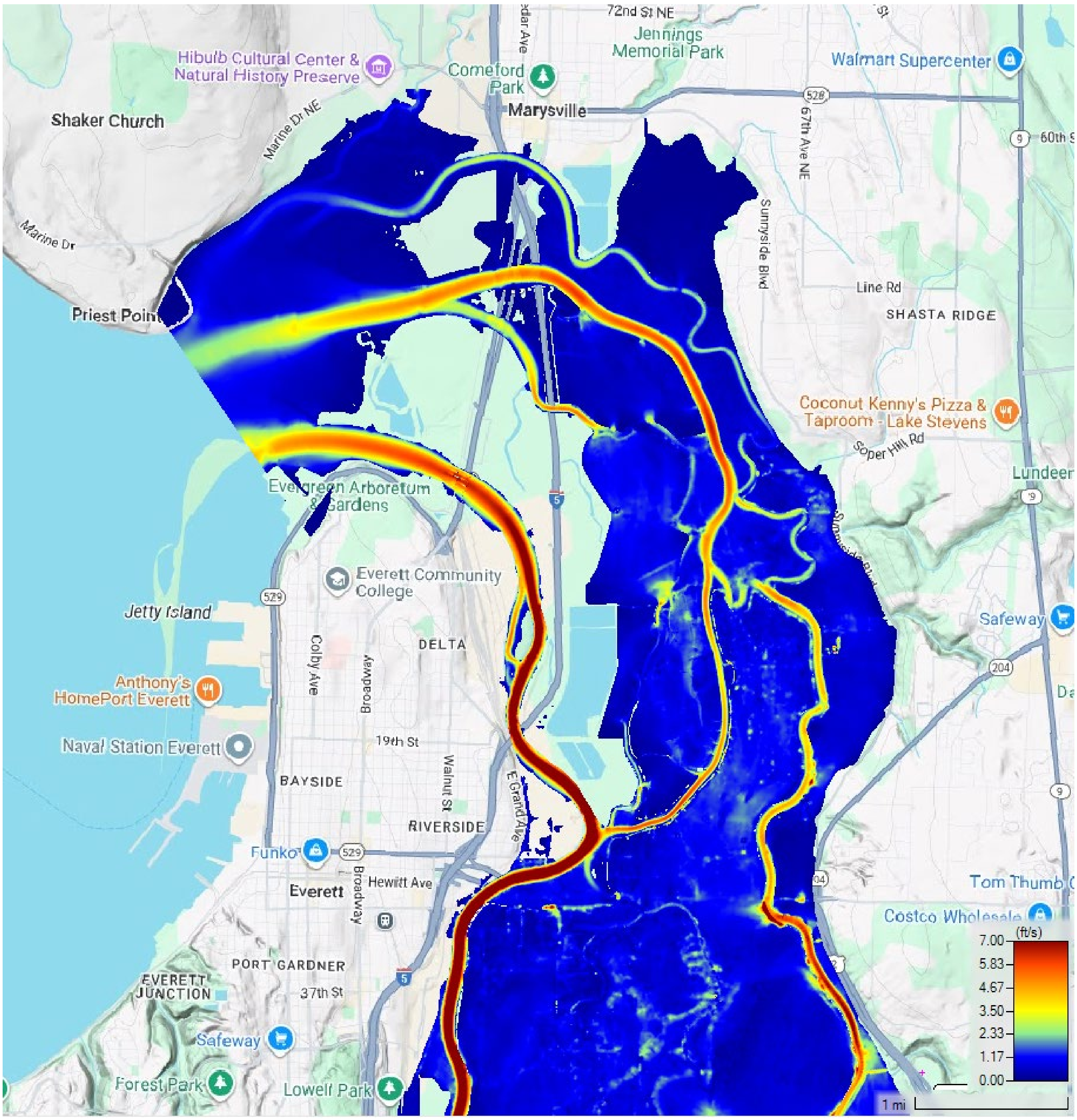


Figure 61. Proposed Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 2% AEP Flows

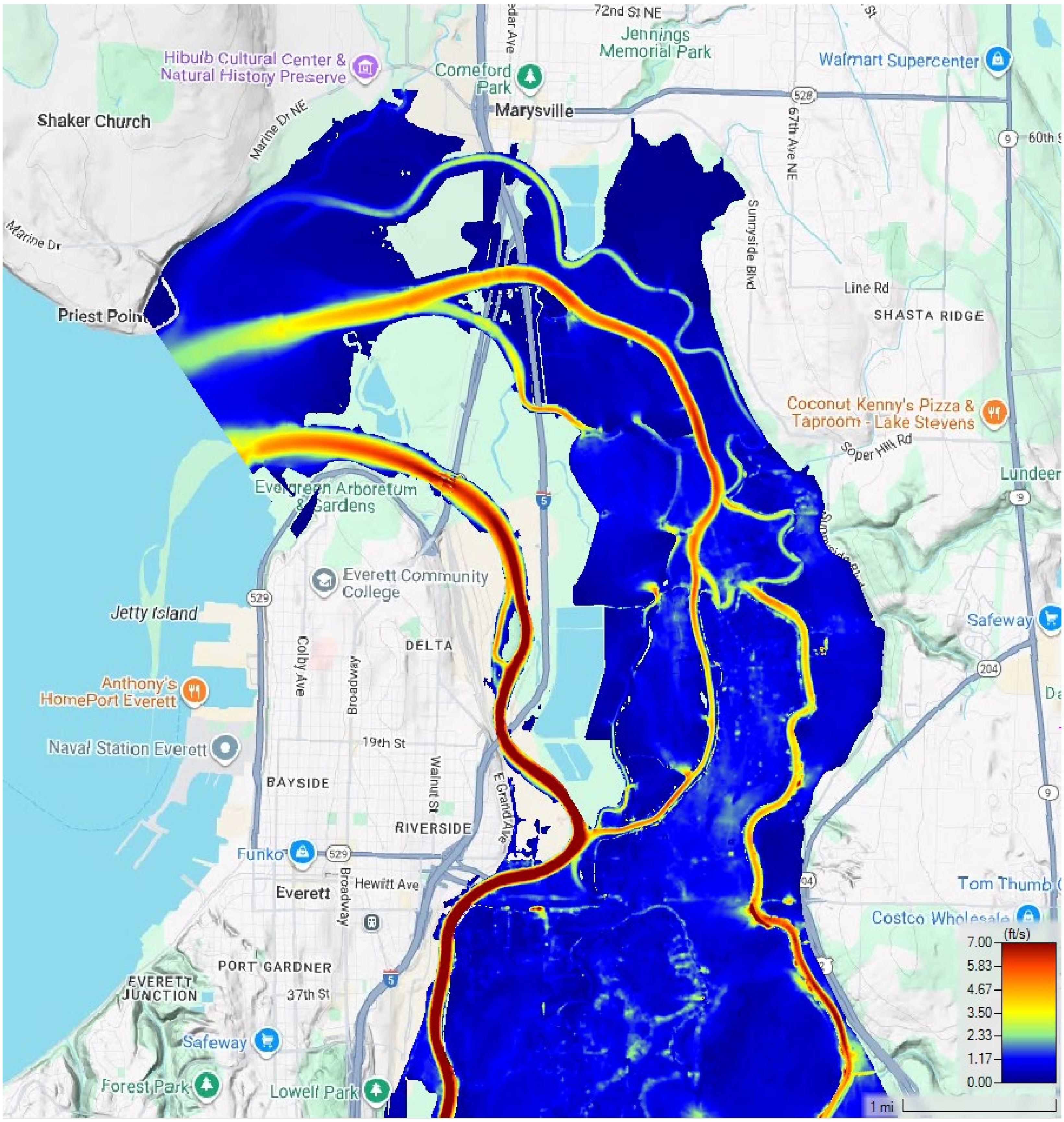


Figure 62. Existing Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 2% AEP Flows

4.4 1% AEP Existing Flows (Scenario 10)

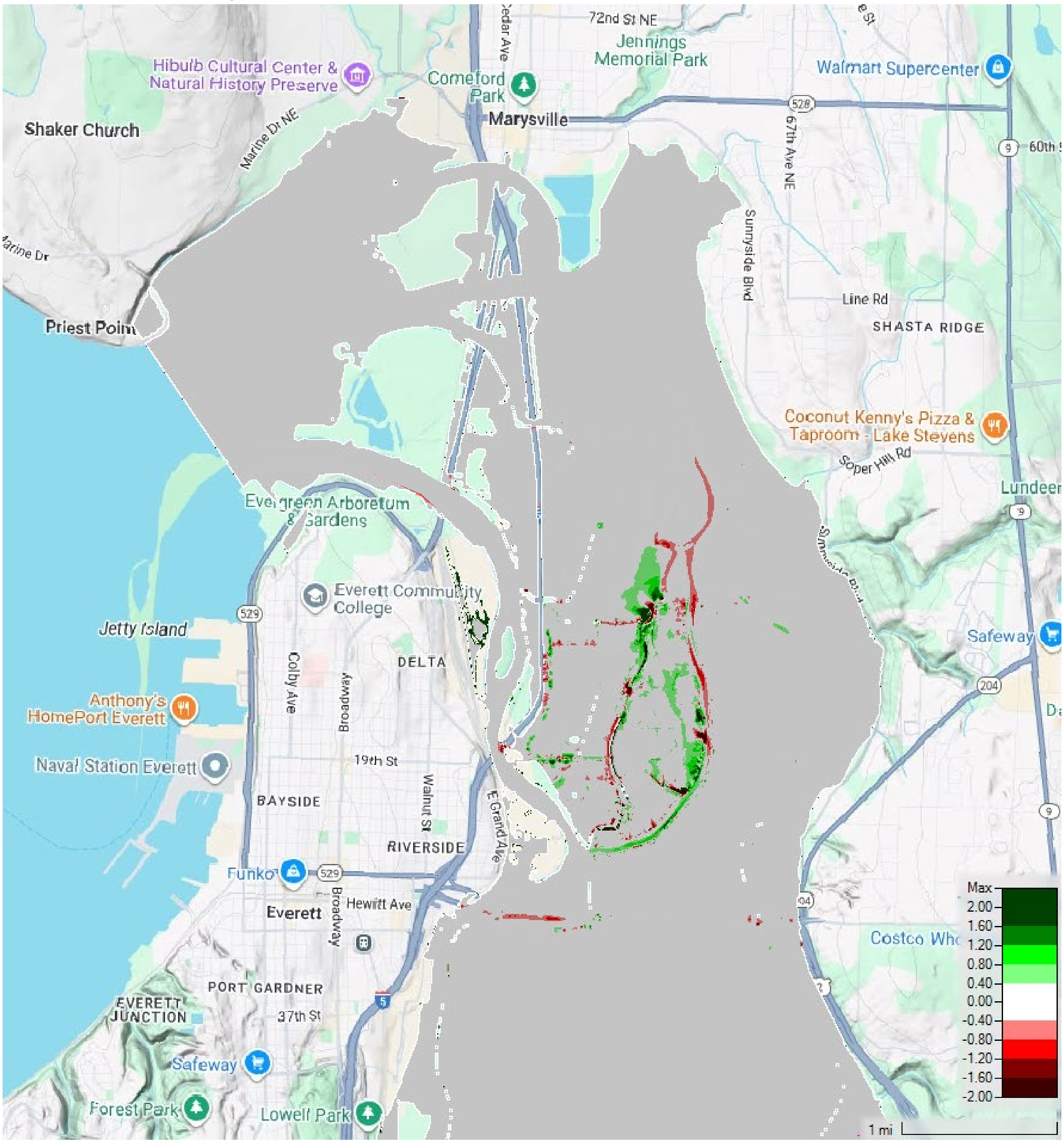


Figure 63. Velocity Difference Plot: MHHW + 1 ft Tidal Condition, 1% AEP Flows

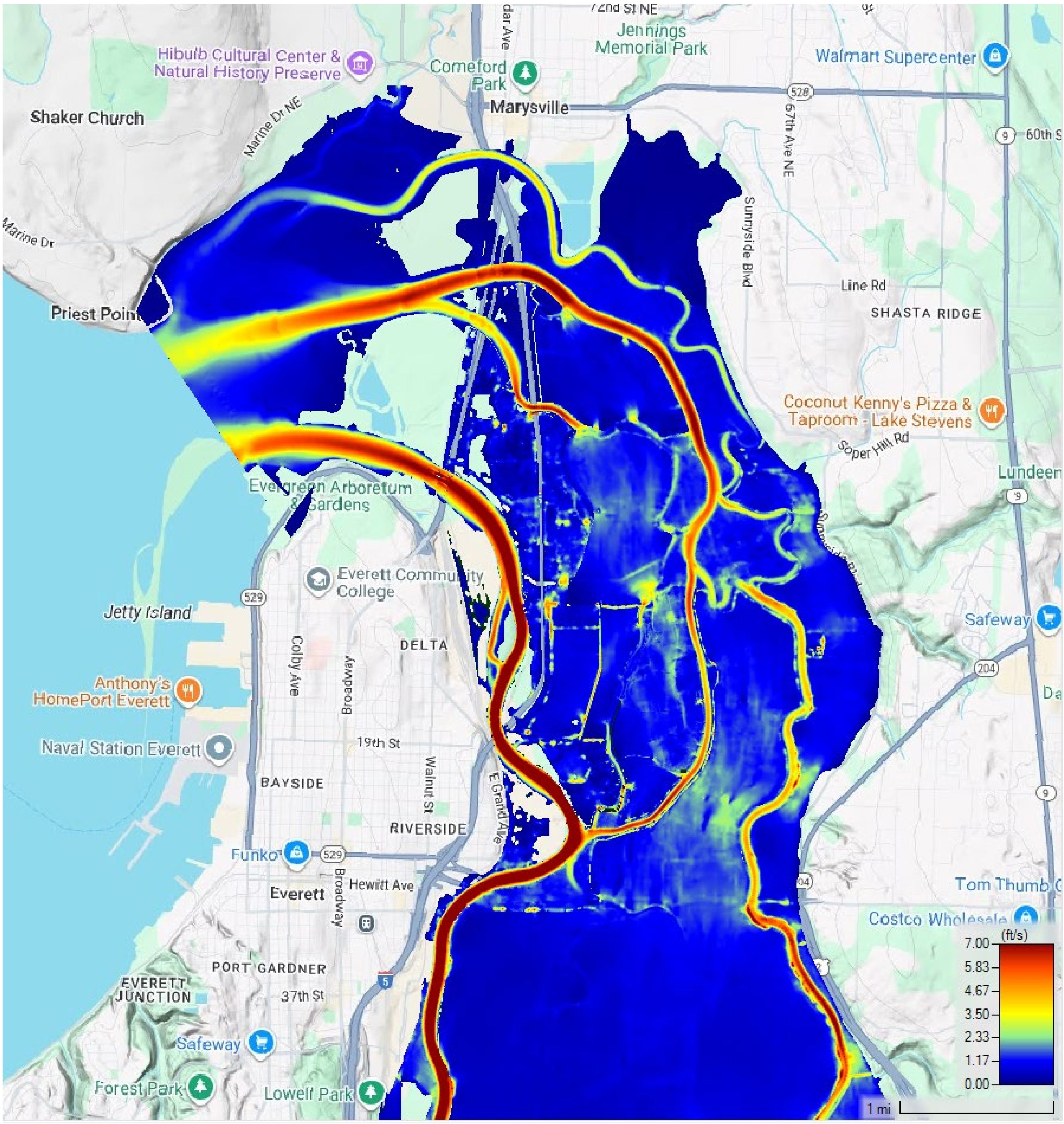


Figure 64. Proposed Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 1% AEP Flows

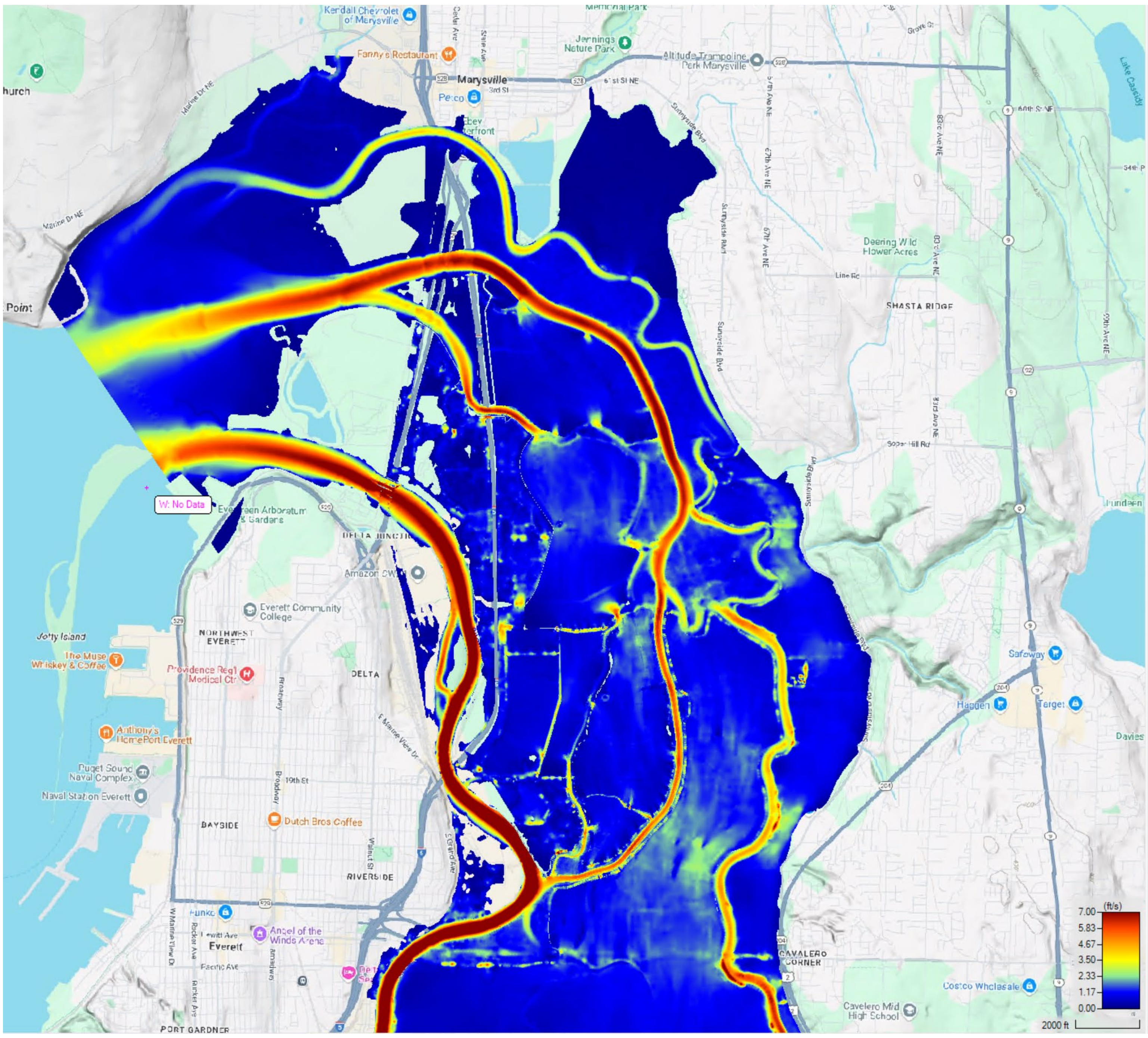


Figure 65. Existing Conditions Velocity Plot: MHHW + 1 ft Tidal Condition, 1% AEP Flows

5. Duration Plots

The following inundation maps illustrate the range of expected conditions with respect to duration of inundation. The first condition (Figure 66, Figure 67) spans several days of wintertime king tides (when coastal flooding occurred) coincident with normal river flows. The second condition illustrates potential inundation associated with the 1% AEP river flood, when levee overtopping is widespread (Figure 68, Figure 69). Duration of inundation for depths exceeding 0.1 feet are presented. During large floods areas behind levees will become inundated for well over 24 hours near Spencer Island for both existing and proposed conditions. The duration of inundation is unchanged for large floods and king tides, except for areas that have been excavated or filled as part of project construction. Channels and wetlands (blue areas) are inundated for more than half the time of the simulations (king tide and river flood). Red and orange areas (levees and uplands) are inundated less than half the time.

5.1 Winter king tide series (typical ordinary highwater conditions)

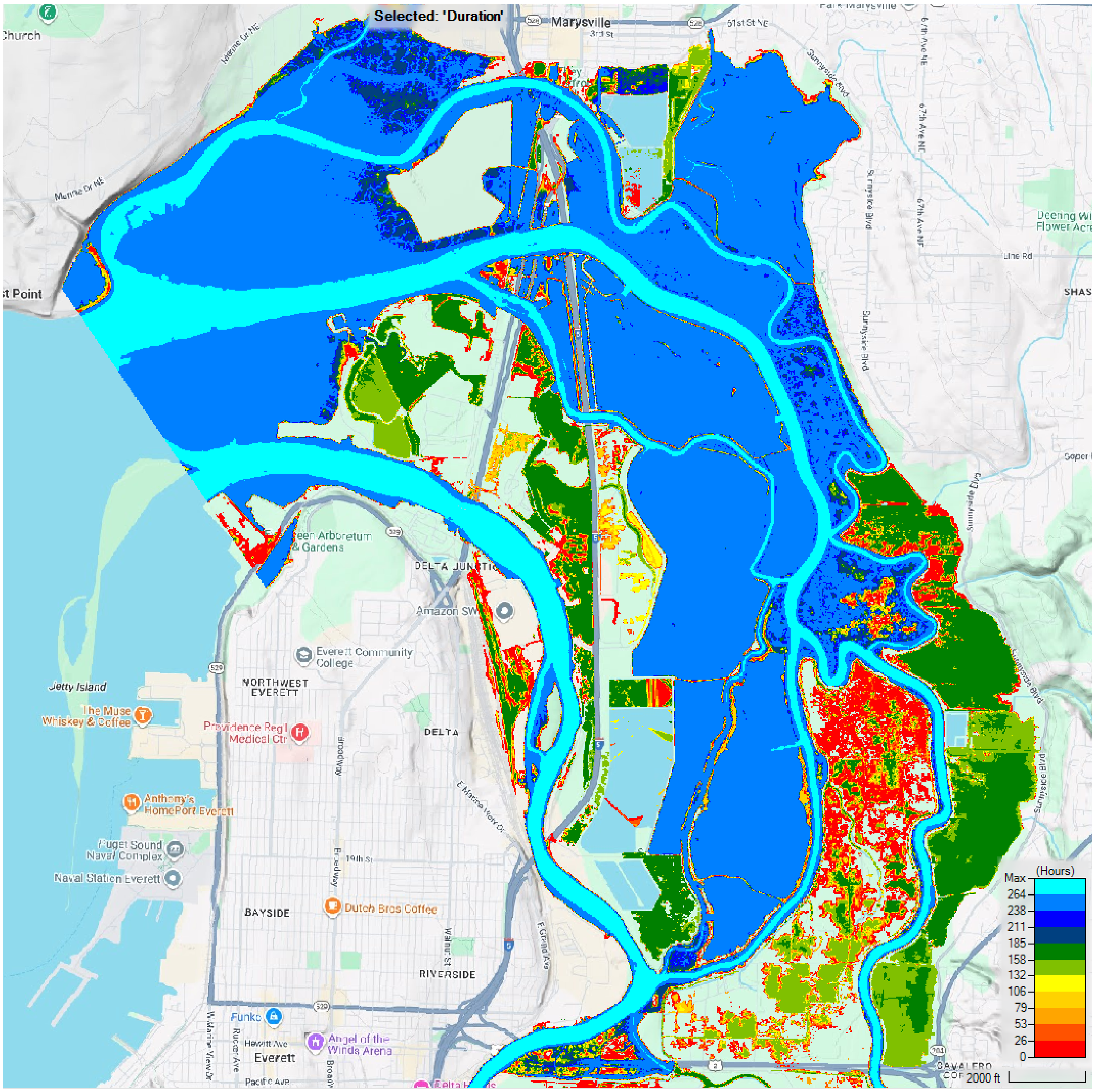


Figure 66. Duration of inundation for existing conditions for Dec 2022-Jan 2023 260-hour simulation that includes coastal flooding from record king tide

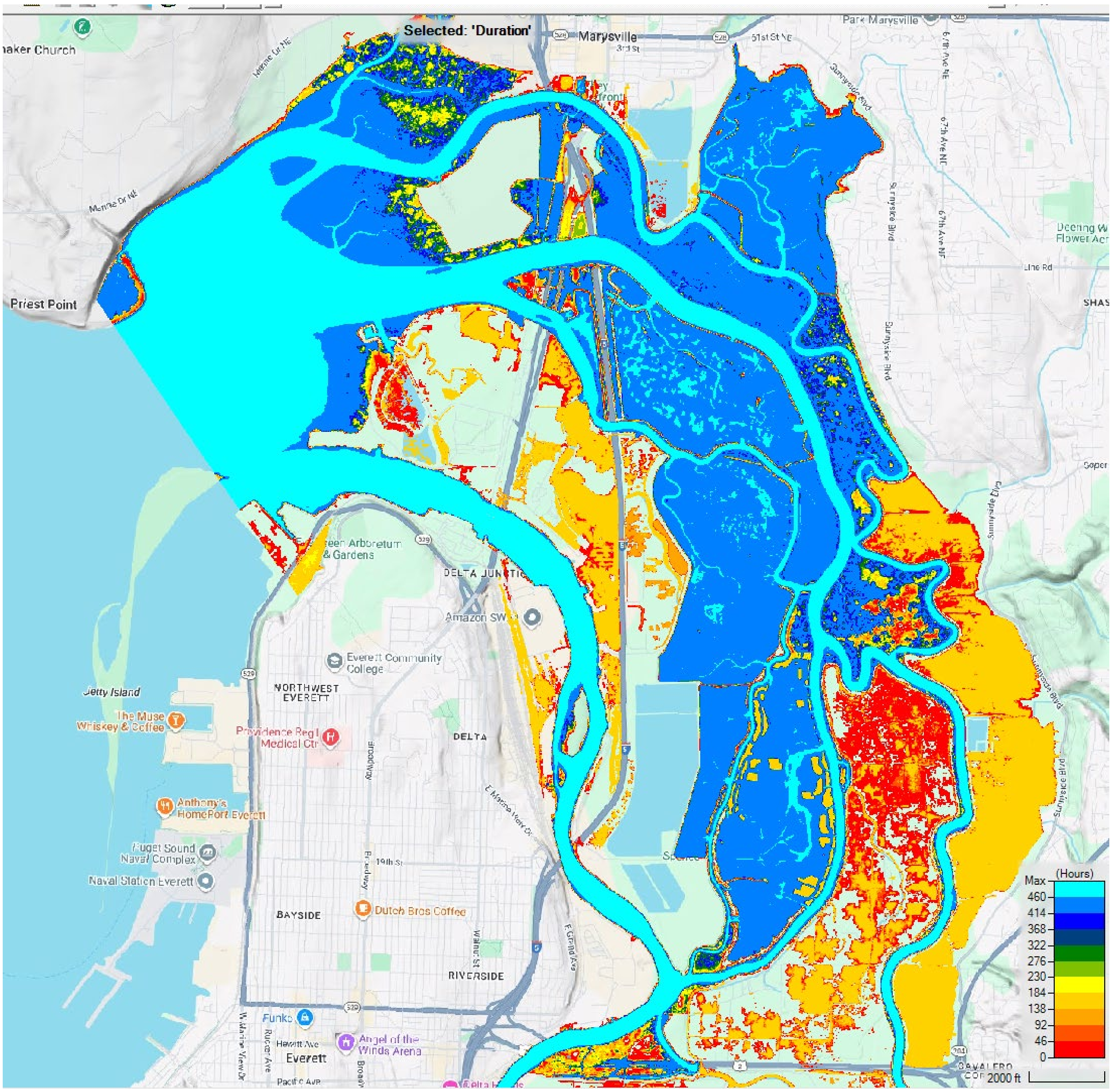


Figure 67. Duration of inundation for <u>proposed conditions</u> for Dec 2022-Jan 2023 460-hour simulation that includes coastal flooding from record king tide

Note that the existing conditions and proposed conditions scenarios for king tide flooding have different simulation durations.

5.2 Scenario 10 (1%AEP river flood)

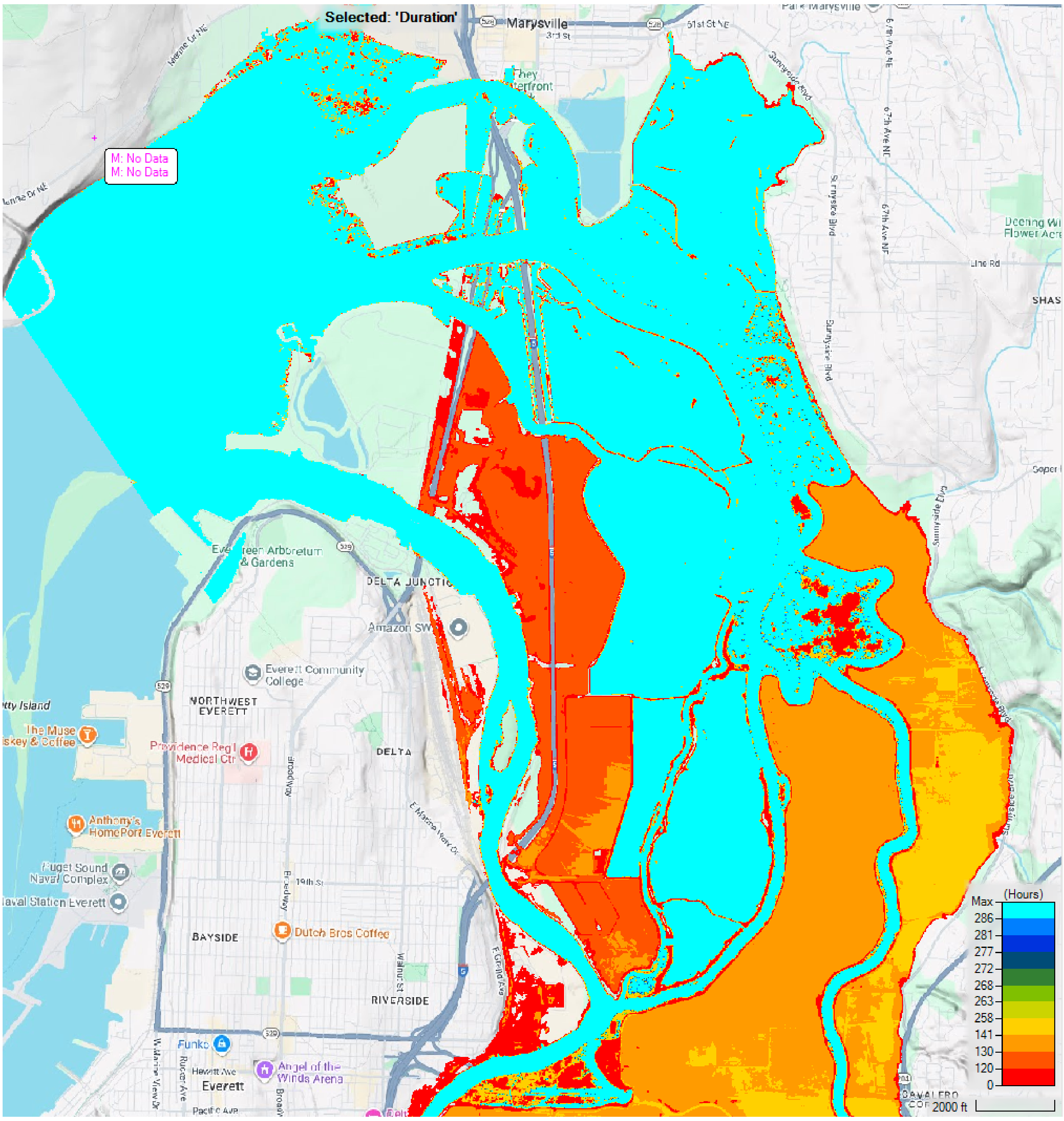


Figure 68.Existing Conditions Inundation Duration, 1% AEP River Flood Event

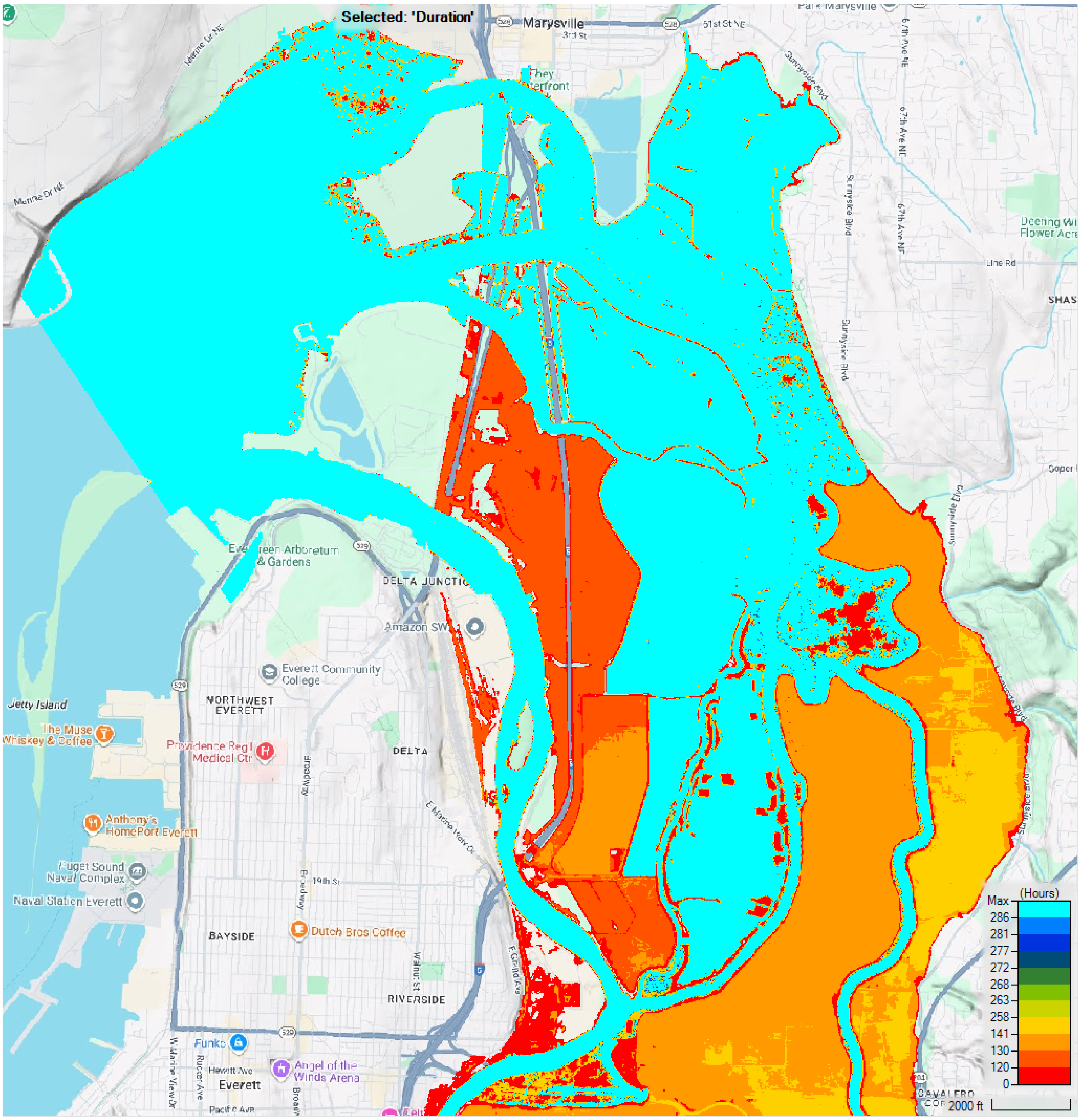


Figure 69.Proposed Conditions Inundation Duration, 1% AEP River Flood Event

Feasibility Phase Design Documentation Report

Spencer Island Ecosystem Restoration

HH&C Annex D-3: Geomorphology for Feasibility Phase

Snohomish County, WA

20-Jan 2026 35% ATR

Prepared by

US Army Corps of Engineers®
Seattle District

Contents

Figures

Tables

1. Overview

This hydraulics, hydrology and coastal (HH&C) Annex compiles existing conditions hydrologic, hydraulic, coastal, topographic, and geomorphic data at the Spencer Island project site. This annex also compiles preliminary hydraulic modeling performed to refine the design of the Tentatively Selected Plan. This annex also includes a GIS analysis of the Spencer Island marsh tidal channel network and topography relevant for ecosystem restoration project design. The same analysis was performed on nearby Snohomish River estuary reference sites including the north tip of south Spencer Island, Otter Island, Mid-Spencer, Smith Island (Figure 1) to differentiate sites that are higher functioning ecologically and to develop restoration metrics from that data.

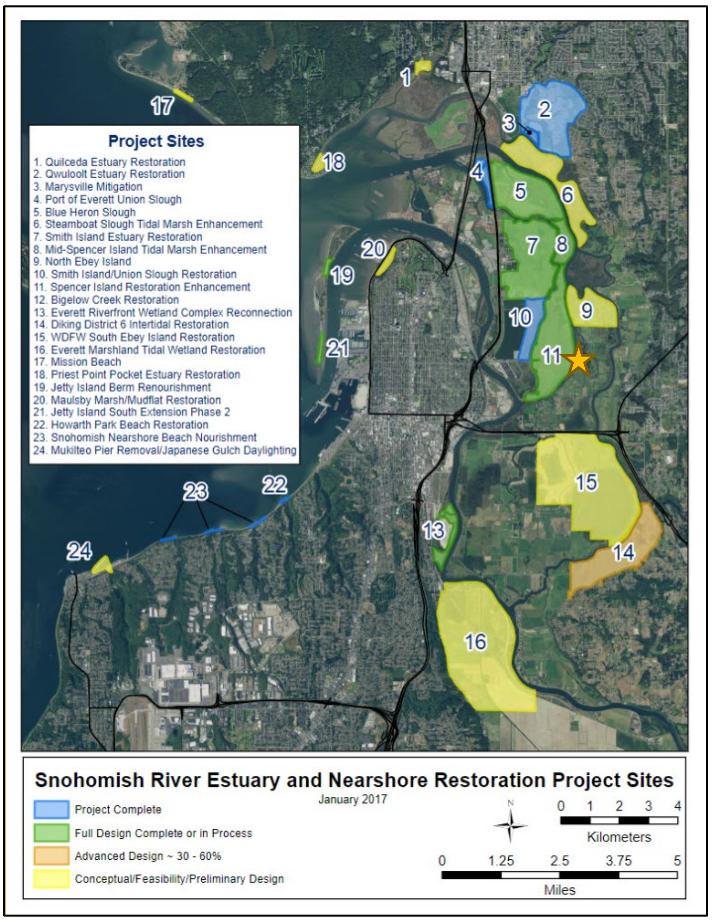


Figure 1. Spencer Island ecosystem restoration project in context with nearby completed and proposed projects. Spencer Island is starred (site 11).

Project Area

The Spencer Island ecosystem restoration project (project) is bounded by the City of Everett wastewater treatment plant and Union Slough ecosystem restoration project to the west, the north tip of Ebey Island and southern half of Otter Island to the east, Ebey Island and US Highway 2 to the south and west, and the Buse Cut and Mid-Spencer Island to the north. The entire island is part of unincorporated Snohomish County. Land ownership is divided roughly equally in terms of area between Snohomish County and the State of Washington (WDFW). The municipal boundary between the City of Everett and State and County land is the centerline of Union Slough. The County has zoned the island and surrounding area as density fringe (Figure 2), which strictly limits development, due to the importance of the island for conveying floodwaters.

According to Table 2 of the WDFW Desktop Review (WDFW, 2023), several easements are present on the site. Easements have been granted to the WA DNR, Northwest Pipeline Corp., Puget Sound Energy, Dike District #5, Snohomish County PUD, and the RCO.

Location data:

PLSS: Township 29N, Range 5, Portions of sections 10, 15, 16, 21, 22

City: Unincorporated

County: Snohomish County

State: Washington

Basin: Snohomish

River: Snohomish River, Union Slough, Steamboat Slough

Tributary drainage area: 1,665 square miles

River Mileage: Steamboat Slough: 3.65 to 5.95; Union Slough: 2.86 to 5.03.

Land Ownership: State of Washington, Snohomish County

General Site conditions

Per Salish Sea Wiki:

> *The Snohomish is one of the largest river delta sites in Puget Sound. Recovery of historical wetland area is a target of Salmon Recovery in the Snohomish Watershed. Portions of the Estuary are in the City of Everett but most are in Snohomish County. It is in usual and accustomed harvest areas of the Tulalip Tribes of Washington with portions within the tribal reservation. The lower delta is being modified under a series of large scale restoration projects including Qwuloolt Restoration, Smith Island Restoration, and Blue Heron Mitigation Bank among others. These projects are reestablishing a large area of tidal inundation in the saline mixing zone, and when complete will be the largest*

estuary restoration by area in Puget Sound. Upstream, freshwater tidal lands are in agricultural production, divided into diking districts such as Marshlands and Ebey Island, and depend on diking and pumping to lower water tables. There is controversy over the loss of agricultural lands as Snohomish County works to increase Snohomish Agricultural Resilience. Sea Level Rise effects may be important to long term planning. The Estuary is a study area of the Snohomish Sustainable Lands Strategy.

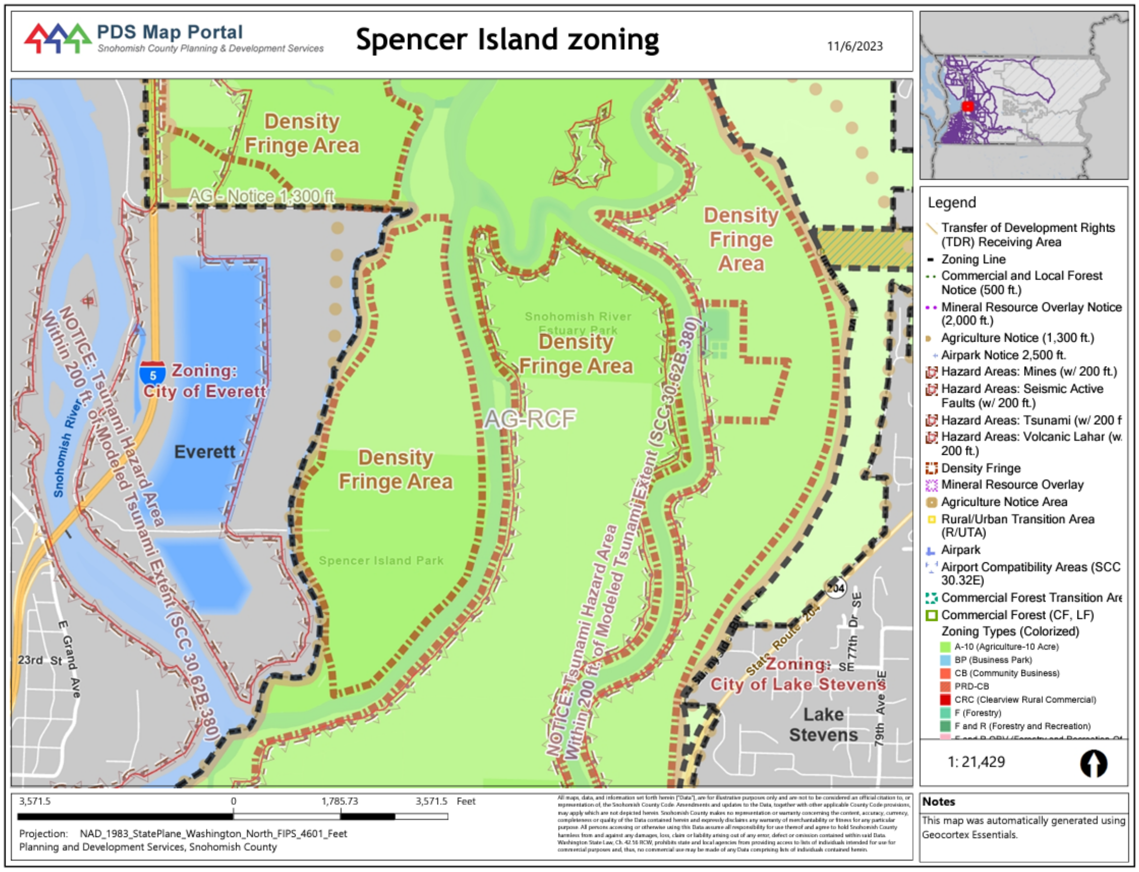


Figure 2. Snohomish County zoning in the vicinity of Spencer Island

Spencer Island is subject to daily inundation by semi-diurnal tides and less frequently by river flooding. Tides at the site track closely with the Seattle tide station. Daily high tides are slightly higher than the daily high tide at Seattle, however low tides at the site can be much higher due to the variable amount of freshwater from the Snohomish River in the sloughs. Refer to Annex D1 for a full description of tidal and fluvial forcing.

2. Supporting Data

Geology and soils

The following descriptions are from interpretations from available geologic maps for the site and others. Refer to the Smith Island 90% design report (Snohomish County, 2014) for more complete descriptions of surface soils and geologic conditions. The Smith Island project is immediately west of the north end of Spencer Island, separated by Union Slough. Geologic maps for the Snohomish valley and estuary (USGS 1985a, 1985b) indicate that Spencer Island and adjacent sloughs and floodplain soils consist of 1- to 20-meter-thick deposits of Holocene alluvium (Qa, Qyal) consisting of organic-rich, fluvially deposited, loose, clay, silt, and fine sand. At Smith Island these deposits were found at a depth of 9 to 30 feet below ground surface (bgs). Peat deposits and buried logs and stumps were found throughout the estuarine layer in the Smith Island borings. Borings at Smith Island encountered deep deposits of loose to dense sand (alluvium) originating from late Pleistocene recessional outwash, deposited on a prehistoric submarine river delta, to a depth of 60 to 80 feet bgs. Soft to medium stiff organic silts, clayey silts, and silty clays underly the sand layer to a depth of 85 feet. The source of the modern alluvium is reported by the USGS (1985) to be older (early Pleistocene) actively eroding outcrops found along valley walls upstream.

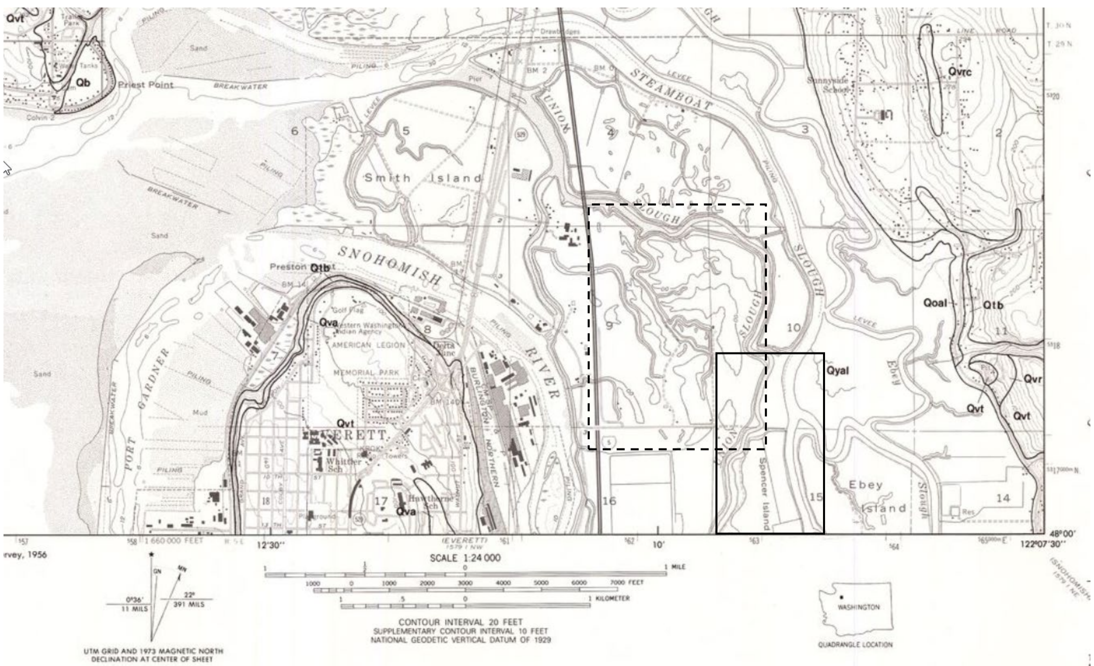


Figure 3. Marysville Quadrangle soils map (USGS 1985a)

Snohomish County mapped extensive fine grained, poorly drained, soft (hydric) Puget silty clay loam soils (typical of wetlands) throughout Smith Island in their design studies. Anecdotally soils throughout Spencer Island match this description. No detailed soil surveys have been conducted at Spencer Island. Refer to the Engineering Appendix for more descriptions of site soils and geotechnical conditions.

Vertical land movement

Vertical land movement is important factor in understanding the influence on large-scale, deep-seated land motion on ground surface elevations at a site, especially in the context of relative sea level change. Newton et al. 2021 compile available data along the coast of Washington State including Puget Sound. Estimates for the mouth of the Snohomish River are close to 0.0

mm/year, with uncertainty of 0.5 mm/year (slightly aggradational). This suggests absent global climate change induced sea level rise and localized land-use related subsidence, baseline conditions in the estuary are stable to slightly aggradational.

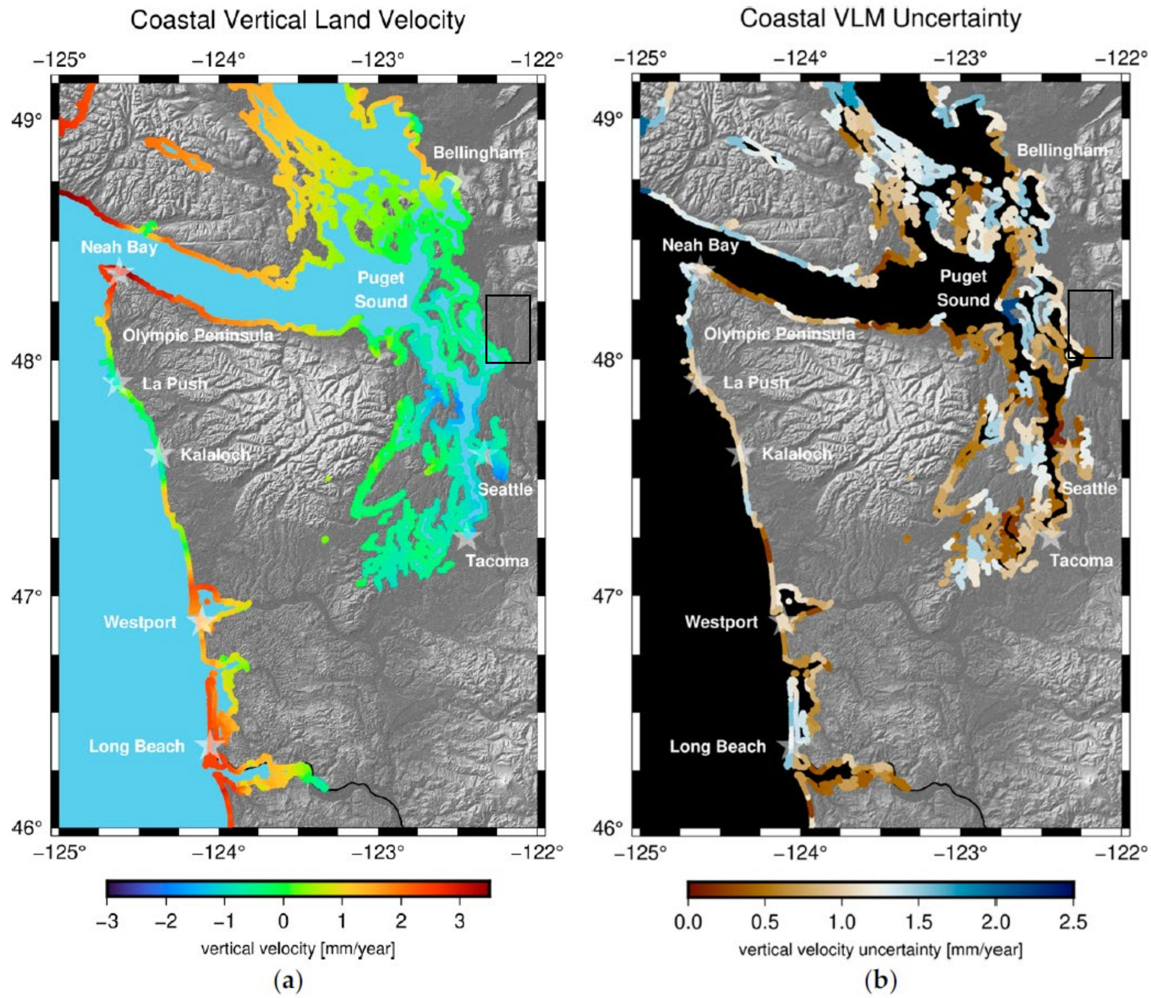


Figure 4. VLM (velocity) and uncertainty estimates from Newton et al. (2021).

Historical map comparisons

US Coast and Geodetic Survey (USC&GS) maps (T-sheets) and interpretations of the pre-development wetland conditions Collins (2002) are shown below in Figure 6. Spencer Island, Union Slough, Steamboat Slough and the mainstem Snohomish River are generally in the same locations and orientations as the T sheet. The most dramatic changes evident when comparing the T-sheet map to modern conditions include the truncation of several large Smith Island channels including a former distributary that connected the “Old River” to Union Slough, (located near the Buse lumber mill, and present through the 1930s), the Buse cut, which connected Steamboat Slough to Union Slough, presumably to make transport of logs to the Buse Mill easier, and the connection of Ebey Slough with Steamboat Slough near the Buse Cut. The mapped distributary channel widths and orientations are very similar to present day conditions, with the exception of the portion of Ebey Slough north of the connection with Steamboat Slough, which appears to have narrowed, likely in response to diversion of flow to Steamboat Slough.

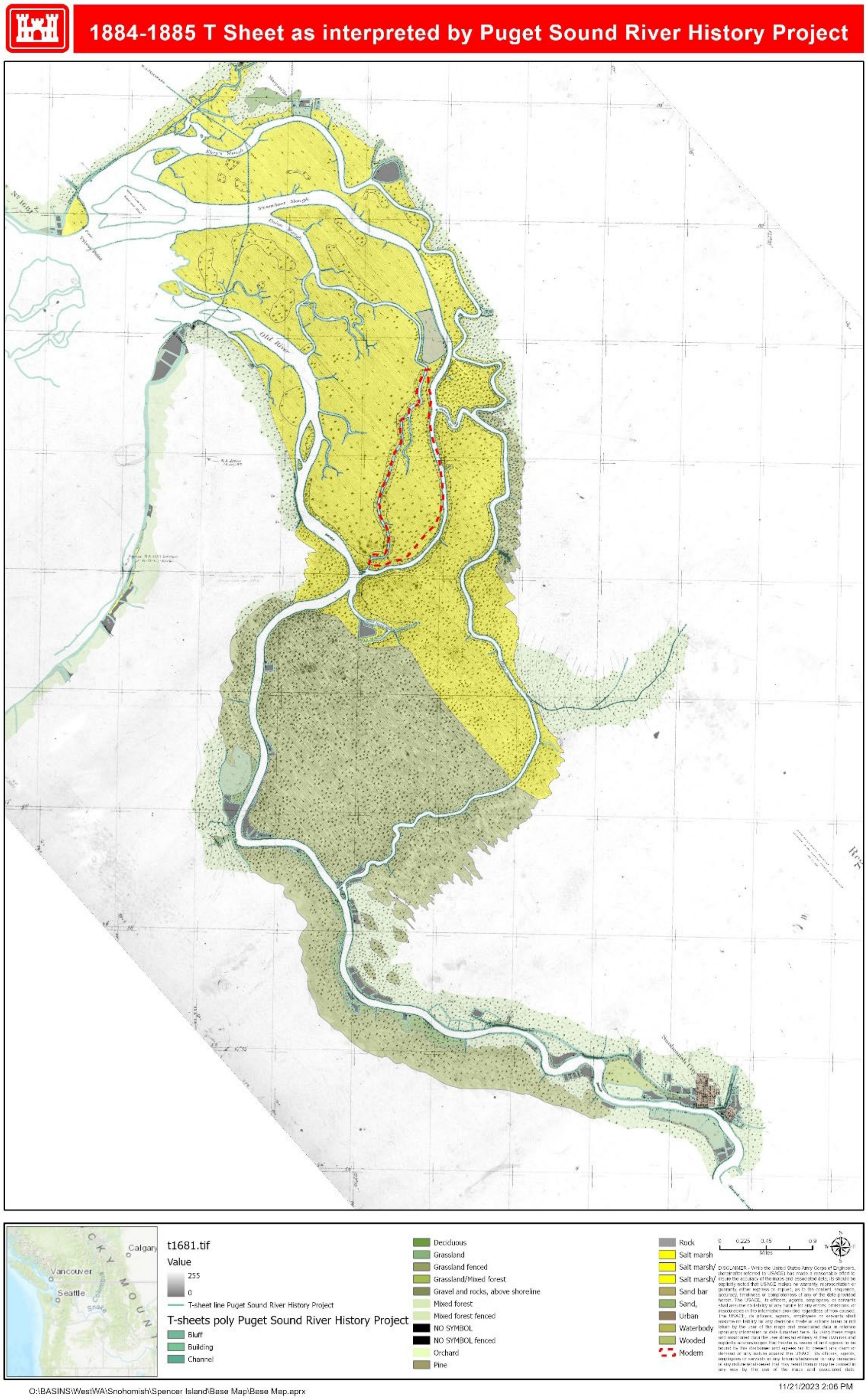
Collins (2002) mapped land cover types for marsh islands include salt marsh/pine west of Steamboat Slough and salt marsh/mixed forest east of Steamboat Slough. A large tidal channel is mapped that spans the northern half of the island connecting to Union Slough at the northwest corner of the restoration site where an enlarged tidal channel is proposed. A small tidal channel is mapped at the location of an existing restored tidal channel on the Snohomish County parcel, restored in the 1990s. No other large tidal channels are indicated. Small channels are indicated at two locations at Ebey Island and one location at Otter Island.

It was estimated by Haas and Collins (2002) that prior to settlement 3,950 hectares of tidal marsh existed in the estuary (excluding tide flats). The cartographers interpreted landcover types from GLO survey bearing tree records and government maps and identified three primary tidally influenced habitat types in the vicinity of Spencer Island including estuarine emergent marsh, emergent/forested transition, and forested riverine/tidal zone. Using 1996 maps Haas and Collins delineated 600 hectares of remaining tidal marsh habitat, a loss of 3,350 ha (85%). The reported that sixty-one blind tidal channel networks greater than 6-m wide at the mouth were lost. Only 25% of the blind tidal slough are remained intact and connected to the distributary channel network. Distributary channel margins were heavily modified by development, but the channel network changed little, otherwise.

The T sheet map shows a higher density of tree symbols along the shoreline that interior of the marsh islands and at the upstream head of Spencer Island near the Snohomish mainstem. Currently areas with higher concentrations of trees correlate with areas that have ground elevations at or above high tide elevations. Mature conifers are present along the Union Slough for the full length of the island and from the existing large breach channel northwards along Steamboat Slough in the 1938 air photo (Figure 7). Scrub shrub conditions are present in the southern portion of the island along Steamboat slough suggesting trees there had been logged. Mature trees are also present along the margins of the relict tidal channel (and all other nearby marsh island major tidal channels).

As shown in Figure 8, by 1938 agricultural development (for grazing) had cleared large portions of the interior of the island. Levees were constructed to their modern extents with the exception of the cross dike at the south end of the island that was built in the mid-2000s. The large tidal channel in the T sheet is present but the width appears to decrease in the northern direction suggesting ditches were conveying drainage to the Sloughs and the old channel was cut off and in the process of filling in. A large ditch is visible in the 1938 photo at the south end of the site, near the location of the cross-dike bridge. This ditch is the present location of the channel connecting the south end of the island to Steamboat Slough. The air photo resolution is too poor to identify other ditch locations. The large ditches present on site today were constructed in response to subsidence of the interior caused by pumping of local drainage. Subsidence is common throughout many agricultural sites in the estuary.

Localized bank failures are common in the Lower Snohomish estuary however these do not seem to develop into reach scale issues. Stability is attributed to inherent properties of the marsh floodplain soils adjacent to the sloughs and bank stabilization efforts. The lack of significant channel movement in the estuary since the 1880s, despite the occurrence of several large floods, indicates channel conditions are generally stable. The bed elevations within individual distributary channels appear to experience more fluctuation. This is discussed in the following sections.


1884-1885 T Sheet as interpreted by Puget Sound River History Project
Calgary
Vancouver
Seattle
t1681.tif
Value
255
0
T-sheet line Puget Sound River History Project
T-sheets poly Puget Sound River History Project
Bluff
Building
Channel
Deciduous
Grassland
Grassland fenced
Grassland/Mixed forest
Gravel and rocks, above shoreline
Mixed forest
Mixed forest fenced
NO SYMBOL
NO SYMBOL fenced
Orchard
Pine
Rock
Salt marsh
Salt marsh/
Salt marsh/
Sand bar
Sand,
Urban
Waterbody
Wooded
Modern
0 0.225 0.45 0.9
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O:\BASINS\WestWA\Snohomish\Spencer Island\Base Map\Base Map.aprx
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Figure 5. USC&GS T sheet showing pre-development channel locations and landcover/vegetation for Snohomish River and estuary

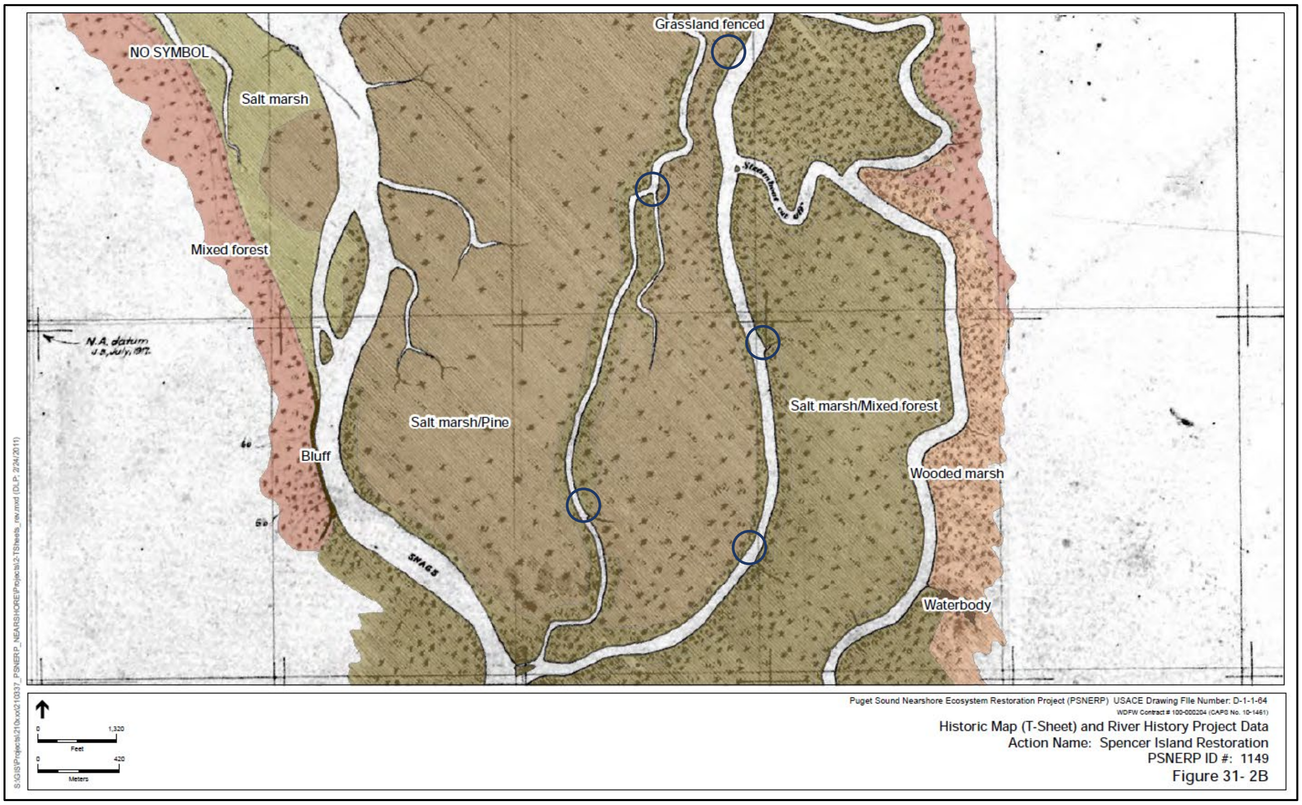

Figure 6. USC&GS T sheet showing pre-development channel locations and landcover/vegetation at Spencer Island with locations of connected channels called out with blue circles

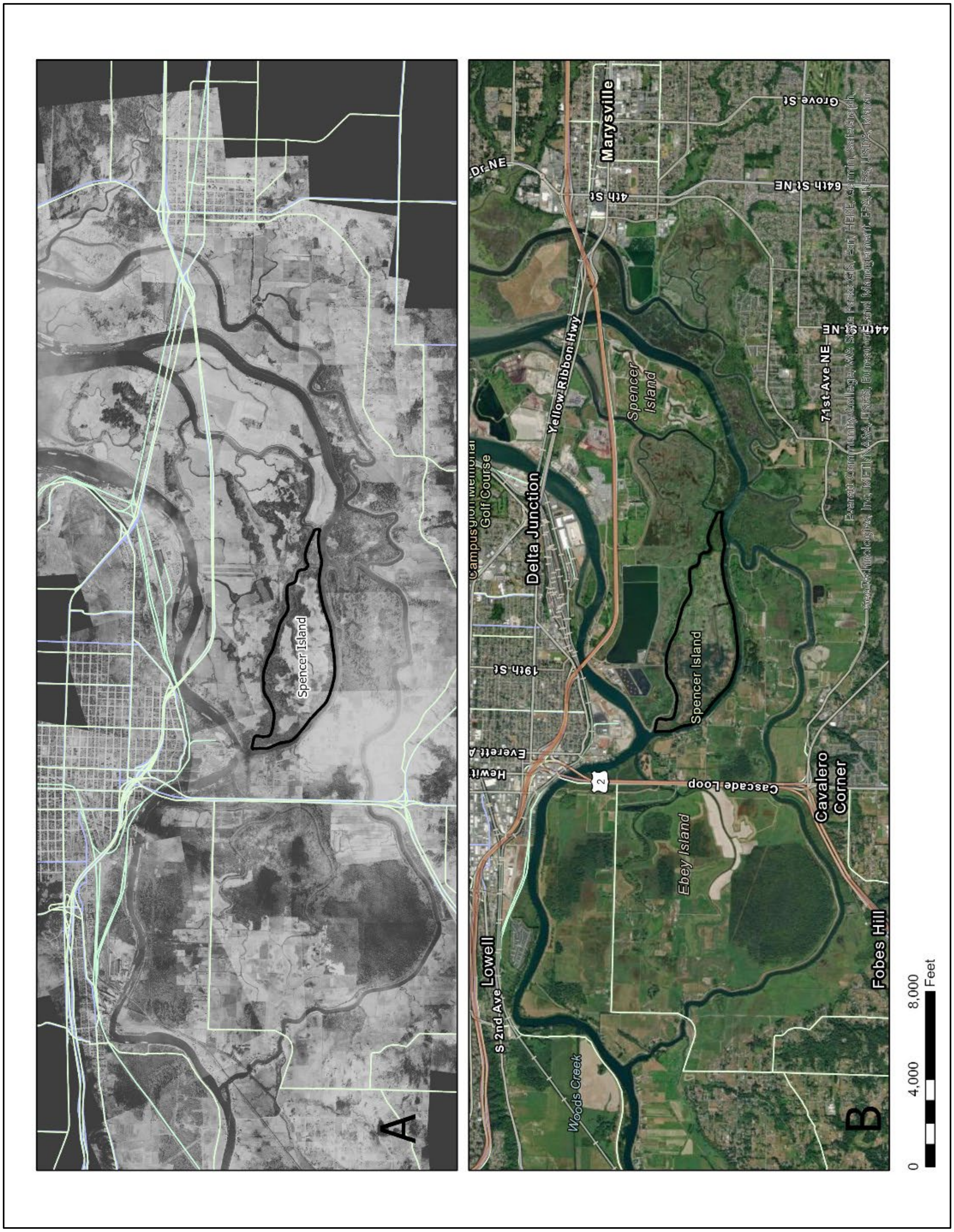

Figure 7. Snohomish estuary 1938 air photo (A) and current conditions (B)

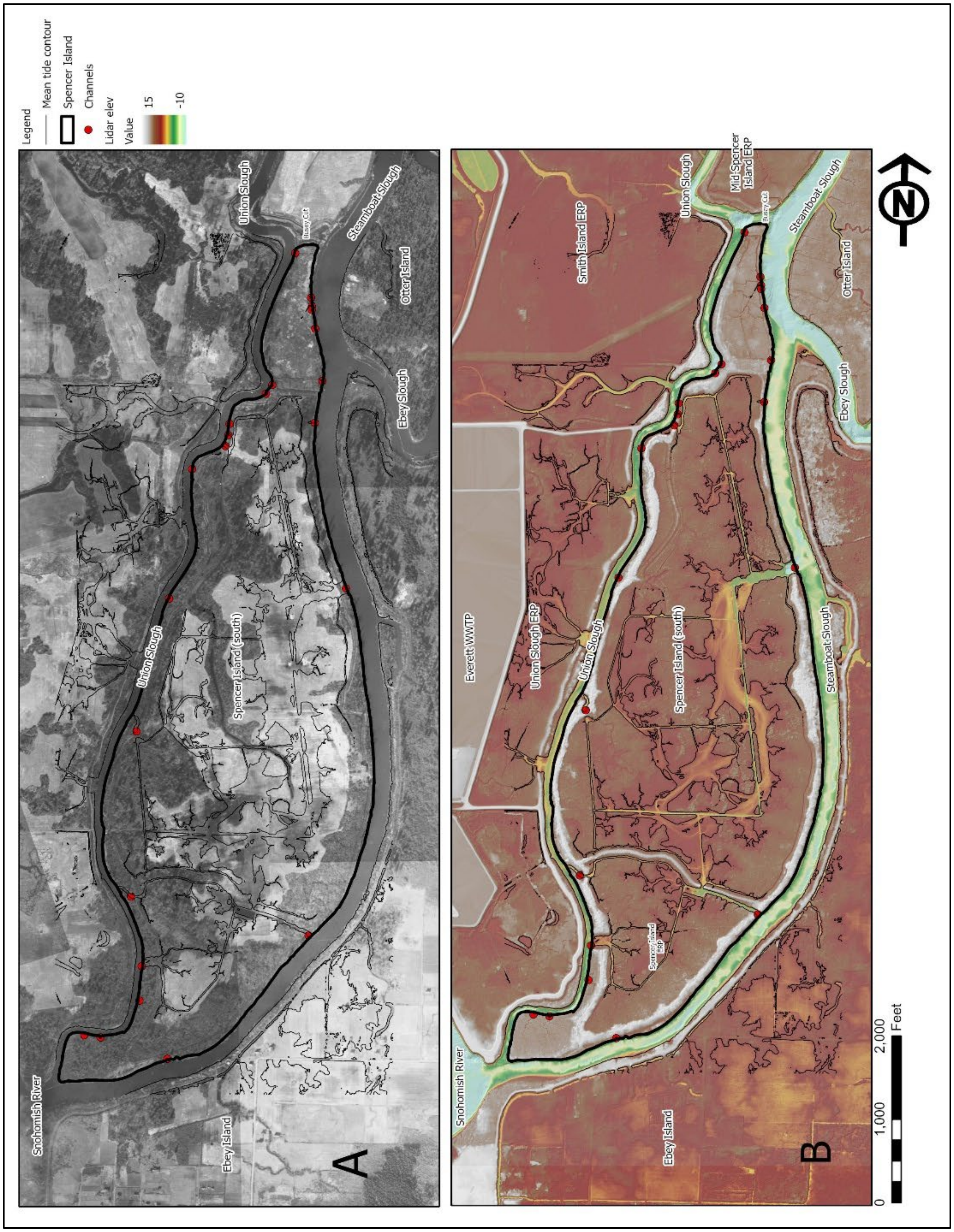

Figure 8. Spencer Island 1938 air photo shoreline locations (A) vs. 2019 Lidar and mean tide contour (B)

Relevant previous studies and findings

Spencer Island Restoration by WDFW and Snohomish County

Tanner et al. (2002) documents changes experienced at Spencer Island when the dikes at the south end of the island were purposely breached in 1994. Spencer Island was one of the first large scale marsh restoration projects completed in Snohomish River estuary. At the time of the publication the site had not undergone a transition to brackish conditions as expected, but remained fresh water dominated. Observed changes in included: Die-off of vegetation, development of tidal mudflat and emergent wetlands, recruitment of wetland vegetation, juvenile salmonid usage, benthic invertebrate colonization, and some invasive plants.

Puget Sound Nearshore Ecosystem Restoration (PSNERP)

Spencer Island restoration project was identified as a restoration site by the PSNERP Project team. An initial evaluation of the project was completed as described in the 2011 conceptual design report (PSNERP 2012). The project was combined with several others in the Puget sound basin into an alternative for the Draft Feasibility Report and EIS (PSNERP 2014). The final selected plan under PSNERP (in the final 2016 report) did not include Spencer Island, however due to several compelling factors it was developed into a project under the Puget Sound and Adjacent Waters Authority (PSAW). Technical information relevant to descriptions of geomorphic conditions and potential response to restoration are compiled below. PSNERP uses a process-based restoration framework. At Spencer Island the targeted ecosystem processes include the following:

- Tidal flow
- Freshwater input (including alluvial sediment delivery)
- Erosion and accretion of sediments
- Distributary channel migration
- Tidal channel formation and maintenance
- Detritus recruitment and retention
- Exchange of aquatic organisms

2012 Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) Strategic Restoration Conceptual Engineering – Final Design Report

The conceptual design report presents two alternative configurations, a low scope project with perimeter dike breaching and construction of one additional breach channel (referred to as "partial restoration", and another version of this design with interior marsh channel network (referred to as "full restoration").

> From the PSNERP Conceptual Design report (PSNERP 2012):
> *Spencer Island lies on the salinity gradient from estuarine scrub-shrub to riverine tidal forested wetland zones (Collins 2002). Historically the Snohomish River had extensive freshwater wetlands, more than four times the amount of tidal wetlands, due to the broad, gently sloping valley eroded by continental ice sheets (Figure 6). Deposition patterns associated with the distributary channels created natural levees.*
> *Coarser, better drained soils are found in the natural levees that line the banks of the*

> *distributary channels and create distinctive riparian corridors in the deltas. The island was diked in the early 1900s and used primarily for grazing. During this period, drainage practices and lack of tidal inundation resulted in up to 4 feet of subsidence which alters the effectiveness of creating the historic type and range of habitats. These practices also altered the restored drainage patterns. Tidal inundation, with a maximum diurnal tide range of approximately 12 feet, was restored to part of the site in the 1990s.*
>
> *The evolution of the site subsequent to breaching in the 1990s is described by Tanner et al. (2002). The site was colonized by a plant assemblage characteristic of tidal freshwater wetlands, a habitat that has become uncommon in our region due to human impacts in estuaries. Invertebrate assemblages and densities were similar to those found at reference sites just to the south of the island. Breaching of the dikes resulted in access by several species of juvenile salmon.*
>
> *Since the northern dike breached in 2005, it appears that mudflat sedimentation and vegetation colonization are occurring within the site. However, the preexisting field drain system appears to have captured tidal flows, precluding the development of a typical tidal marsh sinuous dendritic channel network.*

The PSNERP project also provides guidance for sizing of tidal channels (Figure 9) in the Feasibility Report Engineering Appendix C (PSNERP 2012). This tool was intended to provide guidance for a wide range of settings including sizing a single large levee breach channel to drain the entire tidal prism of a restored marsh (approach used at Qwulloolt). Theoretically this approach could be scaled to individual portions of marshes based on the likely drainage area to the outlet. Potential difficulties of applying this are apparent when plotting data from Spencer Island and the Otter Island reference sites. While the trend in the data matches the regressions, wide scatter of the site data relative to the prediction lines on the log-log plot is high enough to prevent (at least for small low order connections) confident use when sizing channels, requiring use of other tools, such as numerical models and local empirical data and professional judgement.

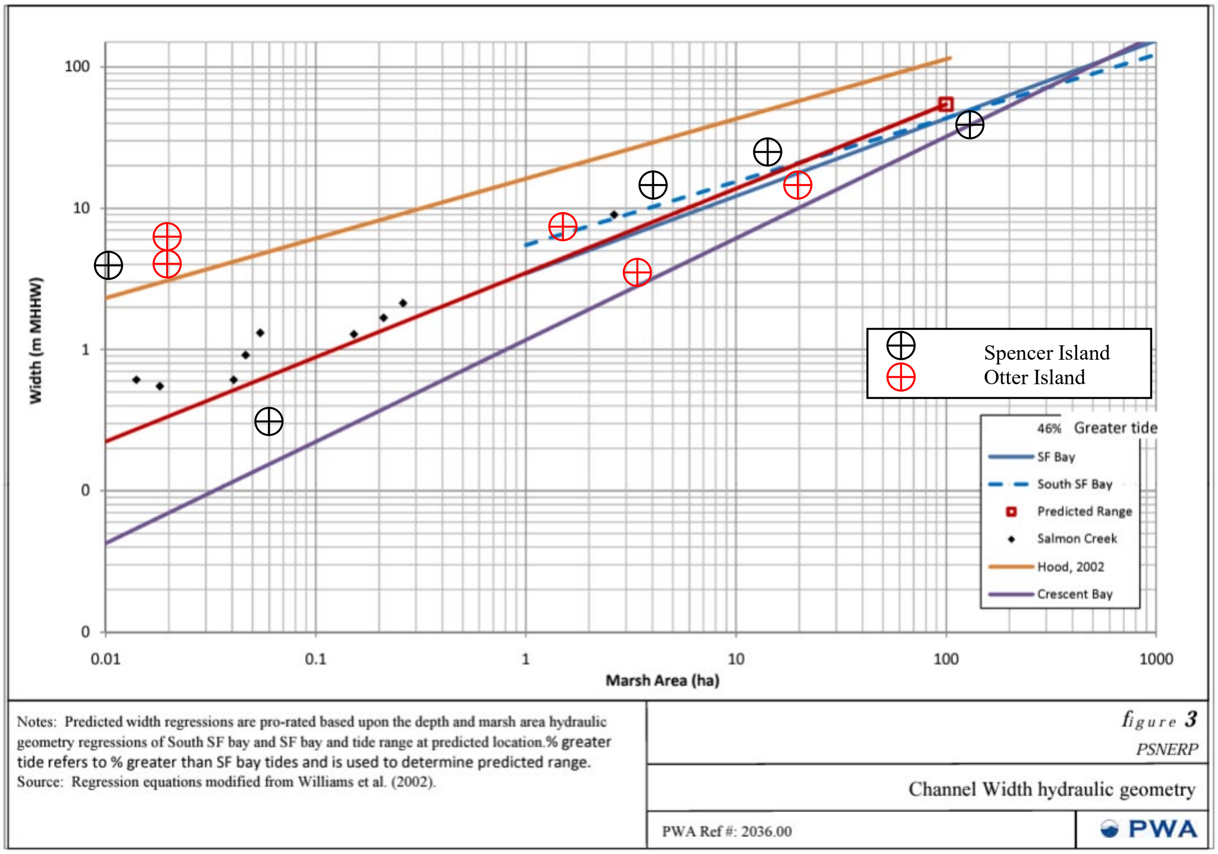

Figure 9. Channel width hydraulic geometry from PSNERP 2012 overlaid with the two largest, two smallest, and one average tidal marsh drainage from Spencer Island and Otter Island

2014 Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) Draft Integrated Feasibility Report and Environmental Impact Statement

This draft integrated feasibility study and EIS provides a comprehensive high-level analysis and determination of feasibility for restoring the Spencer Island site. The partial restoration concept identified in the conceptual design report was selected for evaluation in the final feasibility study.

Relevant excerpts from that document are provided below:

> **“Project-induced changes obligating mitigation**
> Mitigation, in the context of this site, applies to compensation of local stakeholders for any loss of function or detrimental project-induced changes. The breaching of dikes and the consequent natural development of a tidal channel network will allow increased tidal prism at the site. The work is likely to result in increased flows to the surrounding sloughs and redistribution of sediments impounded as result of diking and ditching. Properties across the slough channels and downstream of the site may experience some changes in flow patterns and sedimentation. Any sediment mobilized as a result of dike lowering and removal may have temporary effects on local ecology. The amount and potential areas of flow changes and sedimentation will be addressed during PED.”

The engineering appendix used the 300-acre portion of the site (upstream of the south cross dike) to estimate sizes for proposed tidal channels:

Max Channel Depth Below MHHW (feet) 11 (Elev. -2 ft NAVD 88)
Channel Top Width at MHHW (feet) 160
Channel Cross-Sectional Area at MHHW (SF) 1050

In considerations of the effects of sea level rise:

> "…the range of sea level change projections for the 50-year project life, indicating a maximum sea level change of 2.83feet in 50 years. The largest risk associated with sea level change at this site is the displacement of habitat upstream, with freshwater habitat becoming intertidal habitat and intertidal habitat becoming subtidal habitat. Tidal marshes can adapt to sea level change by building elevation to keep pace with the rising water levels, but this requires an adequate supply of sediment and/or organic matter accumulation. Future studies should include a sedimentation analysis to determine what impact the restoration will have on sedimentation rates and if there is sufficient sediment accumulation to keep pace with the projected sea level change."

It is anticipated that this sedimentation analysis will be performed in PED using SET local table data, and potentially numerical modeling.

> "No water quality information has been reviewed for this site. The restoration is not anticipated to generate any long-term effects on surface water quality. Anticipated water quality effects are as follows:
> • Construction-related turbidity and suspension of sediments may occur due to dike lowering and breaching. At present, barge access is considered as an option for dike lowering and breaching. Barge navigation and positioning may suspend or erode bottom sediments in the slough. Sediment control will have to be carefully considered in the construction planning.
> • Temporary changes in sedimentation may occur downstream of the site because of the evolution of tidal channels within the site. These effects, together with other sedimentation issues, should be evaluated during PED.
> • Dike breaching may increase salinity within the site due to the increased tidal prism. If needed, water quality sampling and analysis of water quality effects can take place during PED."

Recent work by Hall and others (2024) to document the effects of nearby restoration projects in the estuary supports these assumptions.

The potential for physical damages was qualitatively evaluated, however these issues are largely moot now that the bridges have been removed from the project:

> "Potential physical damages that can occur during flooding will be addressed by the hydraulic analyses conducted during PED. This will include an evaluation of the need for stabilization of the westernmost dike breach, scour protection of abutments or piers at the pedestrian bridge crossing and any cross channel effects of dike breaching. It will also address the issues of erosion and sedimentation in the channels adjacent to the site."

Existing and post-project sedimentation was qualitatively evaluated:

> The entire Snohomish River Estuary is an active accretionary environment. Distributary channels in the estuary may shift or avulse as part of natural sedimentation patterns. If conditions at Spencer Island remain as they are presently, the interiors of the diked slough island will likely continue to subside from lack of new sediment inflows. The breaching and lowering of dikes and the consequent development of a distributary channel network will allow increased tidal prism and sediment inflows at the site. The work is also likely to result in increased flows to the surrounding sloughs and redistribution of sediments impounded as result of diking and ditching. The amount and potential areas of flow changes and sedimentation will be addressed during PED."

Smith Island ecosystem restoration project

2011 Smith Island Restoration Project report "Geomorphic characterization and channel response for Union Slough" by GeoEngineers

This report by GeoEngineers is based partly on the companion WEST Consultants HEC-RAS 1D analysis of the project area under three scenarios, the pre-project condition (based on 2009 surveys and lidar), scenario 1 (Smith Island restoration only) and Scenario 2 (Smith Island plus the adjacent Blue Heron Slough restoration project). The analysis evaluated the effects of increased flood conveyance capacity, flood storage area, and tidal storage area on the potential channel response in Union Slough. The findings are primarily based on interpretations of modeled velocity and shear stress outputs from the period (2008-2009), from site reconnaissance, and interpretations from historical aerial photos. The report documents changes expected from the downstream confluence with Steamboat Slough to Steamboat Slough via the Buse cut.

Relevant excerpts are provided below:

> Between the downstream end of Union Slough to I-5:
>
> *"The geomorphic reach characterization and historical photo review indicates there has been negligible channel movement of Union Slough in the project reach since 1938, well prior to construction of I-5 in 1967. A comparison of current channel bathymetry with as-builts of the I-5 bridge over Union Slough indicates there has been no observable change in channel floor elevation in more than 40 years. The lack of bank armoring and/or protection of the I-5 bridge abutments and piers is a strong indicator of stable channel conditions since construction of I-5. Design drawings also indicate that the bridge pier foundations comprise of a pile supported pier and pile cap system, with the pile cap buried over 15 feet below the streambed elevation."*
>
> *"Modeled flow velocities for these conditions are lower than published permissible velocities (erosion threshold velocities) for cohesive soils. These findings are consistent with the results of the geomorphic evaluation conclusions that little channel response is expected in this reach during normal flow conditions…. "*
>
> *"Shear stress values increase from 0.49 lbs/ft^2 under existing conditions to 1.21 lbs/ft^2 under Scenario 1, with 0.63 lbs/ft^2 predicted for Scenario 2. The range of velocities and shear stresses for both proposed scenarios exceed publish erosion thresholds for cohesive soils, suggesting that channel banks are subject to erosion (and likely migration), at and downstream of cross section 5977. However, this finding is not consistent with physical geomorphic conditions observed in the field and on aerial photographs. Erosion is clearly taking place in the form of bank undercutting and sloughing, undercutting and block failures of levee materials. But, based on model results, most of the erosion is likely occurring during low frequency storm events over a full tidal cycle. It is also likely that the actual erosion thresholds of on-site cohesive soils are higher than published values….Based on this information, we expect a possible increase in bank erosion in the vicinity of Cross Section 5977, but only minor channel responses over the long term."*
>
> Between 1-5 and the main breach channel for Smith Island:
>
> *"Tidal flooding will extend farther upstream as a result of the Smith Island project, thus producing increased tidal volumes and a sharper tidal swing represented in the model by slightly higher velocities in both Scenarios 1 and 2. For areas in the middle reach downstream of the Blue Heron*

> *levee breach, Scenario 2 velocities are lower than Scenario 1 velocities. All reported velocities for the „typical‟ flow periods within the middle reach are below published erosion thresholds for cohesive soils. Negligible channel responses are expected in the middle reach as a result of Scenarios 1 and/or 2."*

The Smith Island project was fully complete (reconnected to Union Slough) in 2019, and the Blue Heron Slough project reconnected in 2023. The Mid Spencer Island project was completed in 2020 but was not analyzed as part of this evaluation. the tidal prism of Mid Spencer is negligible because the levees have already breached and thus would not effected the predicted or observed changes.

> Main breach to Buse Cut (Steamboat Slough):
> *"By removing levees and exposing low elevation areas to tidal movements, the upstream reach of Union Slough is subject to greater ebb flow. This process is represented by the increased velocities modeled for Scenarios 1 and 2, during the „typical‟ flow period. As with the other two reaches, velocity changes estimated for the proposed conditions fall well below erosion threshold values for cohesive soils. Supporting geomorphic indicators observed in this reach include an old breach on Spencer Island, opposite the Smith Island project site. Sometime prior to 1990, a levee breach exposed a section of former estuarine wetland that had been isolated by levee construction. Following the breach, hydraulic changes are likely similar to those expected following the Smith Island project. No evidence of surface scour, side channel formation, or main stem in channel responses have resulted from that breach over a 20-year aerial photo record review."*
>
> *Model results simulating the January 2009 flow event indicate larger changes in hydraulic parameters for the proposed conditions…. The flow velocity for Scenario 2, exceeds the published erosion threshold for cohesive soils, suggesting that channel banks are subject to erosion in the vicinity of Cross Section 14104…. As in the case of the Lower Reach, this finding is not consistent with physical geomorphic conditions observed in the field and on aerial photographs. The structure of the bank soils is similar to that described for the Lower Reach, as is the expression of existing erosion (undercutting/sloughing of bank soils, undercutting of levee materials, and loss of blocks of levee material). Consequently, we believe that most of the erosion is occurring during low frequency storm events over a full tidal cycle. Based on this information, we expect a possible increase in bank erosion in the vicinity of Cross Section 14107, but only minor channel responses over the long term."*

2014 Smith Island Estuary Restoration 90% Design Report

This report prepared by Otak Inc. for Snohomish County compiles design and environmental work completed to support the levee setback and tidal marsh restoration project which began construction in 2016 and was completed in 2019. The approximately 400-acre portion of Smith Island was restored to:

> "re-establish a properly functioning and self-sustaining estuarine tidal marsh ecosystem that will provide critical rearing habitat for endangered Chinook salmon and other native fish in the Snohomish River Basin".

The project (Figure 10) involved construction of a 7,800-foot-long setback levee that protects critical infrastructure (I-5, City of Everett WWTP) that extends from the City of Everett WWTP to Union Slough. After settlement the top elevation is 15 feet NAVD 88, which was required by the local diking district. The perimeter levees were removed in two locations (total length of 4,500 feet). Several starter channels were constructed through the breached dike. Pile anchored large wood was included at starter channels to maintain connectivity (creating scour pools).

Members of the technical advisory group that helped Snohomish County develop the plans for Smith Island have advised the Spencer Island PDT. The levee breaching and channel design approach used by the Smith Island project team heavily informs that used at Spencer.

Hydraulic evaluations used to understand potential project effects describe above were updated with Riverflow 2D modeling (Tetratech 2013, NHC 2014). Concerns over erosion of the site in response to dike lowering in the vicinity of an existing buried gas pipeline led to additional 2D hydraulic modeling to improve the accuracy of erosional depth estimates. Despite model results indicating that vegetation establishment would be adequate to resist erosion, a soil berm was placed over the pipeline and windrow (buried) riprap revetments were added near Union Slough to increase the safety factor in the event of channel migration (Figure 11). Review of recent Google earth imagery of the pipeline area indicates vegetation is becoming well established along the pipeline berm, with no obvious breaches or erosion.

Tetratech (2013) analysis also found:

> “The model indicates that increased shear stresses during high flow events could cause erosion within the project site at the lower breach and within Union Slough downstream from the lower breach. Downstream from the Buse log ramp, this erosion would likely be distributed across the channel and could cause some erosion of existing dikes. As reported in previous model studies, the infrequency of these high flow conditions and the historically stable channel position suggest that erosion will be minor and readily mitigated through bank protection.
>
> Sedimentation is not indicated by the model results. Although flow velocities in Union Slough above the lower breach will decrease, this will not inhibit the slough’s sediment transport capacity, particularly given the fine-grained nature of the sediment load through this reach (primarily fine sand and silt). Based on these results, channel depth in Union Slough is not likely to be reduced due to sediment deposition.
>
> Under lower flow conditions, not modeled as part of this study, localized areas of deposition may occur adjacent to the project site, particularly in back-eddies of tidal channel and breach connections to Union Slough. Higher shear stresses below the Buse log ramp will prevent sediment deposition and may help flush existing sedimentation at this location.”

Note that Spencer Island perimeter dikes were breached well before Smith Island was constructed, so any additional tidal prism within Union Slough and associated affects have already manifested. Levee removal at Spencer Island could affect the amount of floodwater conveyed at Smith Island so further evaluation of with and without project erosion risks is warranted to ensure erosion risks are not increased.

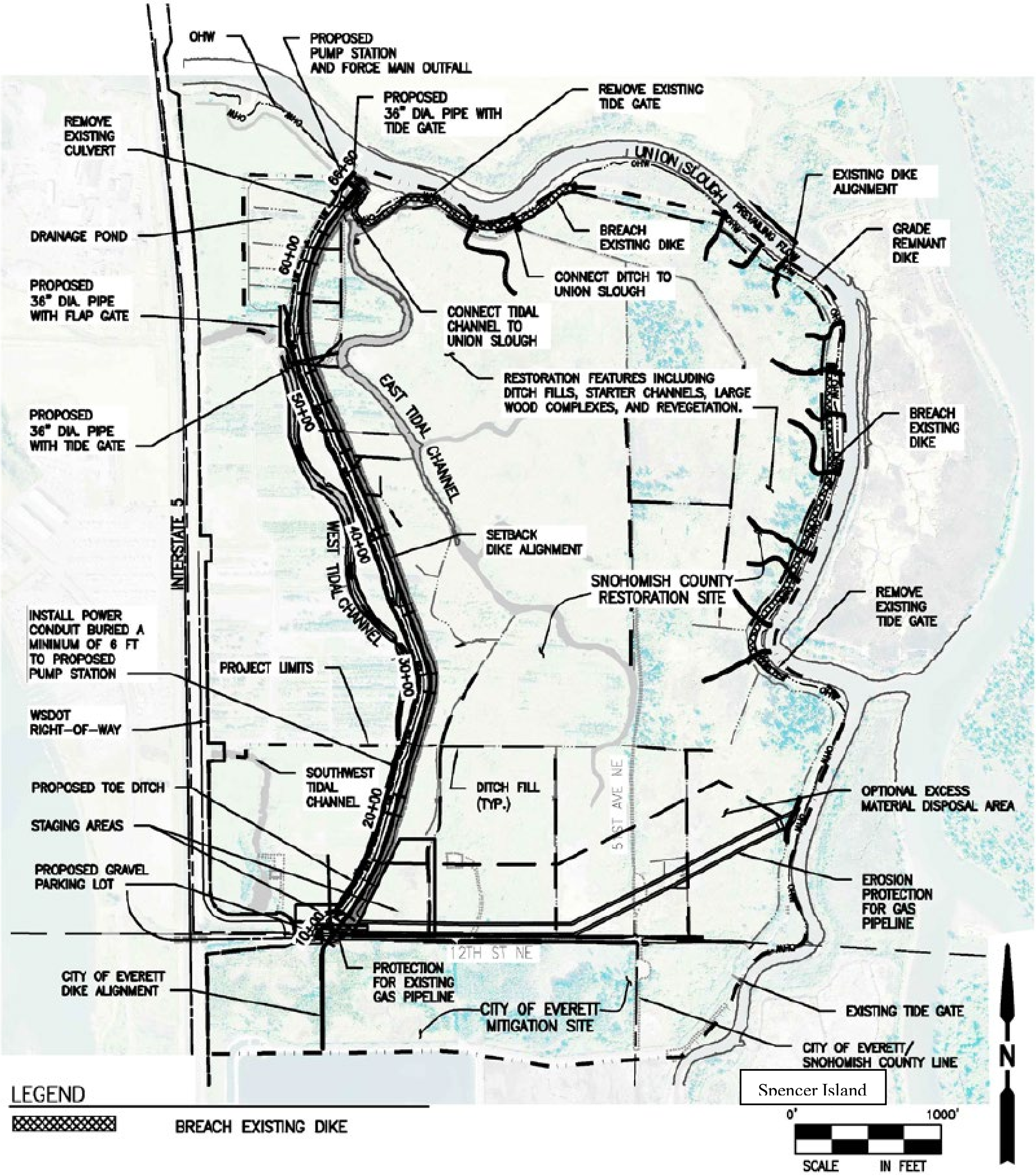

Figure 10. Smith Island restoration project

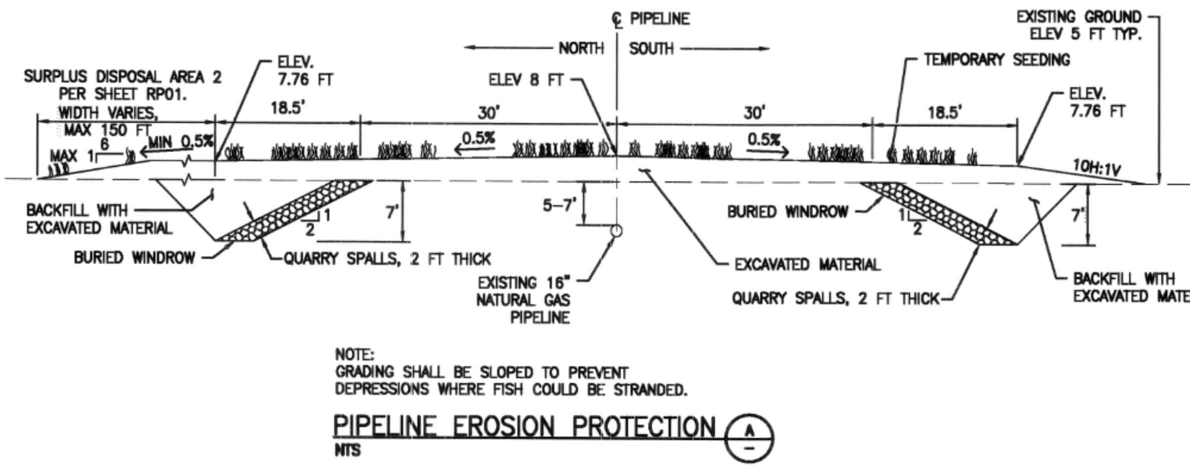

Figure 11. Smith Island restoration project pipeline erosion protection detail

Mid-Spencer Island restoration by Snohomish County

Photos from the completed construction project (completed in 2019 by Snohomish County) just north of this project are illustrative for several reasons. Prior to the Buse cut, Spener Island extended from downstream of I-5 to the Snohomish River. Exposed soils in the photos and stable side slopes should be indicative of conditions the PDT should expect to see during construction. Generally, the island soils are fine grained but stiff and hold relatively steep side slopes (~1:1) (Figure 11). The soils closely resemble those exposed on the mudflats at south Spencer Island. The island perimeter dikes were graded down to elevation 8, to allow daily tidal inundation. Finished invert elevations for starter channels (breach channels) range from +2 feet to -2 feet NAVD 88. These images suggest that the USACE channel designs can likely be narrowed by steepening side slopes if needed to reduce excavation work and cost.

Figure 12. Constructed dike breach and channel at Mid Spencer restoration project

2020 Tulalip multibeam survey

This memorandum (Tulalip Tribes 2020) summarizes high resolution multibeam surveys conducted by Solmar Hydro in March 2020 along 30 miles of the Snohomish distributary channel network. This data was used to update the Snohomish County 2D HEC-RAS model which was used in design and analysis of the Spencer Island restoration project and used to develop sediment budgets for Union Slough and Steamboat Slough. The resulting bathymetric grid is extremely detailed, allowing for identification of scour holes, sand dunes, riprap, logs, and clays/hardpan.

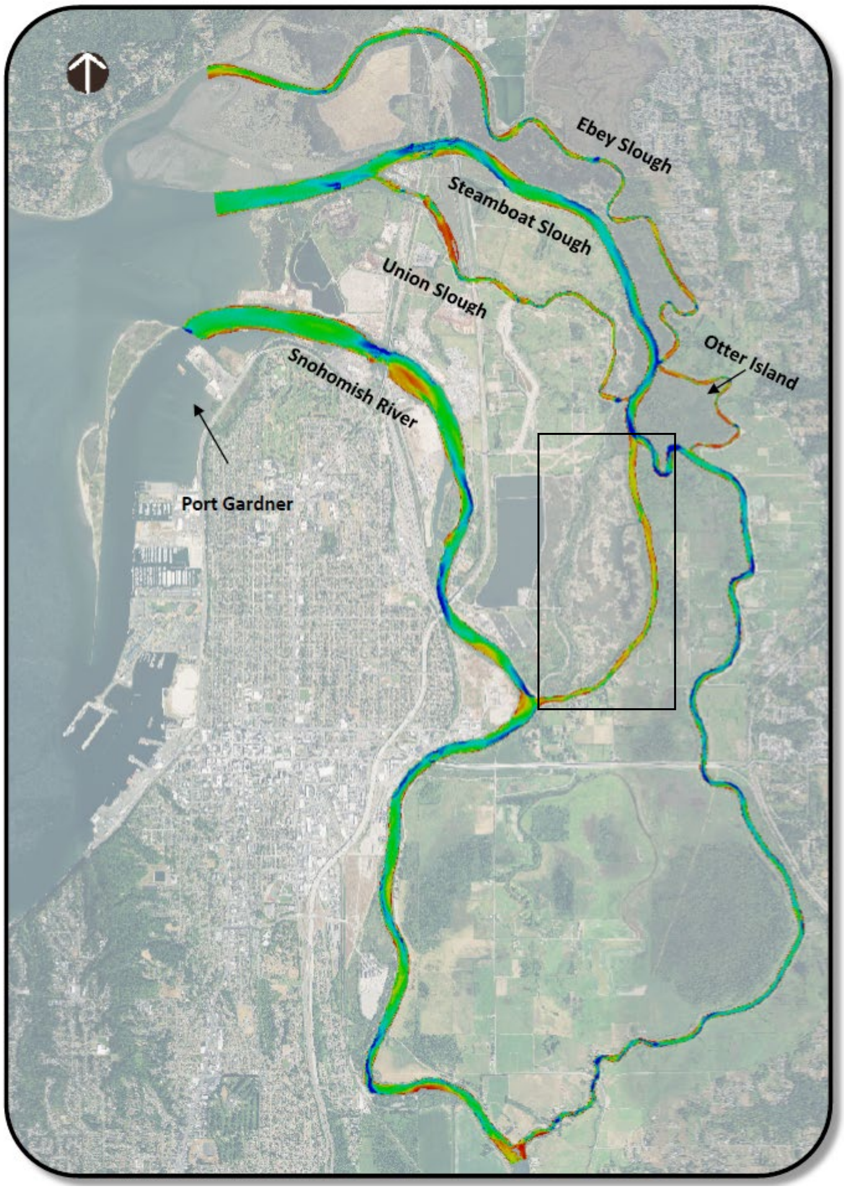

Figure 13. 2020 MBES survey extents in lower Snohomish estuary.

2021 Snohomish County 2D HEC-RAS Modeling report

This report by Watershed Science and Engineering (WSE 2020) compiles modeling work and results for a new HEC-RAS 2D model that combines the mainstem Snoqualmie, Skykomish, and Snohomish rivers. The model includes calibration and validation runs as well as existing conditions and future conditions flood scenarios (accounting for sea level rise and modified hydrology). Bathymetry is based on single beam echo sounder data collected by Snohomish County and the Tulalip Tribes in 2019. USACE is using a modified version of this model for the Spencer Island restoration project (mainstem Snohomish only, from Monroe gage to Puget Sound). The bathymetry data in the WSE model, when compared with data collected by the Tulalip Tribe's surveyors in 2020 allow for evaluation of one year of vertical change throughout the estuary. Union Slough was too shallow to survey along Spencer Island. WSE used updated estimates for peak flow frequencies and the UW Climate Impacts Group (CIG) forecasts for high and low emissions scenario 2080s changes in streamflow (UW CIG 2014) in the model.

ESRP projects

The state of Washington Department of Fish and Wildlife Estuary and Salmon Restoration Program funded to recent research projects in the lower Snohomish estuary which are relevant for this project:

2024 Hall et al. white paper

Jason Hall and Kai Ross (Cramer Fish Sciences) in collaboration with Project Partners Todd Zackey (Tulalip Tribe), Tarang Khangaonkar and Adi Nugraha (University of Washington, Tacoma), Josh Chamberlin (NOAA NWFSC), and Frank Leonetti (Snohomish County Surface Water Management Division) documented changes in salinity, temperature and water level pre and post restoration (of Qwulloolt marsh and Smith Island) using long term datasets from continuous water sensors and periodic water column profiles distributed throughout the Snohomish estuary (Figure 13).

Hall et al. documented several changes in the estuary attributed to levee breaching and large scale marsh reconnection including: Shifts in the upvalley extents of salt intrusion (reduced) with corresponding increases in salinity downstream of the restoration projects believed to associated with the increased tidal prism. The authors attribute the changes to redirection of flood tides into the restored marshes, allowing fresh water originating from the Snohomish River to push further down the distributary channel network.

Data collected around Spencer Island indicate a shift from mesohaline (5-18 PSU) conditions pre-restoration to oligohaline (0.5-5.0 PSU) on Steamboat Slough at station SB2 (Figure 13). Downstream on Union Slough at the Smith Island site at station UN1 salinities changed from oligohaline to mesohaline. Water temperatures at both stations increased by 2-3^{o} C on average. These temperature changes appear to have been beneficial at both the UN1 and SB2 sites, given that pre-restoration average temperatures were about 7^{o} C which is less than optimal for juvenile salmon growth (9-16^{o} C), and after restoration temperatures increased to about 10^{o} C. The authors note background changes in temperature confound some of these findings.

Spencer Island levees were breached well before construction of the Qwulloolt and Smith Island projects, and further changes in temperature and salinity regimes are unlikely. The present design of the project (multiple starter channels to redistribute flow from existing oversized channels) will result in improved access to a marsh that appears to now have optimal salinity and temperatures for juvenile salmon.

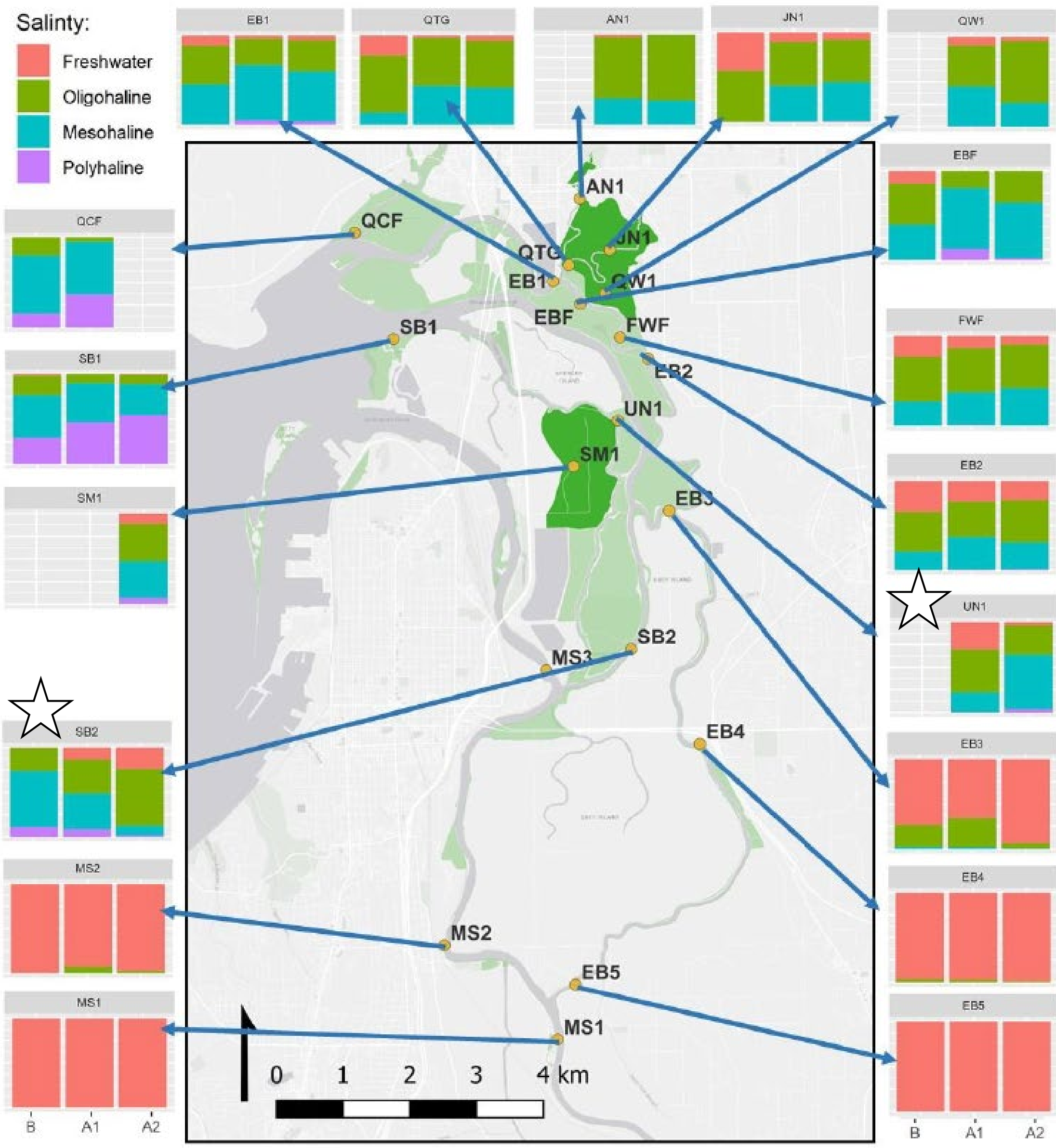

Figure 6. Stacked bar plots showing the proportion of time (0-100%) in mixohaline categories (freshwater 0-0.5 ppt, oligohaline 0.5-5.0 ppt, mesohaline 5.0-18.0 ppt, and polyhaline 18.0-30.0 ppt) during low flow river conditions and periods relative to the Qwuloolt Estuary and Smith Island restoration projects (B = before Qwuloolt Estuary restoration, A1 = after Qwuloolt Estuary restoration but before Smith Island restoration, and A2 = after both Qwuloolt Estuary and Smith Island restoration). Arrows show the location of the sensor in the estuary, with dark green polygons showing the two restoration sites and light green polygons showing connected tidal wetland habitats.

Figure 14. Figure 6 from Hall et al..

2024 3D Modeling of Snohomish Estuary by UW Salish Sea Modeling Center

This modeling report (Nugraha and Khangaonkar 2024) is a companion to the Hall et al. (2024) study, and utilizes the continuous data to calibrate and validate a hydrodynamic model of the

Snohomish estuary pre and post restoration to provide insights on how restoration affected water levels, velocities, salinities and tidal flux. The FVCOM model used previously by Battelle PNNL was updated with the Tulalip Tribe's 2020 multibeam bathymetry and the latest lidar data.

Models were run with the same underlying data and boundary conditions, but with restored areas excluded from some scenarios. The models exclude overbank areas that are not presently connected to the river and are not reflective of conditions during major floods, but rather typical (long term daily average) conditions. The authors report that the effect on water levels from restoration was negligible, with a small change to tidal amplitude and phase in some locations. Velocity changes were more significant near restoration sites. The authors estimate that the combined increase in tidal prism due to the Smith Island and Qwulloolt projects is 9.1% over the pre-project condition. Excerpts from the report relevant for Spencer Island are shown in Figure 14 through Figure 16 below. Summary findings are as follows:

> "Overall conclusion is consistent with our expectation that restoration actions resulted in an increase in total tidal prism that enters the estuary during each flood tide. Salt flux associated with this increased tidal flux results in an increase in saline conditions and intrusion of salt further upstream into the estuary. There is corresponding increase in velocity/flow or volume flux through each distributary downstream of the projects. Changes in peak velocities are significant downstream of restoration sites accompanied by a relatively similar reduction upstream of the restoration sites."

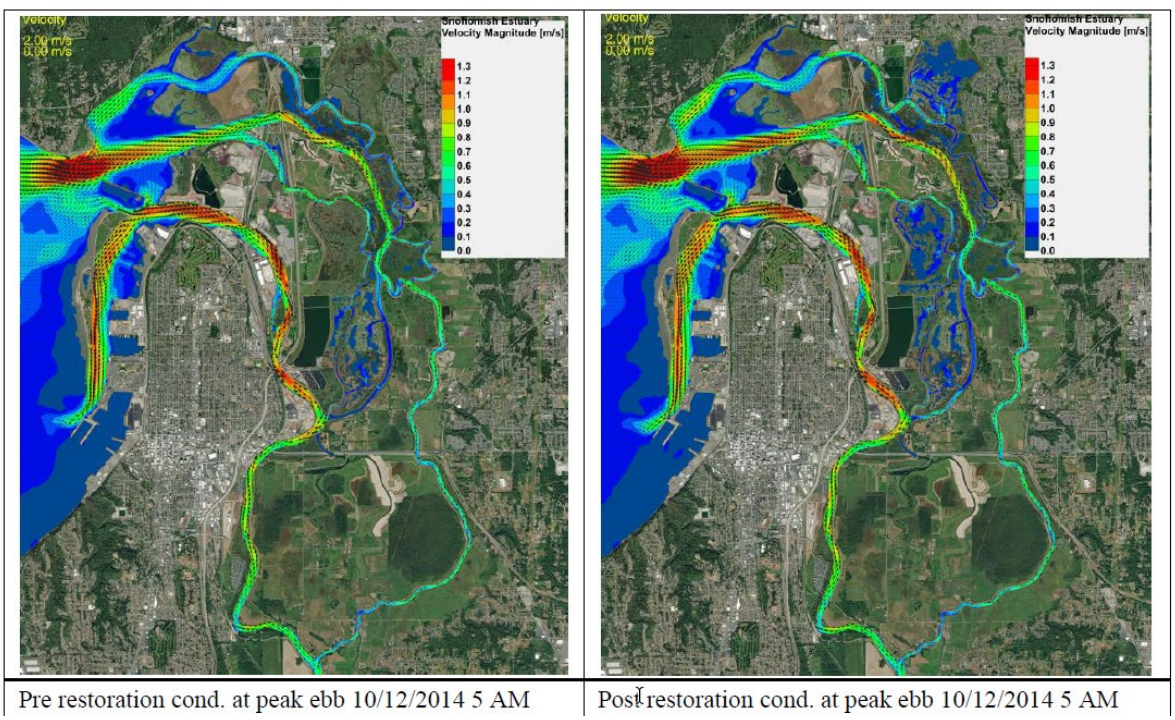

Figure 15. Excerpt from Figure 5-21. The highest modeled velocities for non-river flood conditions are illustrated.

In Figure 14 note the increase in velocities in Steamboat slough at the south end of Spencer Island and near I-5 next to Blue Heron Slough. These changes are a result of the combined effects of Smith Island and Qwulloolt. Note that Spencer Island is connected to both Union Slough and Steamboat Slough indicating that further changes resulting from that project would be negligible (no increase in tidal prism, just redistribution of the prism within the site). The low magnitude of velocities relative to other sloughs suggests a depositional regime would be expected.

Changes in average peak ebb and flood velocities are shown below in Figure 15 and statistically summarized at stations UN1 and SB2 in Figure 16. The largest changes near Spencer Island occur within the Smith Island restoration site under ebb tide. Note the reduction in velocities in the vicinity of the large breach at Spencer Island at ebb and flood tide suggests some of the tidal prism that was entering Spencer Island in a tide cycle was diverted into the larger Smith Island site post-levee breach. The large increase in ebb tide velocities at Buse cut appears to be causing a backwater effect in Steamboat Slough at the north end of Spencer Island which could enhance sedimentation in that area. Small general increases in velocities in Union Slough and Steamboat Slough are likely which is presumably due to diversion of tidal flows to/ from Smith Island into receiving channels downstream of Spencer Island. On the flood tide this would result in lower water surface elevations at the north end of Spencer Island, increasing the water surface slope from the mainstem Snohomish, allowing for more flow to flow north along Union Slough and Steamboat Slough, increasing velocities. On ebb tide the flows likely reverse direction, with the magnitude slightly increased. Addition of more breaches along the sloughs around the perimeter of Spencer Island would allow for diversion of tides into the island further south than is presently occurring. This could allow for filling of the island up to the high tide more efficiently, potentially resulting in a modest increase in the effective tidal prism.

The 3D modeling will be updated in the near future to investigate temperature effects of the restoration and include Blue Heron Slough and Spencer Island. Refer to Annex D-1 for modeled changes in tidal flux and velocity expected from inclusion of additional levee breaches and starter channels based on the HEC-RAS 2D hydrodynamic model.

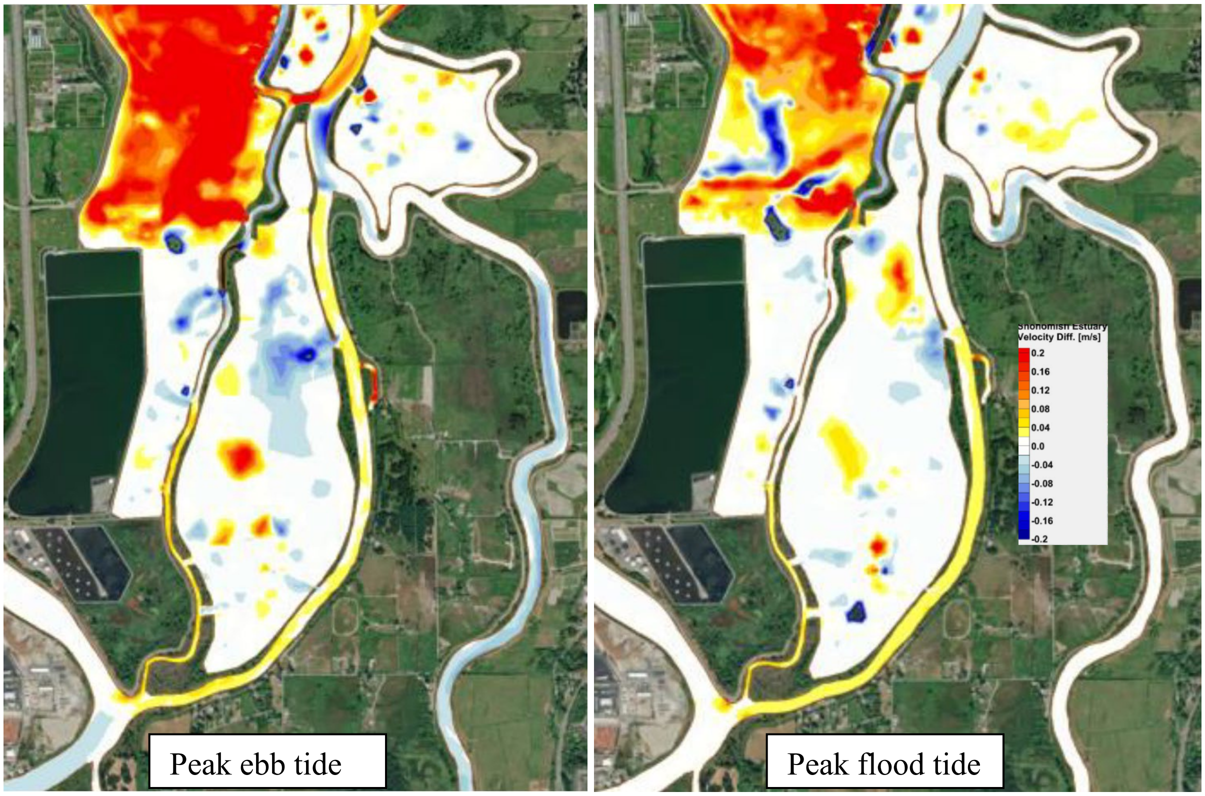

Figure 16. Excerpts from Fig. 5-23 and 5-24 showing modeled peak ebb and flood tide velocity changes resulting from the combined effects of the Smith Island and Qwulloolt restoration in the vicinity of Spencer Island

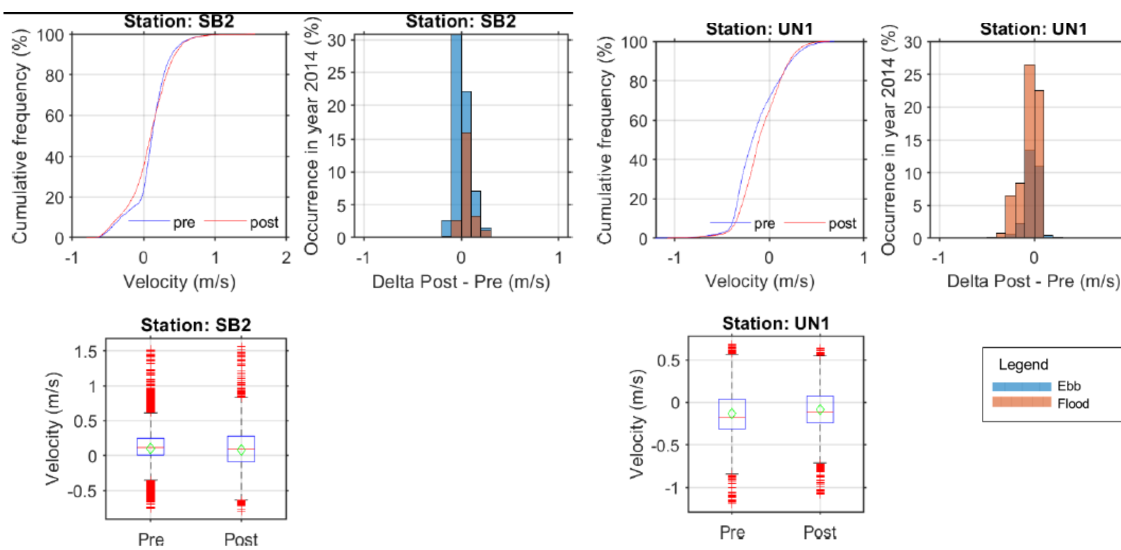

Figure 17. Excerpt from Figure A.3-6 and A.3-7 showing pre and post restoration changes at SB (steamboat slough) and UN1.

The plots above show that ebb and flood tide velocities at Steamboat Slough increase and decrease, but on average remain unchanged. Ebb tide velocities are more impacted (increase) than flood tide but remain well below magnitudes that would be considered erosive. At Union

Slough flood tide velocities are more impacted than ebb tide, with a slight increase in the average velocity. Note that negative velocities in the plots above reflect upstream flowing water (flood tide).

Modeled high tide salinities are shown below in Figure 17 for pre and post restoration conditions. The model results suggest that Spencer Island has become more brackish due to completion of nearby restoration sites. High tide, post restoration salinities range from 22.5 PSU on Steamboat Slough at the south end of the island to less than 2.5 PSU at the north end near the confluence with the Ebey Slough connector. Salinities within the island become more uniform, and remain in the oligohaline range (0.5-5 PSU) which is believed to be well suited for out-migrating juvenile salmonids. Smith Island in contrast is much saltier. It is worth noting that the 3D hydrodynamic model predicts upstream increases in salinity which is in contrast with the observed salinity data presented by Hall et al. (2024). The reasons for this discrepancy are unclear and imply that use of models to predict restoration outcomes with high confidence remains difficult.

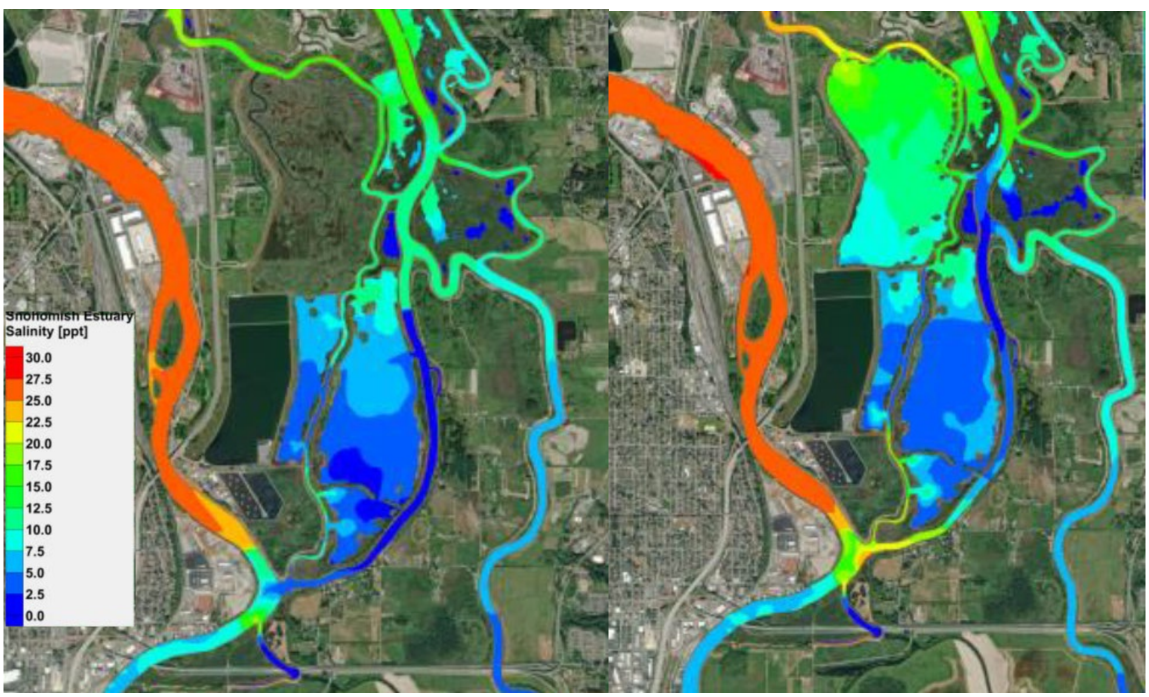

Figure 18. Excerpt from Fig. 5-17 showing modeled salinity during high tide pre and post restoration

3. Geomorphology and Sediment

Reconnaissance findings

Site visits in 2022, 2023 and 2024 indicate the site is very well connected to Steamboat Slough due to the 2005 breach. Boat inspections (Figure 18, Figure 19), Google Earth imagery (Figure

21) and bathymetric surveys of the largest ditches within the site interior (Figure 22, Figure 23) indicate the marsh plain is eroding due to the flux of tidal flows and that marsh soils are stiff, holding near vertical slopes in some locations at the primary breach channel and many of the smaller connected tidal channels (USACE 2023). Head-cutting is evident where the ditches converge at the location of the remnant levee breach in the primary tidal channel. Ground elevations of the marsh plain adjacent to the breach are generally above minus tide elevations (tides that have a lower low water elevation less than the MLLW datum).

Figure 19. Main breach channel looking south during high tide (October 2022) from Steamboat Slough. Spencer island is to the right.

Figure 20. Main breach channel looking north during high tide (October 2022) from Steamboat Slough. Spencer Island is the left.

Figure 21. Spencer Island at high tide looking west from main levee breach channel, with foraging seal in background

Figure 22. Low tide erosion of marsh plain into main breach channel due to undersized ditch showing formation of velocity barrier (hydraulic jump)

Figure 23. Ditch looking west towards Jackknife bridge at low tide (March 2023)

Figure 24. Eroded marsh plain at south end of site looking northeast near south cross dike at low tide (March 2023)

Figure 25. Existing levee breach at northwest corner of Spencer Island, connecting site to Union Slough at high tide, looking into interior of site. North end of breach shown above, south end shown below.

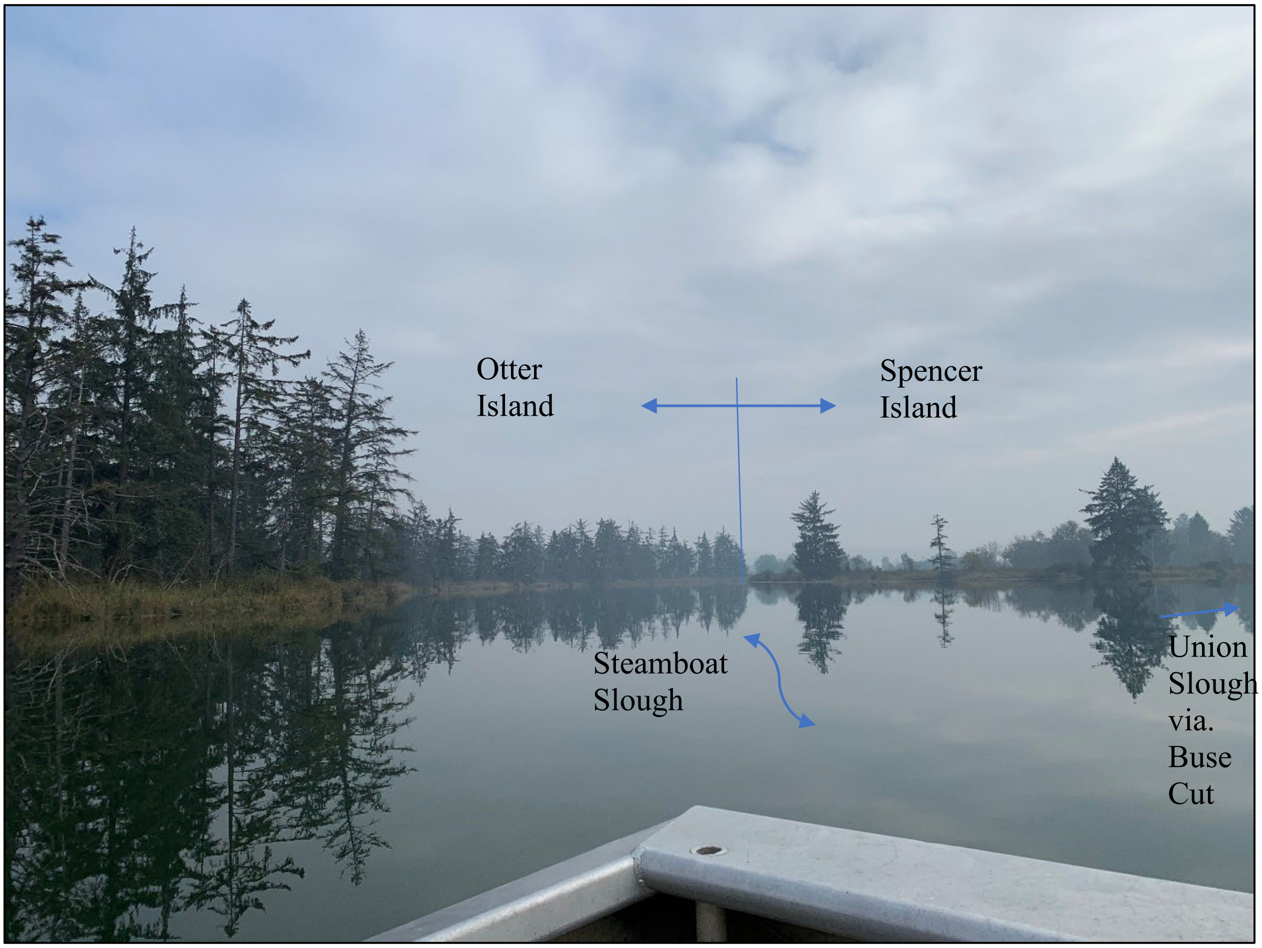

Figure 26. Looking south toward north tip of Spencer Island and Otter Island reference site at high tide

OHW survey

Ordinary high water (OHW) surveys by USACE, WDFW, and WA Dept. of Ecology conducted in August 2024 in the south portion of the project are plotted in Figure 26 (overlaid with existing lidar 1-foot contours and the 50% AEP (2-year) river flow inundation) and summarized in Table 1.

The average OHW elevation of the data collected in the south end of Spencer Island is 9.1 feet, with a minimum of 7.73 feet and a maximum of 11.54 feet. Spatial trends in the data show that there is a east-to-west and south-to-north gradient in elevation within the sampling zones caused by existing levees. The locations of surveyed OHW points track very closely with inundation boundary for the 2-year river flood scenario (approx. elev. 10 to 10.5 feet). There is as much as 1.9 feet of elevation difference between the OHW line along the outboard levee face at Steamboat and Union Slough levees and about a half foot between the south and north side of the South Cross Dike and the inboard to outboard side of the Union Slough levee. This suggests that levee removal will lower the OHW line along Steamboat Slough and increase it along Union Slough as water will be able to move freely between the sloughs and equilibrate.

The target levee lowering elevation of 10.5 feet used for feasibility level design is based on the average of the daily high tides measured at the Union Slough breach and Snohomish County cross dike bridge tide gages. This elevation is higher than the average surveyed OHW but less than the maximum. Further survey and discussion with the TAG is warranted to refine this elevation in the design phase.

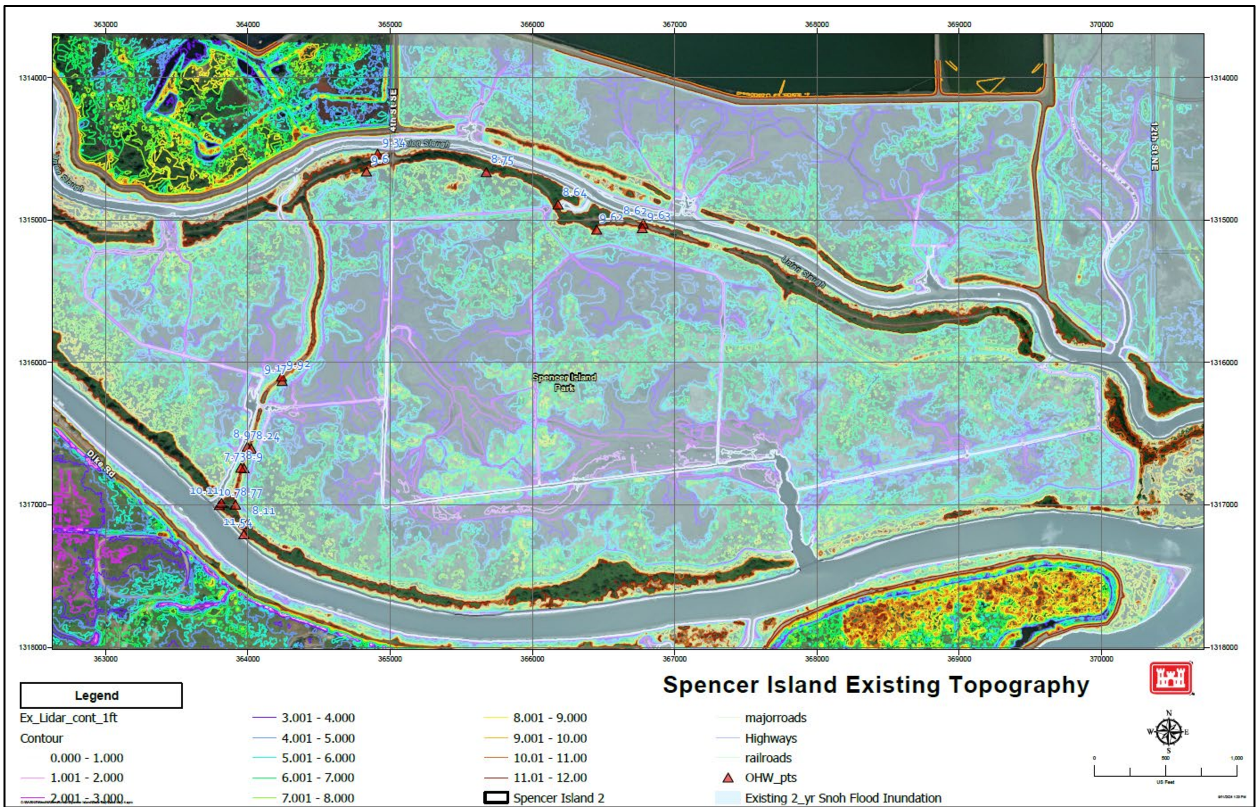

Figure 27. August 2024 OHW data at south end of Spencer Island overlaid with existing lidar and 2-year river flow inundation

Table 1. Statistics for OHW by sampling zone

Statistics by location (elev. feet, NAVD88)	Inboard of Union Slough Levee	Outboard of Union Slough Levee	South of South Cross Dike	North of South Cross Dike	Inboard of Steamboat Slough Levee	Outboard of Steamboat Slough Levee
Min	8.8	8.6	8.9	7.7	8.1	10.1
Max	9.6	9.3	9.2	9.9	8.8	11.5
Avg	9.4	8.9	9.0	8.6	8.4	10.8

Comparison of surveyed cross sections

To determine if there are general trends in bed elevation (aggradation, degradation, stable) occurring within the various sloughs and channels cross section data from 2006 (collected by Tulalip nation) were compared with cross sections derived from Snohomish County single beam sonar and lidar data from 2019 (WSE 2020), and with cross sections derived from multibeam sonar data collected in 2020 by the Tulalip Tribe (SHI 2020).

The North Arrow Research Cross Section Viewer tool was used to compare 1D cross sections originating from the Snohomish County Smith Island 1D HEC-RAS CLOMR model, and models created from the 2019 WSE single-beam sonar + Lidar and 2020 Tulalip multibeam sonar data. The Cross Section Viewer tool automates computation of mean bed elevations and longitudinal bed and volume changes. The comparisons allow for estimation of short-term trends and variability in bed elevations in the vicinity of Spencer Island.

The geographic area of comparison was restricted to the Sloughs and mainstem downstream of the Snohomish River-Ebey Slough flow split. Only the portions of the channel between the banks are compared. Note that the Tulalip DEM was merged with the WSE DEM so portions of the 2020 cross sections (above MLLW typically) are from the 2019 lidar. Given that channel is laterally stable and inverts are typically below elevation -10 this is not a significant issue.

Because of differences in methods between all surveys some of the differences between surveys at an individual location may be attributed to data gaps, not vertical changes. For example, the 1D cross section cut lines are digitized from paper maps, which introduces uncertainty about their spatial accuracy. The DEM from 2019 interpolates bed elevations from sparse single beam data, which can result in interpolated bed elevations being significantly higher or lower than actual conditions, especially at pools. Sand waves and dunes are evident in the multibeam data from 2020, strongly suggesting seasonal conditions could influence surveyed elevations (variable influence of antecedent flooding, dune behavior and elevations partly influenced by water temperature) and that inferring trends from one point in time needs to consider the inherent variability in the data. Profiles cut from the center of prominent sand waves in the mainstem Snohomish, Steamboat Slough and Ebey Slough are shown below in Figure 27. Dune crest to trough differences in elevation in the 2020 DEM are approximately a maximum of 1.5’ to 2.5 feet (Figure 27, Figure 28). Thus natural, random bed fluctuations due to sand wave passage can be assumed to vary by at least +/- 1 foot for any of the data sets.

Multibeam data show an absence of dunes in upper Ebey Slough and in deep pools. The absence of sand in these locations is interpreted as a location of high excess shear stress/turbulence that is limiting sand deposition. These locations appear to be narrower and deeper than the locations where sand is more common. The slow rates of channel migration and large vertical fluctuations in bed elevation between pools and crossings indicate that the bank sediments are more erosion resistant than the channel bed.

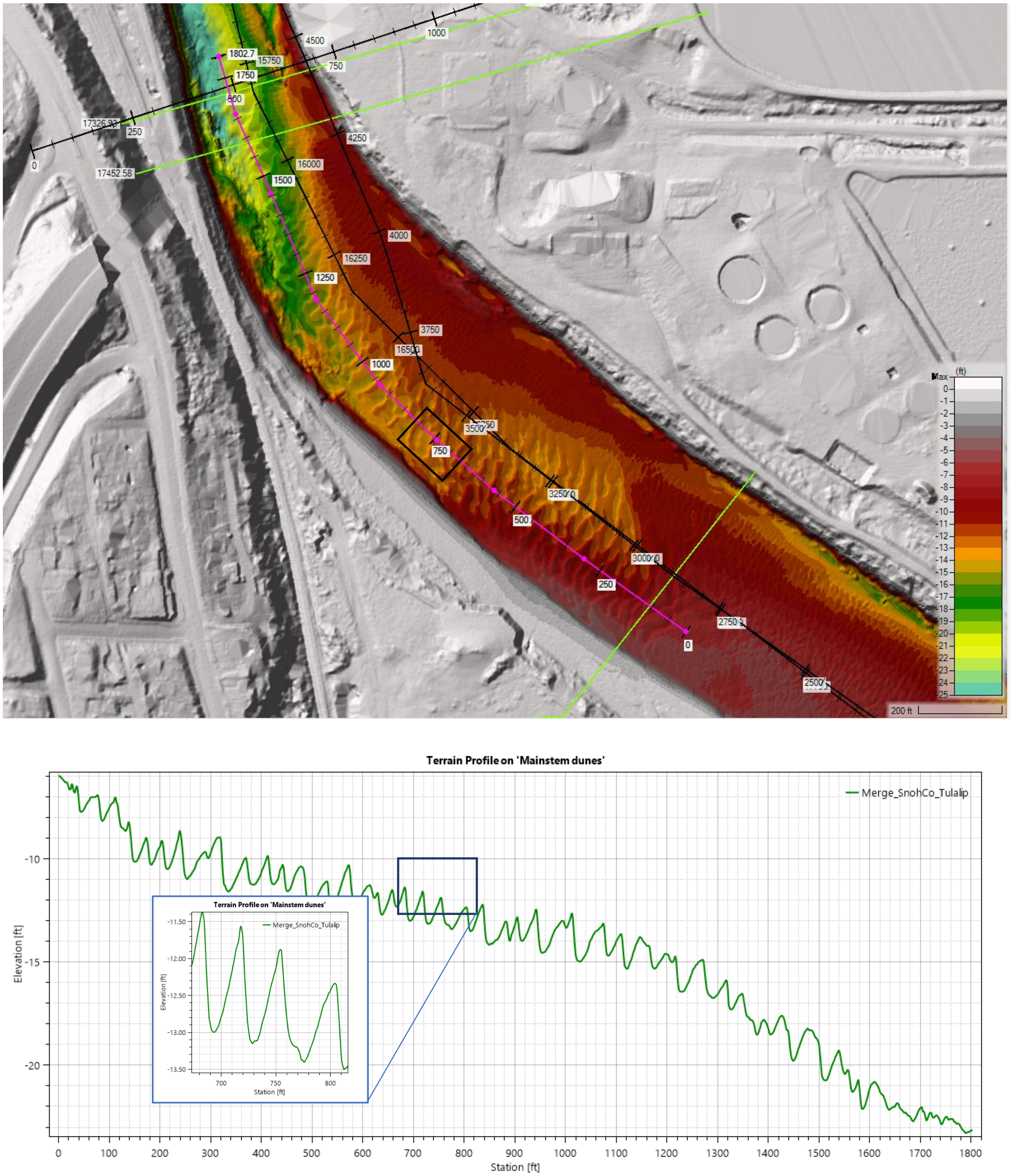

Figure 28. Profile of sand wave near I-5 crossing of mainstem Snohomish River

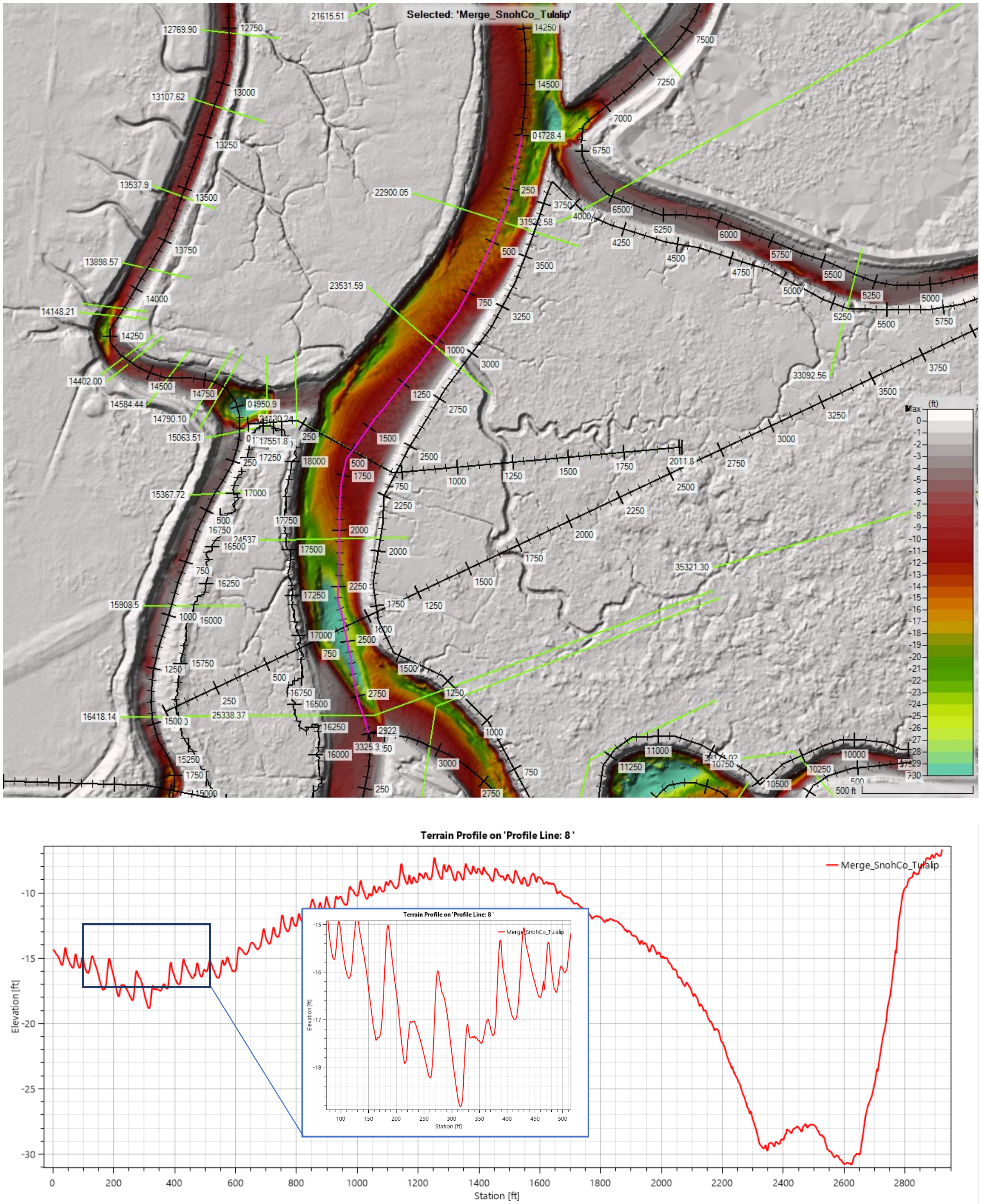

Figure 29. Bed profile along Steamboat -Ebey connector. Note the present of sand dunes in shallower areas, and smooth bed in deep areas (scour pools), and nearly 20-ft variation in the pool to crossing invert elevation.

Analysis of bed elevation changes

For this analysis, if both the 2019 and 2020 data sets depart from the CLOMR model cross section data in the same direction, and the average of the departure exceeds the underlying data accuracy, then the change is considered significant.

Bed profiles of the available data sets were cut from the DEMs and are compared in Figure X. Average elevations of each reach were computed.

Longitudinal volume changes between the CLOMR and 2019 and CLOMR and 2020 surveys were computed in the Cross Section Viewer (North Arrow Research, 2021). The Cross Section Viewer tool uses the average end area method to compute area and volume changes at a cross section and within a reach over time. As shown by the cumulative volume changes in Table 2 below, which are based on the results shown in Figure 29 through Figure 32, all reaches have experienced an increase in bed elevations (on average) over the 14-year period that has elapsed between the surveys that are in the Smith Island CLOMR model and 2020, which is unsurprising given the delta setting. Even though the trends are depositional on average, there are large vertical changes that have occurred in some of these reaches. The average bed elevation at mainstem Snohomish near I-5 (where dredging is common) increased as much as 8-feet, and Steamboat Slough immediately downstream of a reconnected tidal channel and marsh, decreased as much as 5 feet. The reach scale volume change can be converted to reach average bed elevation change by dividing the volumetric change by the average channel width.

Cumulative longitudinal volumetric change by reach is annualized in Table 2 below. The annualized volumetric change can be thought of as an annual sediment budget, or the amount of sediment expected on average to accumulate or erode from an area of interest. The annualized vertical changes in these reaches are small relative to channel depths. For example, maximum depths of the mainstem Snohomish River exceed 40 feet at high tide yet the reach average vertical changes (<0.1 feet/year) represent a small percentage of the available conveyance. The availability of adjacent distributaries means that sedimentation in one location can redistribute flow into another distributary, maintaining the river's ability to convey flood flows despite localized changes.

The small vertical bed changes and stability of the banks in the lower Snohomish, combined with the small (modeled) effect on tidal fluxes in adjacent distributaries, suggests that Spencer Island is not heavily influenced by sediment transport in the distributary channels. Since sediment transport modeling is unlikely to provide information valuable for feasibility phase decision making, it has not been conducted. Focused sediment transport modeling may be beneficial in PED to help optimize designs of tidal channels and dike breaches. Since the project actions will directly restore natural processes on Spencer Island such as erosion and deposition, more extensive sediment transport modeling would primarily inform questions about the rates that these processes occur in the vicinity of the island. Since reliable sediment transport modeling tends to be difficult and costly, it will likely be preferable to forego modeling in favor of pre-post implementation monitoring of site topography.

Table 2. Lower Snohomish Estuary Sediment Budget Estimate

Reach	Length	Width	2006-2014 cumulative volumetric change	Annualized Volumetric Change	Reach Avg. Vertical Change	Annualized Vertical Change
	(mi)	(ft)	(cy)	(cy/yr)	(ft)	(ft)
Snohomish River	8.0	583	1,051,017	75,073	1.1	0.08
Steamboat Slough	7.0	620	255,874	18,277	0.3	0.02
Union Slough	4.8	235	210,168	15,012	1.0	0.07
Ebey Slough	13.6	310	57,249	4,089	0.1	0.00

As shown in Figure 29 below the Snohomish River mainstem channel has degraded slightly between Ebey Slough and 1 mile upstream with split to Steamboat/Union Sloughs. Most aggradation occurs between I-5 and the flow split, where dredging is common. Aggradation continues downstream to the mouth.

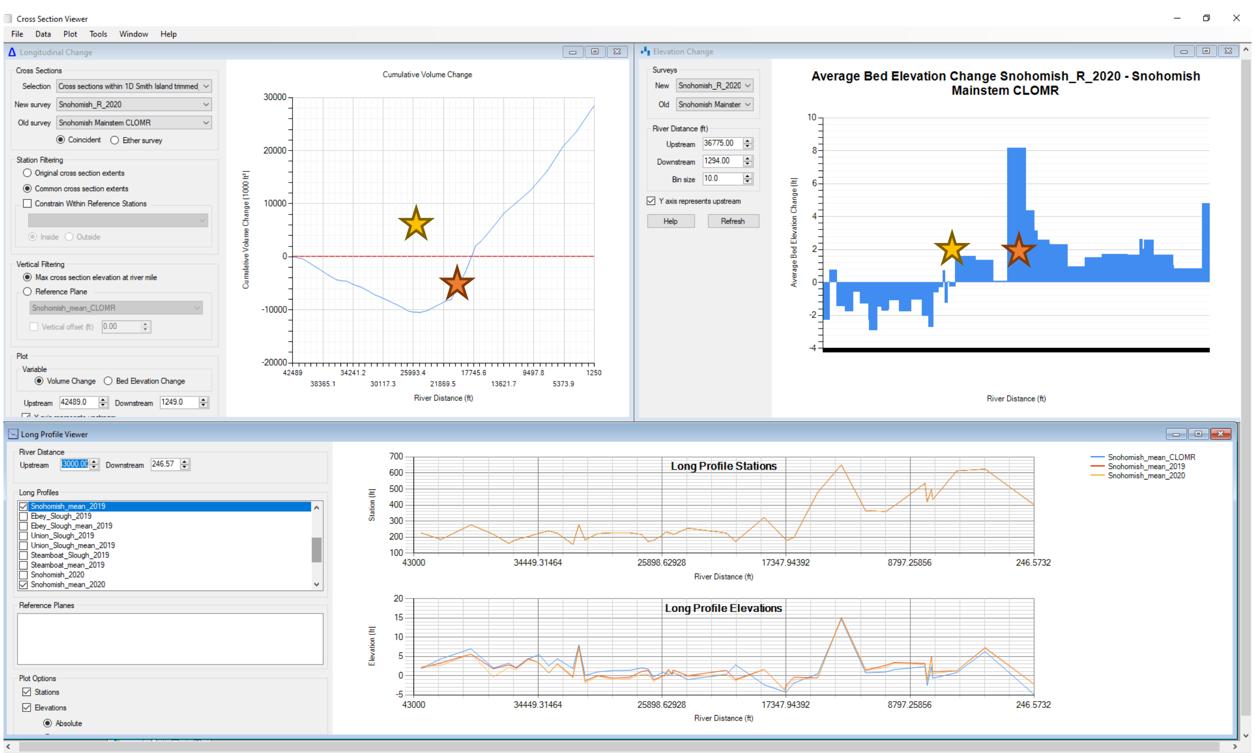

Figure 30. Mainstem Snohomish from Ebey Split to mouth analysis.

As shown in Figure 30 below Ebey Slough is not significantly aggradational until the Highway 2 bridge, then the channel bed slowly aggrades until SR 529 where the channel appears to begin scouring moderately in response to increased flows into the Qwulloolt restoration site.

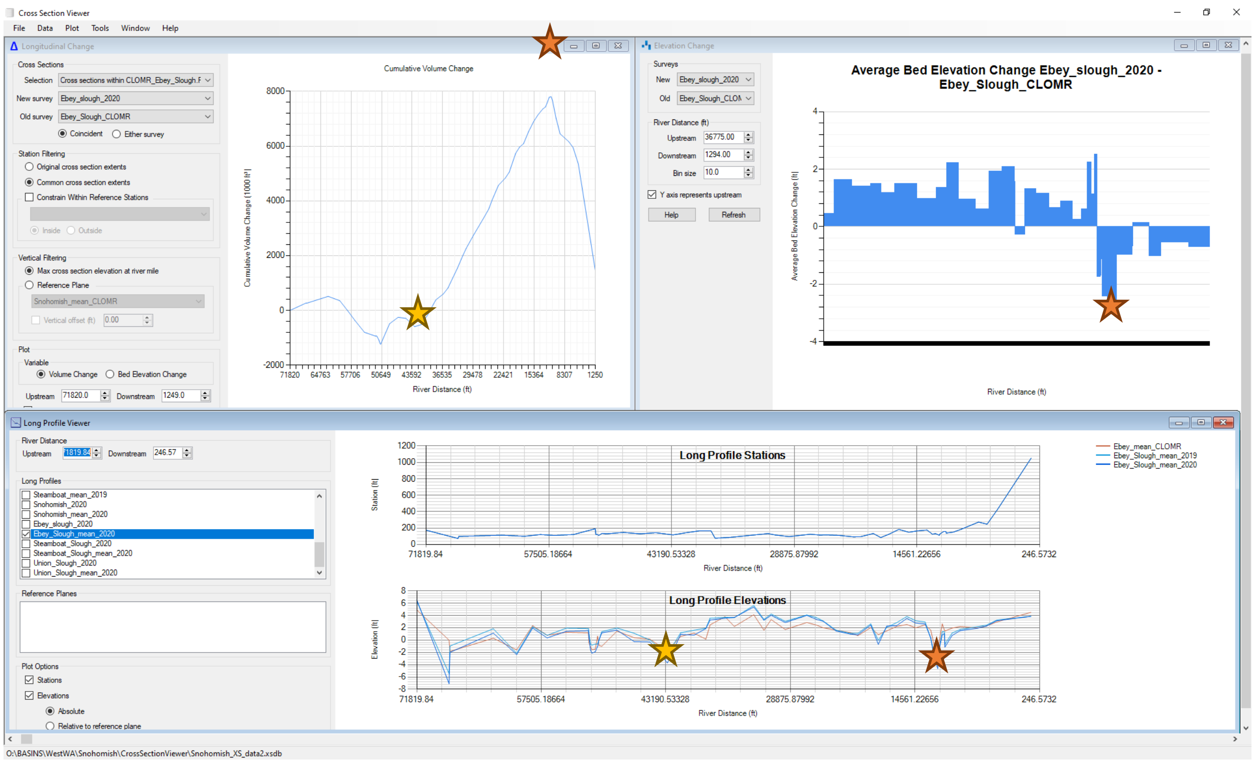

Figure 31. Ebey Slough from mainstem to mouth analysis.

As shown in Figure 31 below Steamboat Slough is aggradational until joining Ebey Slough at the north end of Spencer Island. Downstream of the confluence, the channel elevation is stable until the outlet of the Smith Island restoration project, where it begins to fluctuate over a short distance. Aggradation is concentrated upstream of the Spencer Island levee breach. Scour is evident downstream of the breach. This is similar to what was measured at Union Slough downstream of the Smith Island project and Ebey Slough downstream of the Qwulloolt site.

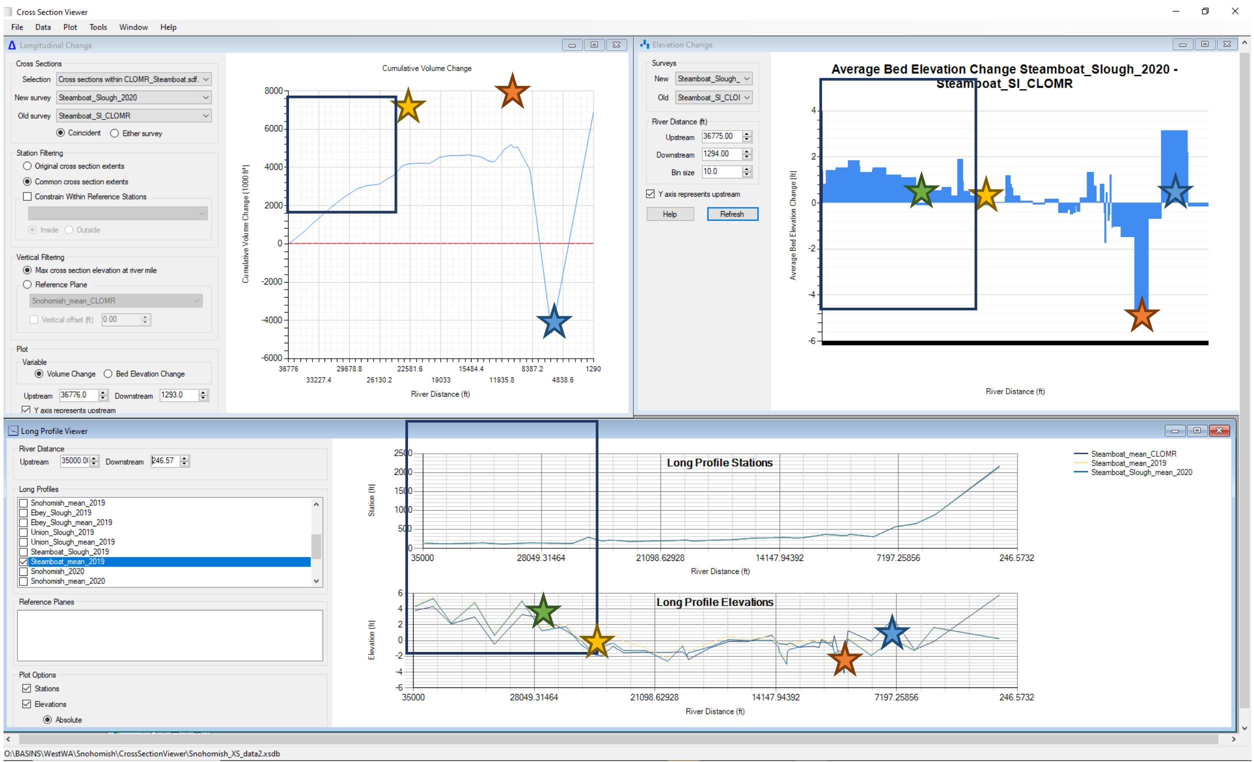

Figure 32. Steamboat Slough from mainstem to mouth analysis.

As shown in Figure 32 below, average bed elevations have increased about 2 feet for the southern half of Union Slough adjoining Spencer island. The area may be a local depositional site that has been increasing the general elevation of the southern half of Union Slough, causing portions of the slough to be dry at low tide. Note that modeled flood tide currents in Union Slough during “typical” river flows converge from the north and south as they enter the mitigation site west of Spencer Island. Tidal currents in Union Slough then diverge to the north and south as the tide ebbs. Currents are stronger to and from the north than south due to deeper channel depths.

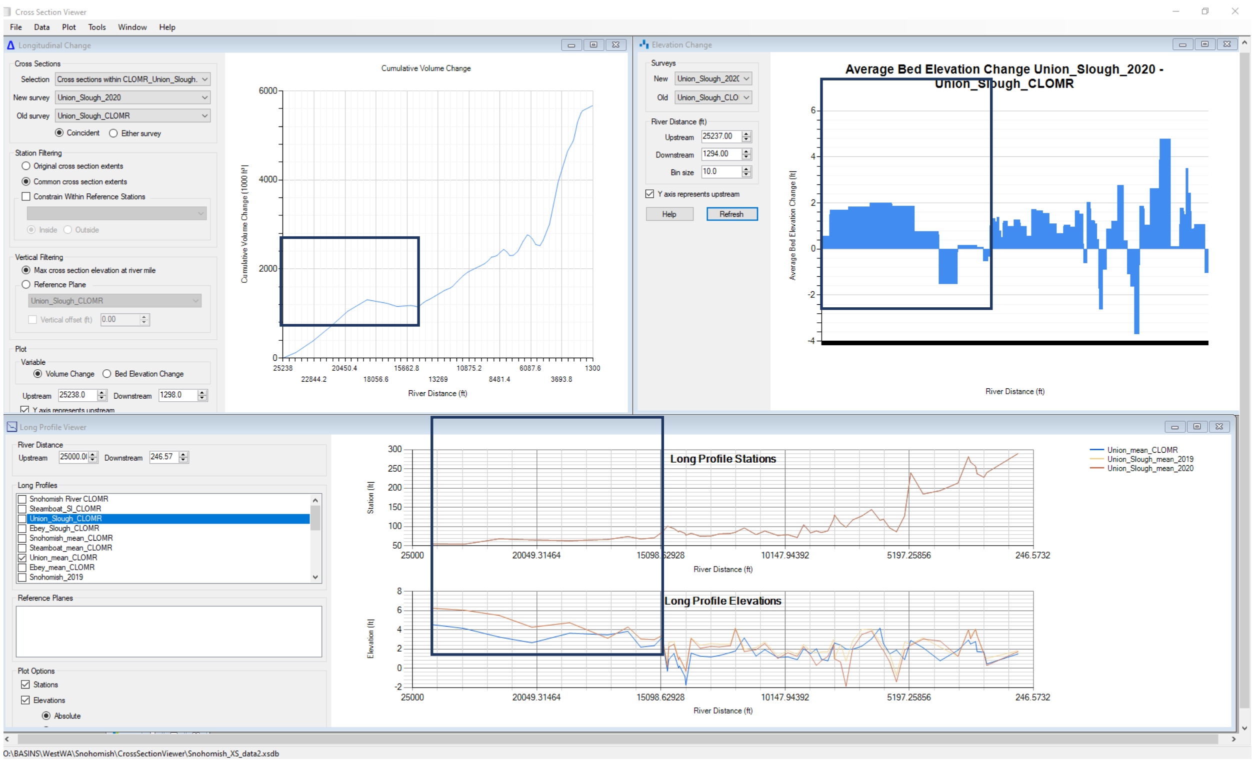

Figure 33. Union Slough from Mainstem split to Lower Steamboat Slough analysis.

4. GIS analysis of Spencer Island existing geomorphic conditions:

This GIS analysis includes all lands interior of the mean tide level contour for Spencer Island south of the Buse cut, including the restoration site, lands south of the south cross dike. All data are compiled and analyzed in ArcGIS Pro.

Data sources:

The following data sources were used in the GIS analysis of digital elevation model (DEM) terrains described below.

- Snohomish River Lidar (Snohomish County, 2019)
- Snohomish River single beam bathymetry (Snohomish County, 2020)
- Snohomish River multibeam bathymetry (Tulalip Tribe, 2020)
- USACE single beam bathymetric survey of existing Spencer Island ditches (USACE 2023)
- USACE Spencer Island feasibility level design terrain (USACE 2024)

A shaded relief DEM of existing conditions in the vicinity of Spencer Island is shown below Figure 33 and Figure 34. Elevations higher than elevation 20 feet (top of levees in vicinity of Spencer Island) are shaded grey, and elevations lower than 5.5 feet (analogous to mean tide) are highlighted in blue.

Note eroded conditions south of main breach channel, dissection of natural drainage patterns with ditches, formation of dendritic channels in former agricultural lands as vegetation dies off, and shoaling in Union Slough, sand dunes in Steamboat Slough.

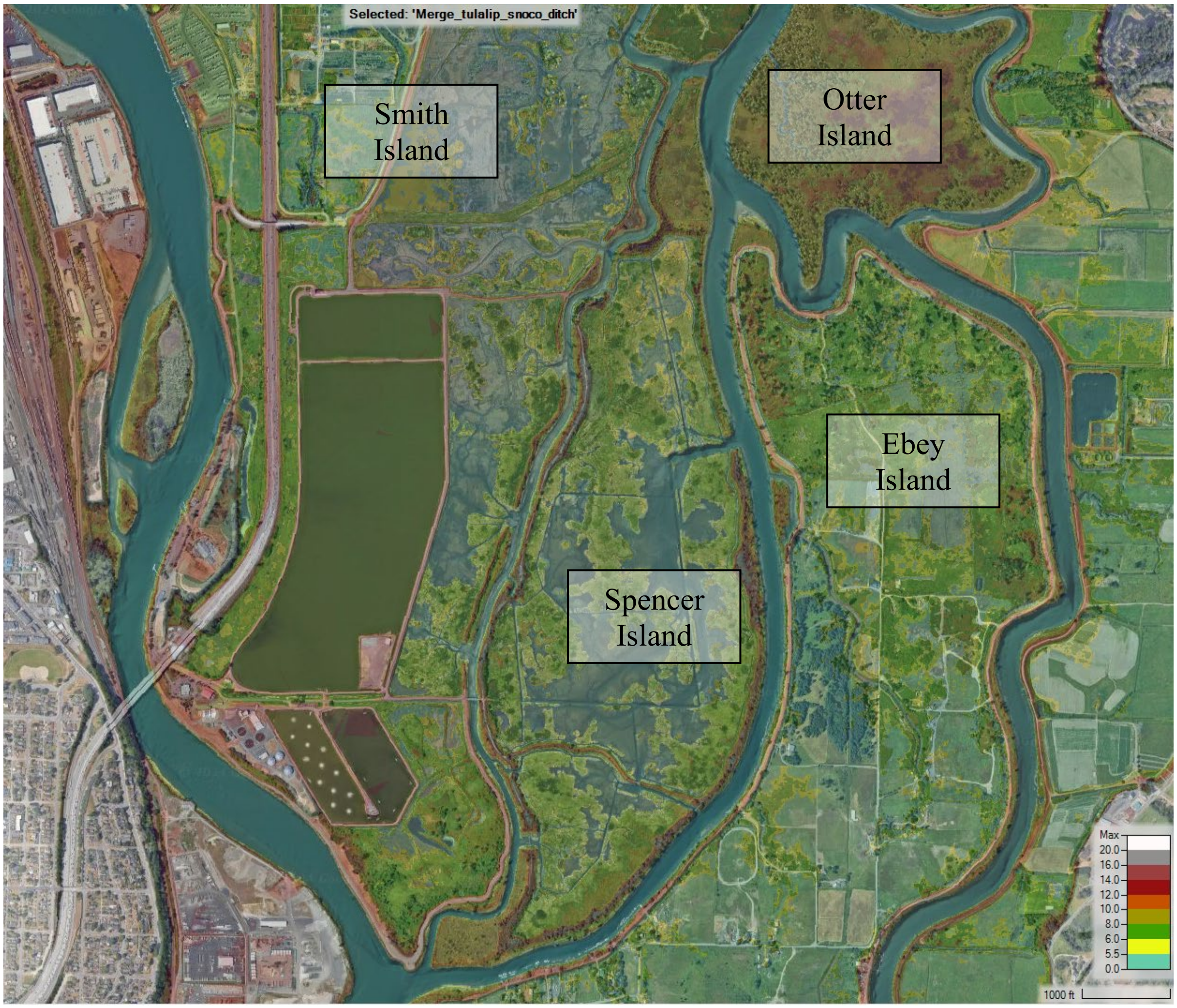

Figure 34. Shaded bare earth lidar showing relative elevations and land cover at Smith, Spencer, Otter and Ebey Islands

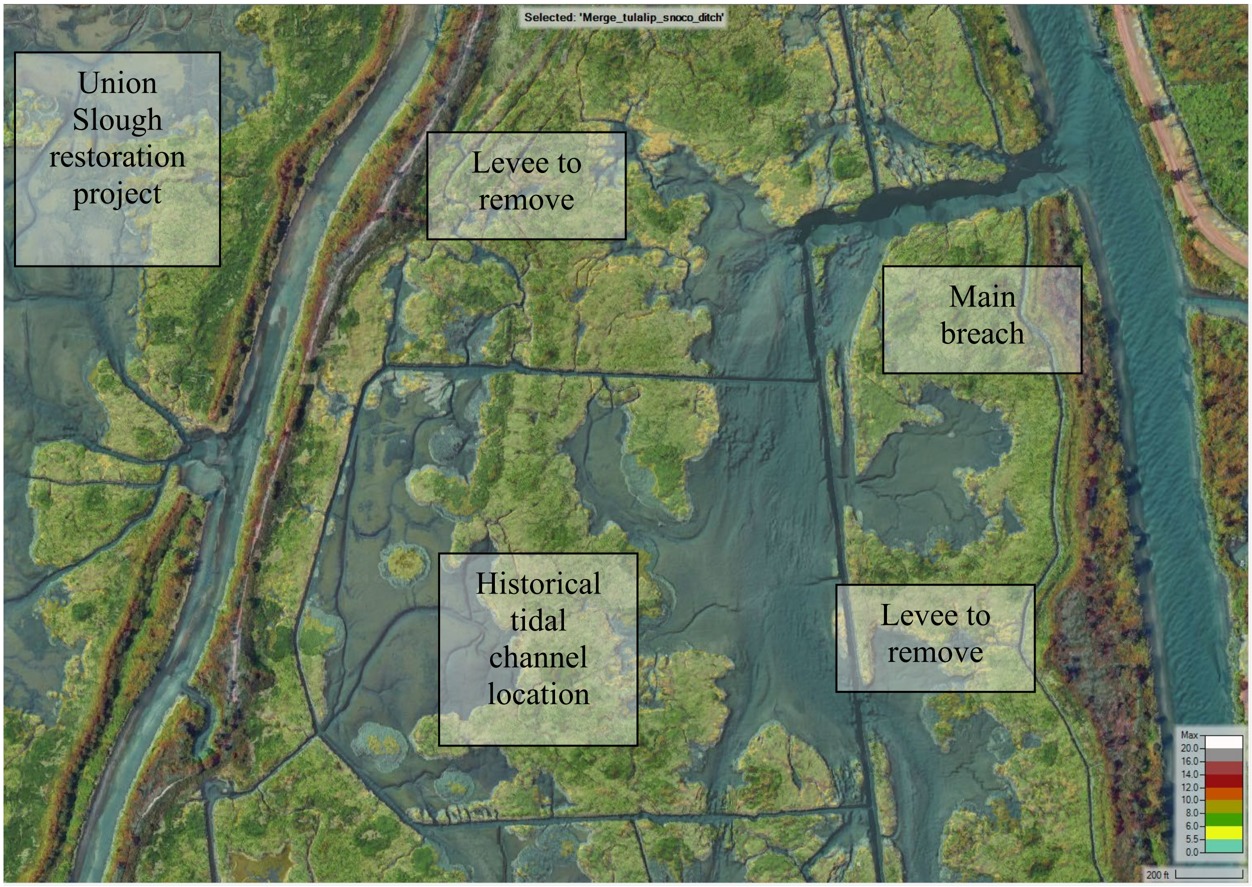

Figure 35. Detail of topographic and vegetation conditions at Spencer Island

Digital elevation model analysis

The project DEM was manually adjusted by USACE within Spencer Island using HEC-RAS Mapper to clean up small artifacts to improve the automatic delineation of the drainage network. ArcGIS pro was then used to identify marsh island drainage channel outlet locations, compute contour lines, cut surface profiles, calculate areas and volumes, and to derive the drainage network (stream order) and tributary watershed areas for the marsh.

Pertinent data derived from GIS analysis of the Spencer Island existing conditions DEM include:

- Island area above mean tide level (MTL): 424 acres
- Island elevation range: -17.5 to 22.5 feet
- Average island ground elevation: 6.8 feet
- Inundation storage volume and depth at MHHW (tidal prism): 1160 acre-feet, 9.0 feet
- Shoreline perimeter: 24,455 feet
- Shoreline crest elevation profile: Average 13.75 feet, min. -16.5 feet, max. 22.0 feet.

Conditions at the Otter Island reference site are summarized below

- Island area above mean tide level (MTL): 146 acres
- Island elevation range: -1.75 to 15.2 feet
- Average island ground elevation: 9.5 feet
- Inundation storage volume and depth at MHHW (tidal prism): 81 acre-feet, 9.0 feet
- Shoreline perimeter: 12,250 feet
- Shoreline crest elevation profile: Average 9.3 feet, min. -1.5 feet, max. 12.2 feet.

The relationship between elevation and inundation area and stored water volume (blue dashed line, orange lines) are shown below in Figure 35 and Figure 36 and summarized in Table 3. The dashed Elevation/area/volume data for the portion of the island north of the south cross dike are presented in Table 4.

In Figure 35 the effects of proposed grading are illustrated by the differences between the proposed elevation-inundation area relationship and the existing relationship. Tidal inundation would increase mean tide and MLLW extents due to channel and breach construction, but would be reduced during MHHW since the levee spoils (marsh berms) would occupy marshlands. During flood tides and high river flows the tops of degraded dikes and marsh berms would be inundated, increasing inundation area further.

The elevation volume relationship (Figure 36) is not as dramatically altered. There would be a small increase in the amount of water stored in Spencer Island under mean to low tide conditions, less during high tides, and essentially no change during flood tides and river floods. This result fits the balanced cut and fill plans for the material.

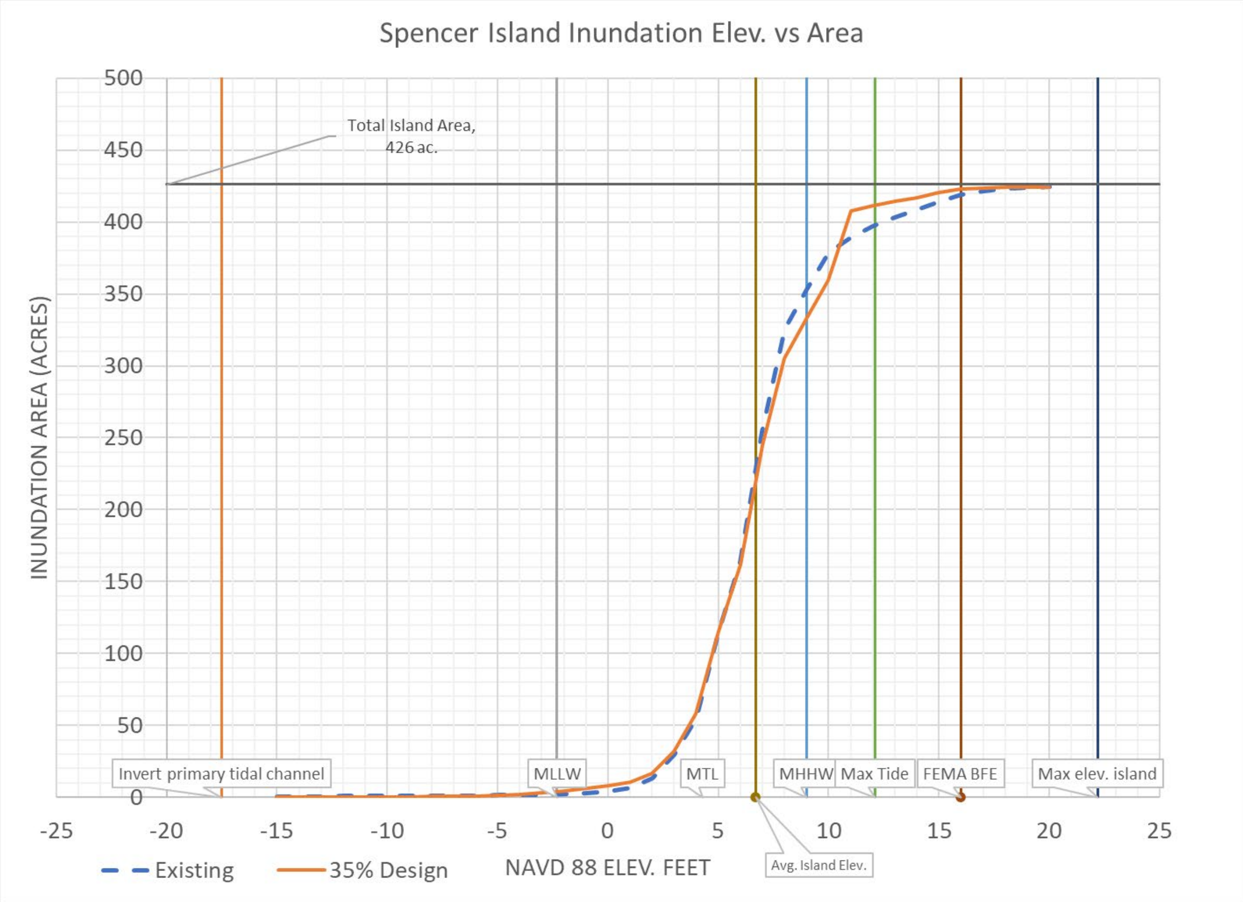

Figure 36. Spencer Island elevation – inundation area relationship

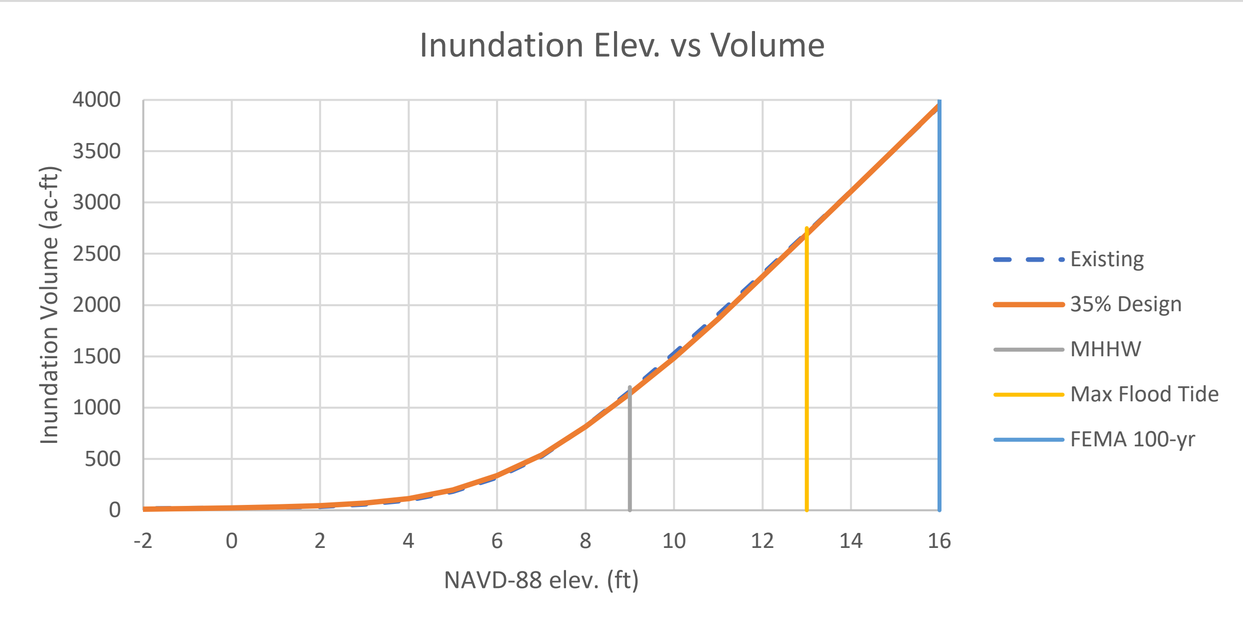

Figure 37. Spencer Island elevation – elevation-storage volume relationship

Because these charts are somewhat difficult to discern differences, inundation area, volume, and average inundation depth (storage volume divided by inundation area) for existing conditions, proposed conditions, and the Otter Island reference site at specific elevation reference planes are tabulated below in site Table 3 through Table 5.

Table 3. Spencer Island total wetted acres and volume relative to elevation references

Elevation reference	NAVD 88, ft	Inundation Area (acres)	Volume (acre feet)	Avg. Depth (feet)
Invert primary tidal channel	-17.5	0	0	-
MLLW	-2.3	2.2	16.2	7.3
MTL	4.3	55	98	1.8
Avg. Island Elev.	6.7	254	525	2.1
MHHW	9	353	1161	3.3
Max Tide	13	403	2706	6.7
FEMA BFE	16	419	3940	9.4
Max elev. island	22.2	424	5630	13.3

Table 4. Spencer Island proposed (35% design) conditions total wetted acres and volume relative to elevation references

Elevation reference	NAVD 88, ft	Inundation Area (acres)	Volume (acre feet)	Avg. Depth (feet)
Invert primary tidal channel	-13	0	1	-
MLLW	-2.3	5	11	2.2
MTL	4.3	58	112	1.9
Avg. Island Elev.	6.7	245	537	2.2
MHHW	9	333	1137	3.4
Max Tide	13	414	2692	6.5
FEMA BFE	16	423	3949	9.3
Max elev. island	22.2	424	6578	15.5

Table 5. Otter Island reference conditions total wetted acres and volume relative to elevation references

Elevation reference	NAVD 88, ft	Inundation Area (acres)	Volume (acre feet)	Avg. Depth (feet)
MLLW	-2.3	0.0	0.0	-
Invert primary tidal channel	-1.75	0	0	-
MTL	4.3	2	1	0.5
MHHW	9	47	41	0.9
Avg. Island Elev.	9.5	77	81	1.1

Max Tide	13	144	510	3.5
Max elev. island	15.23	146	801	5.5
FEMA BFE	16	146	946	6.5

The lowest point on Spencer Island is the main levee breach along Steamboat channel. The bottom of the channel is about 15 feet below the MLLW elevation. At the Otter Island reference site, the largest tidal channel has an invert that is essentially at the low tide elevation/ The invert of the design channel is lower due to grading proposed there to widen and shallow the channel to stabilize the channel. At MHHW.

Tidal channel drainage network analysis

ArcGIS Pro Hydrology tools were used to automatically delineate watersheds and channels tributary to tidal channels connected to Union and Steamboat Slough using high resolution terrain and bathymetric data provided by Snohomish County for Spencer Island (existing and 35% design conditions) and Otter Island (reference condition).

The Lidar based terrains were clipped to the island boundaries prior to analysis. The island boundaries were based on the location of the mean tide contour (4.3 feet NAVD 88). Connections between interior marsh channel networks and distributary channels (sloughs) were identified by reviewing multiple aerial photos, Lidar, and elevation contours. The connection points are the intersection of the low point in the tidal channel with the island perimeter.

The Hydrology tools condition the clipped DEM for the island and compute the drainage basin boundary and flow paths to the channel outlets. Some outlet points were moved manually in GIS to coincide with locations of high flow accumulation to ensure that the watershed analysis was capturing all flow tributary to the outlet. Resulting channel flow paths, Strahler stream order (increasing in downstream direction), and drainage basin boundaries were reviewed for consistency with onsite observations and hydraulic modeling.

Results for Spencer Island, existing conditions are presented in Figure 37 and summarized in Table 7. Results for Spencer Island, proposed (35%) conditions are presented in Figure 38 and summarized in Table 8. Results for Otter Island, (reference) conditions are presented in Figure 39 and summarized in Table 9

The derived stream network within the tidal marsh reflects conditions at the point of low ebb when all flow is directed to basin outlets. This represents a relatively brief period of the tide cycle but is the only condition that the automated tools are set up to handle. When drainage divides are submerged on incoming and outgoing tides, water flow directions deviate from the drainage network derived from the topographic data. Flow directions are dynamic and highly variable as water in the marsh follows the most hydraulicly efficient (highest gradient) path which is constantly changing depending on tides and river flows. During peak ebb or flood tides (when erosive forces are greatest) water flow direction is more influenced by topography and consistent with the low tide drainage network. Note that widths of outlet channels were manually measured at based on estimated top width at mean tide level measured at the South Cross Dike and Union Breach tide gages (~ 6.5 feet NAVD88), and the lowest elevation across the width transect sampled to estimate the outlet invert elevation.

Average characteristics of each delineated tidal basin are summarized in Table 6 below. The most striking finding in this table is that the main breach channel on Spencer Island currently drains two thirds of the entire island area at ebb tide, in contrast with Otter Island, where the largest channel drains only a third of the island area. With proposed addition of new breach channels, the flow through the largest breach should be reduced significantly, much closer to Otter Island conditions. This is expected to normalize hydraulic connectivity between the sloughs and the island, allowing fish to reside throughout the site and throughout typical tide cycles.

Other notable characteristics include:

- From inspection of Figure 37, under existing conditions, only 12 of 31 identified channels (39%) connect into the interior of the marsh island which means that more than half of the tidal channels on Spencer Island are narrow, short, first and second order channels truncated by existing levees, degrading connectivity and habitat conditions generally.
- Because no levees are present on the Otter Island reference site, 100% of delineated channels, even the very short ones, extend beyond the shoreline perimeter crest into the island interior.
- With restoration (levee removal and breach construction) the proportion of connected channels improves to 31 of 44 channels (70%).
- Channels on Otter Island are generally more frequent along the shoreline, smaller in terms of drainage area, width, and order and higher in terms of outlet elevation than Spencer Island.

Table 6. Summary of drainage network data for Existing Conditions, proposed conditions, and reference site

Location/ Condition	# Outlet Connections	Average Drainage Area (ac.)	% Island area	Avg. Channel Stream Order	Avg. channel outlet width (ft)	Largest Channel Strahler Stream Order	Largest Outlet Drainage Area	% Island area
Spencer Existing	31	13	3%	3	24	7	277	65%
Spencer 35% Design	44	9	2%	3	38	6	123	29%
Otter Reference	43	3	2%	2	15	5	49	34%

Figure 38. Existing Conditions Spencer Island Lidar derived tidal channel network for existing conditions – note large size of watershed tributary to 7th order channel at main breach

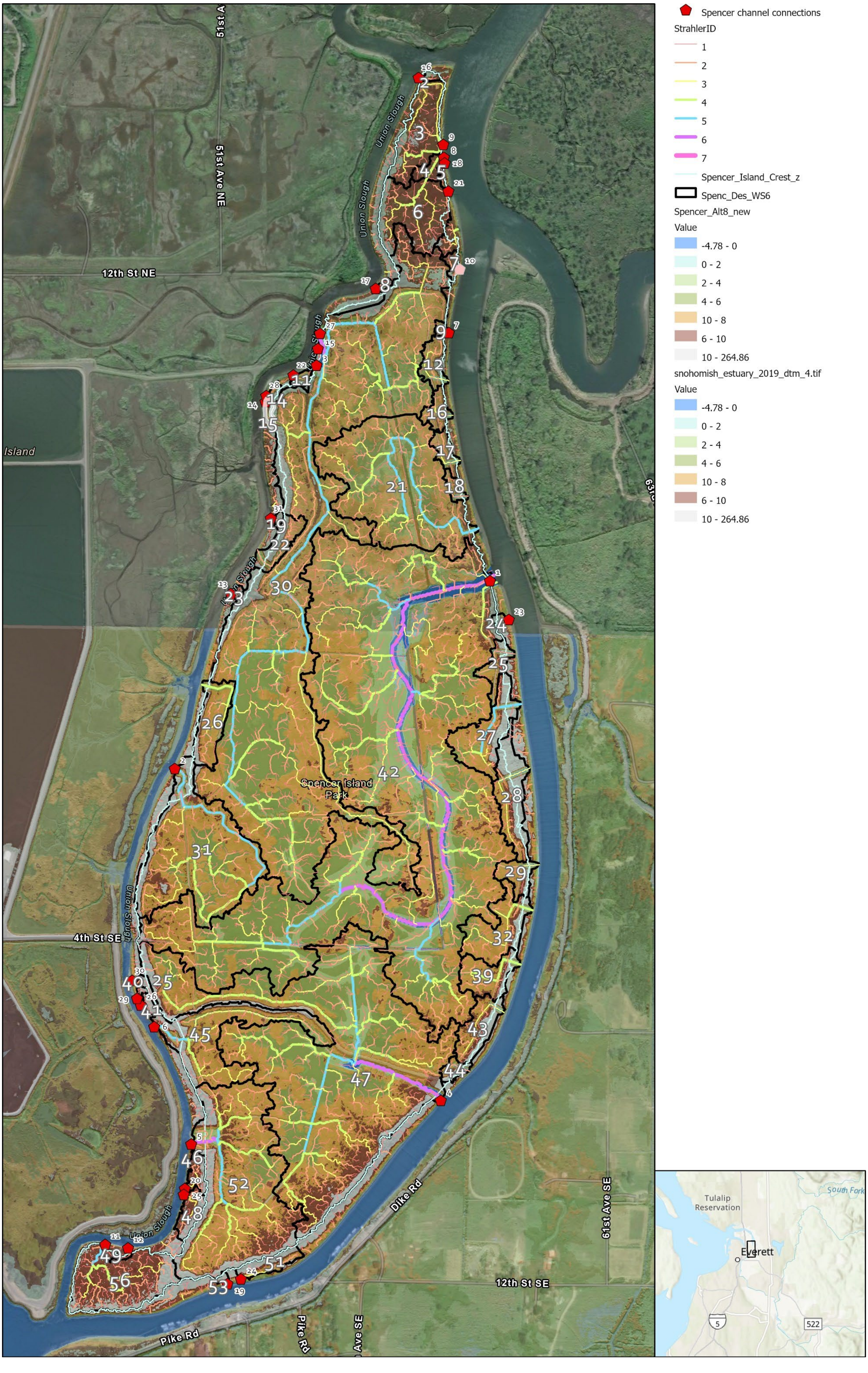

Figure 39. Proposed Conditions Spencer Island Lidar derived tidal channel network– note significantly reduced size of watershed tributary to 6th order channel at main breach – indicating redistribution of flow to new channels along island perimeter

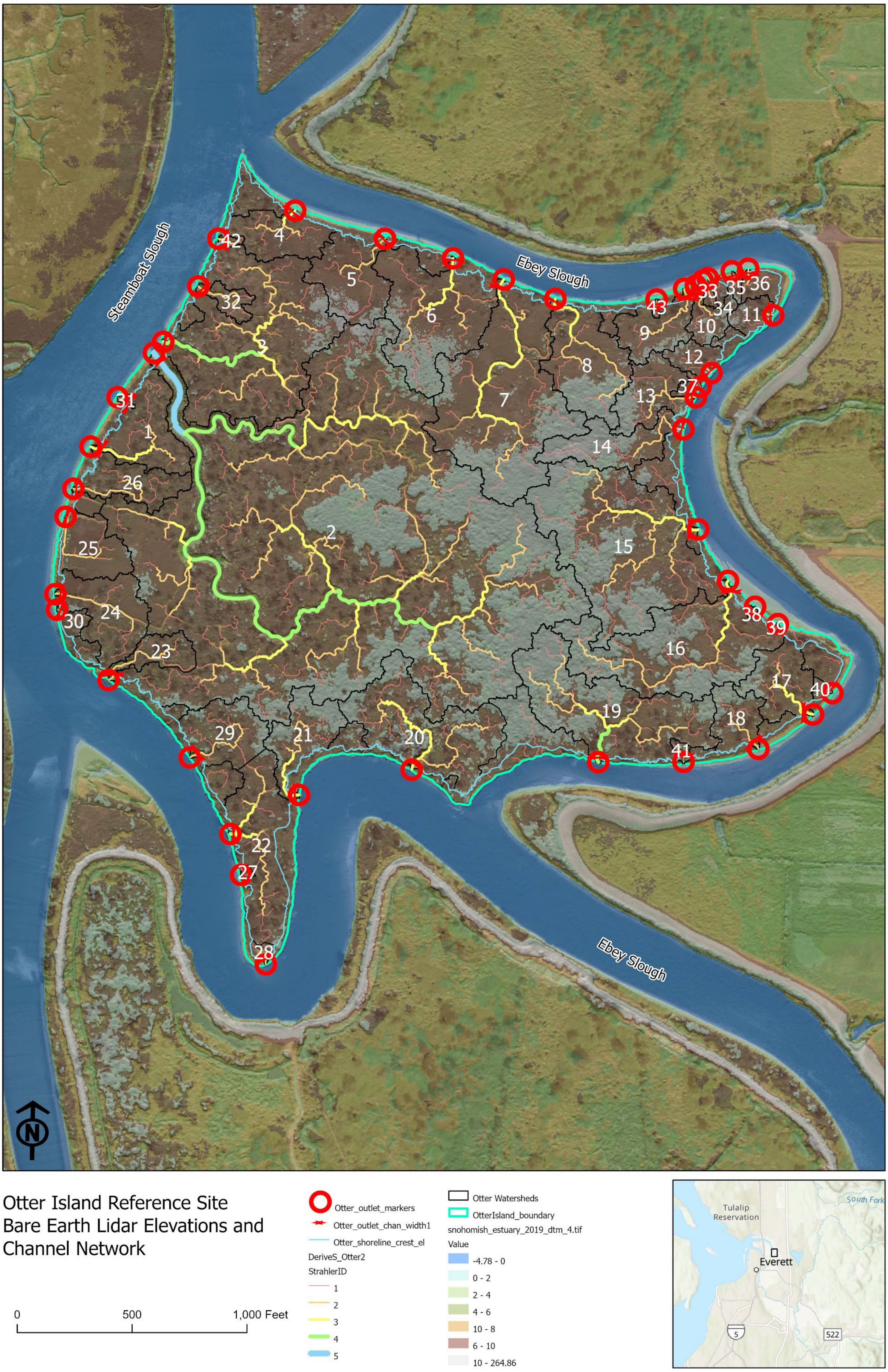

Figure 40. Lidar elevations and tidal channel network at Otter Island

Table 7. GIS analysis results for existing Spencer Island tidal marsh outlet channel connections and watersheds

Location	Connected Slough	Tidal Channel Connection	Marsh Channel Watersheds			Channels within watershed				
		Connection ID	Watershed ID	Area (sf)	Area (ac)	Marsh channel total length (lf)	Count of Channel segments	Largest Channel Strahler Stream Order	Largest channel outlet width (ft)	Outlet min. z elev. (ft)
North of North Cross Dike	Union	22	1	11079	0.3	236	9	2	10	6.8
	Steamboat	**10**	**2**	**179280**	**4.1**	**4420**	**96**	**4**	**30**	**1.1**
	Steamboat	25	4	9108	0.2	204	1	1	15	3.6
	Steamboat	**29**	**5**	**22140**	**0.5**	**545**	**13**	**4**	**13**	**7.0**
	Steamboat	**8**	**6**	**305712**	**7.0**	**7232**	**152**	**3**	**15**	**0.2**
	Steamboat	**11**	**7**	**173655**	**4.0**	**4502**	**90**	**4**	**15**	**2.5**
Middle Island	Union	23	8	14724	0.3	300	7	1	12	6.3
	Union	40	9	1206	0.0	10	1	1	13	4.2
	Steamboat	7	10	10341	0.2	162	3	2	28	4.5
	Union	19	11	1494	0.0	8	1	1	15	2.6
	Union	30	12	14328	0.3	217	3	2	15	3.7
	Union	42	13	9162	0.2	165	5	2	19	5.5
	Union	18	14	10611	0.2	169	3	2	11	5.5
	Union	**3**	**16**	**436770**	**10.0**	**10320**	**197**	**4**	**43**	**0.5**
	Union	45	17	7506	0.2	137	3	2	11	2.9
	Union	16	19	14949	0.3	361	9	3	6	5.9
	Steamboat	31	20	9252	0.2	181	7	3	6	5.3
	Union	**2**	**23**	**302976**	**7.0**	**6725**	**147**	**4**	**29**	**-0.3**
	Union	44	24	9828	0.2	258	3	2	7	5.7
	Union	43	25	6561	0.2	183	3	2	4	7.9
	Union	37	26	16227	0.4	420	8	3	7	6.5
	Steamboat	**1**	**28**	**12075696**	**277.2**	**294532**	**5956**	**7**	**143**	**-14.5**
South of South Cross Dike	Union	**6**	**29**	**367857**	**8.4**	**7798**	**198**	**4**	**27**	**0.6**
	Union	27	31	41589	1.0	1013	23	3	12	6.9
	Steamboat	**4**	**32**	**1441782**	**33.1**	**34308**	**710**	**5**	**51**	**-1.3**
	Union	36	33	58941	1.4	1440	30	3	17	2.9
	Union	33	34	58932	1.4	1129	37	3	17	5.7
	Union	**5**	**35**	**1022625**	**23.5**	**25598**	**484**	**6**	**111**	**1.5**
	Steamboat	26	36	6435	0.1	114	4	1	14	4.3
	Union	**15**	**37**	**232128**	**5.3**	**6253**	**130**	**5**	**9**	**4.4**
	Union	**13**	**38**	**127746**	**2.9**	**3599**	**74**	**4**	**11**	**5.5**

Bold = connected to island interior

Table 8. GIS analysis results for 35% Design Spencer Island tidal marsh outlet channel connections and watersheds

Location	Connected Slough	Distance from South End of Island (ft)	Design Status	Tidal Channel Connection	Marsh Channel Watersheds			Channels within watershed				
				Connection ID	Watershed ID	Perimeter (lf)	Area (ac)	Marsh channel total length (lf)	Count of Channel segments	Largest Channel Strahler Stream Order	Largest channel outlet width (ft)	Outlet min. z elev (ft)
North of North Cross Dike	**Steamboat**	**11783**	**Existing**	**9**	**3**	**2788**	**4.9**	**4838**	**106**	**4**	**30**	**1.2**
	Union	**11717**	**Existing**	**16**	**2**	**463**	**0.2**	**188**	**3**	**2**	**10**	**6.7**
	Steamboat	**11682**	**Existing**	**8**	**4**	**1044**	**0.8**	**627**	**17**	**4**	**15**	**0.8**
	Steamboat	**11637**	**Existing**	**18**	**5**	**591**	**0.2**	**197**	**1**	**1**	**15**	**3.8**
	Steamboat	**11406**	**Existing**	**21**	**6**	**3083**	**6.1**	**5889**	**135**	**4**	**13**	**7.0**
	Steamboat	**10755**	**Existing**	**10**	**7**	**839**	**0.4**	**440**	**10**	**3**	**15**	**2.6**
Middle Island	**Steamboat**	**10231**	**Modified Ex.**	**7**	**9**	**463**	**0.3**	**156**	**4**	**2**	**42**	**-3.2**
	Union	9878	Existing	17	8	391	0.2	202	6	2	12	6.5
	Steamboat	**9838**	**New**	**46**	**12**	**1469**	**1.5**	**1280**	**33**	**3**	**43**	**-3.5**
	Steamboat	**9558**	**New**	**43**	**16**	**1367**	**1.2**	**1184**	**22**	**3**	**45**	**-3.5**
	Steamboat	**9191**	**New**	**42**	**17**	**1322**	**1.0**	**860**	**13**	**3**	**42**	**-3.4**
	Union	**9189**	**Modified Ex.**	**15**	**30**	**23382**	**82.7**	**78576**	**1755**	**6**	**249**	**-1.7**
	Steamboat	**8896**	**New**	**41**	**18**	**879**	**0.5**	**516**	**5**	**2**	**45**	**-3.2**
	Union	8793	Existing	22	11	592	0.4	221	5	2	15	3.8
	Steamboat	**8623**	**Existing**	**40**	**21**	**6052**	**21.1**	**21247**	**441**	**5**	**46**	**-3.2**
	Union	8506	Existing	28	14	495	0.3	152	3	2	19	5.5
	Union	**8462**	**Modified Ex.**	**14**	**15**	**596**	**0.3**	**207**	**6**	**2**	**36**	**3.2**
	Steamboat	**8207**	**Modified Ex.**	**1**	**42**	**26295**	**122.6**	**124578**	**2694**	**6**	**143**	**-11.7**
	Steamboat	7838	Existing	23	24	419	0.2	133	9	2	6	5.5
	Steamboat	**7550**	**New**	**39**	**25**	**1707**	**1.4**	**1106**	**13**	**2**	**45**	**-3.3**
	Union	7507	Existing	31	19	416	0.2	79	3	2	11	3.0
	Union	**7230**	**New**	**44**	**22**	**1543**	**1.8**	**1282**	**36**	**2**	**55**	**0.8**
	Steamboat	**7147**	**New**	**38**	**27**	**2962**	**4.7**	**4096**	**86**	**5**	**46**	**-3.5**
	Union	6814	Existing	13	23	367	0.2	190	7	2	15	6.0
	Steamboat	**6625**	**New**	**37**	**28**	**3044**	**4.3**	**2522**	**67**	**3**	**47**	**-3.6**
	Union	**6030**	**New**	**45**	**26**	**2093**	**3.2**	**2869**	**65**	**4**	**56**	**0.7**
	Steamboat	**5842**	**New**	**36**	**29**	**1448**	**1.5**	**1247**	**19**	**3**	**44**	**-3.3**
	Steamboat	**5470**	**New**	**35**	**32**	**3163**	**4.6**	**4418**	**95**	**4**	**45**	**-3.4**
	Union	**5323**	**Modified Ex.**	**2**	**31**	**5377**	**17.7**	**16973**	**356**	**5**	**29**	**-0.3**
	Steamboat	**5016**	**New**	**34**	**39**	**2021**	**2.8**	**2612**	**51**	**4**	**45**	**-3.4**
	Steamboat	**4606**	**New**	**33**	**43**	**1906**	**2.7**	**2120**	**45**	**3**	**47**	**-3.3**
	Steamboat	**4052**	**New**	**32**	**44**	**928**	**0.7**	**341**	**6**	**2**	**45**	**-3.3**
South of South Cross Dike	**Steamboat**	**3731**	**Modified Ex.**	**4**	**47**	**16329**	**59.5**	**55800**	**1269**	**6**	**82**	**-5.2**
	Union	3537	Existing	30	40	771	0.3	345	5	2	7	5.7
	Union	3388	Existing	29	57	427	0.1	115	1	1	4	7.9
	Union	3323	Existing	26	41	638	0.3	349	7	3	7	6.6
	Union	**3108**	**Existing**	**6**	**45**	**5611**	**9.1**	**7868**	**188**	**5**	**27**	**0.7**
	Union	**2089**	**Existing**	**5**	**52**	**6418**	**23.2**	**23598**	**500**	**6**	**111**	**1.6**
	Union	1727	Existing	20	46	1174	0.9	930	19	3	12	6.9
	Union	1676	Existing	25	48	1315	1.3	1299	32	3	17	3.1
	Steamboat	1473	Existing	24	51	1421	1.3	1074	35	3	17	5.7
	Steamboat	1348	Existing	19	53	356	0.2	99	5	2	14	4.4
	Union	**955**	**Existing**	**12**	**49**	**882**	**0.3**	**348**	**1**	**1**	**9**	**4.7**
	Union	**770**	**Existing**	**11**	**56**	**3162**	**8.0**	**8613**	**185**	**5**	**11**	**6.0**

Bold = connected to island interior

Table 9. GIS analysis results for Otter Island (reference site) tidal marsh outlet channel connections and watersheds

Location	Connected Slough	Design Status	Tidal Channel Connection	Marsh Channel Watersheds			Channels within watershed				
			Connection ID	Watershed ID	Perimeter (lf)	Area (ac)	Marsh channel total length (lf)	Count of Channel segments	Largest Channel Strahler Stream Order	Largest channel outlet width (ft)	Outlet min. z elev (ft)
Otter Island	Steamboat	Reference	1	1	2326	2.3	1324	6	3	16	7.3
	Steamboat	Reference	2	2	14796	49.2	26256	131	5	45	-0.6
	Steamboat	Reference	3	3	5549	8.8	4923	27	4	12	5.6
	Ebey	Reference	4	4	1911	1.7	884	7	3	10	6.3
	Ebey	Reference	5	5	2320	2.3	947	5	2	16	5.7
	Ebey	Reference	6	6	3706	4.7	2553	13	3	11	5.8
	Ebey	Reference	7	7	4971	8.4	4150	23	3	18	4.3
	Ebey	Reference	8	8	2768	3.1	1771	9	3	19	4.6
	Ebey	Reference	9	9	1952	1.5	613	3	2	14	7.8
	Ebey	Reference	10	10	1340	0.7	423	3	2	9	6.3
	Ebey	Reference	11	11	830	0.5	222	2	2	9	8.5
	Ebey	Reference	12	12	1061	0.6	345	4	2	5	8.9
	Ebey	Reference	13	13	2373	1.7	909	6	2	14	4.4
	Ebey	Reference	14	14	2747	2.0	1048	4	2	7	8.3
	Ebey	Reference	15	15	4971	8.8	4691	20	3	18	5.9
	Ebey	Reference	16	16	4930	6.2	3069	16	3	17	5.0
	Ebey	Reference	17	17	1992	1.7	952	6	3	14	5.1
	Ebey	Reference	18	18	1646	1.2	550	4	2	12	7.5
	Ebey	Reference	19	19	4307	5.9	2990	16	4	17	1.6
	Ebey-Steam.	Reference	20	20	3577	4.7	2608	13	3	36	3.5
	Ebey-Steam.	Reference	21	21	2332	1.8	1074	5	3	12	7.6
	Ebey-Steam.	Reference	22	22	2705	3.4	2013	16	4	22	5.4
	Ebey-Steam.	Reference	23	23	1540	0.9	763	4	2	16	5.9
	Steamboat	Reference	24	24	2339	2.4	1132	6	2	15	6.5
	Steamboat	Reference	25	25	1625	1.6	986	7	2	21	4.0
	Steamboat	Reference	26	26	2156	1.6	994	4	2	12	5.9
	Ebey-Steam.	Reference	27	27	402	0.1	173	4	2	15	6.6
	Ebey-Steam.	Reference	28	28	428	0.1	137	2	2	20	6.9
	Ebey-Steam.	Reference	29	29	397	0.1	77	1	1	25	7.2
	Steamboat	Reference	30	30	772	0.5	267	2	2	16	7.8
	Steamboat	Reference	31	31	570	0.2	98	2	1	6	8.2
	Steamboat	Reference	32	32	200	0.0	44	1	1	17	7.5
	Ebey	Reference	33	33	126	0.0	26	1	1	10	9.5
	Ebey	Reference	34	34	338	0.1	54	1	1	8	8.2
	Ebey	Reference	35	35	400	0.1	105	1	1	9	6.8
	Ebey	Reference	36	36	370	0.2	168	2	2	8	6.1
	Ebey	Reference	37	37	638	0.3	162	1	1	8	6.2
	Ebey	Reference	38	38	257	0.1	84	1	1	12	8.8
	Ebey	Reference	39	39	1168	0.5	462	3	2	9	5.6
	Ebey	Reference	40	40	1593	2.0	1064	8	2	4	5.7
	Ebey	Reference	41	41	204	0.1	35	1	1	18	7.2
	Steamboat	Reference	42	42	376	0.1	138	2	2	15	6.9
	Ebey	Reference	43	43	324	0.1	78	1	1	21	6.3

From inspection of Figure 37, six connected channels are located north of the main project area on the undeveloped remnant near the Buse cut. These channels range from 1st to 4th order and have widths that range from 10 to 30 feet (average of 16 feet) and invert elevations that range from 0.2 to 7 feet (average of 3.5 feet).

For the middle portion of the site where most of the ecosystem restoration work is proposed, there are 16 channel outlets identified. Only 3 outlets are present along Steamboat Slough where levee lowering is proposed. The remnant levee is more than 50 feet wide and approaches 20 feet in height in places in this location. The remaining outlets drain 1st to 3rd order channels along Union slough with the exception of the two proposed levee breach locations which are 4th order channels. Top widths of existing outlets range from 4 to 143 feet (average of 23 feet). Elevations range from -14.5 to 7.9 feet (average of 3.3 feet).

South of the main restoration area in the existing WDFW/Snohomish County site there are 9 outlets. The three largest outlets are engineered openings constructed in the 1990s. Widths range from 9 to 111 feet (average of 30 feet), with bottom elevations at the outlet ranging from -1.3 to 6.9 feet (average of 3.4 feet).

The relative frequency of outlet channel stream order for existing and proposed conditions on Spencer island and reference conditions on Otter island is compared in Figure 40 below where it can be seen that Spencer Island has roughly the same number of 1st, 2nd, 3rd and 4th order connections (5 to 8), with two 5th order channels, and one each of 6th and 7th order channels. The 7th order channels is very short and is the confluence point for all of the drainage north and south of the breach. In contrast the Otter Island reference site i has only one large 5th order channel, and a higher frequency of lower (1st, 2nd, 3rd) order channels. After restoration Spencer Island channel distribution more closely resembles the Otter Island reference site, with 2nd order channels being most frequent. The number of 1st order channels is decreased due to removal of the levees and reconnection with the marsh. The constructed breach channels are reflected in the increase in 4th, 5th and 6th order channels.

The largest channel draining Spencer Island is located in the middle of the portion planned for restoration and has a contributing watershed area of 277 acres and is a 7th order channel. This single channel is draining two thirds of the total island area at low tide, which explains the widespread erosion observed near the outlet. If the engineered riprap sill located at the south cross dike were not present more flow would divert south and the total watershed area draining to the largest connection would decrease. Note that the PSNERP design width of this channel is 164 feet with 5:1 side slopes and a 6-ft bottom width, with a bottom elevation of -8. Recent bathymetric surveys indicate that the bottom elevations at the levee breach range from -27 feet to -16 feet, with near vertical side slopes, and a much wider bottom width. This indicates this channel will erode laterally and adjust vertically until reaching a geomorphic equilibrium for the bed slope. The channel will likely evolve to a wider and deeper condition than the proposed channel at this location.

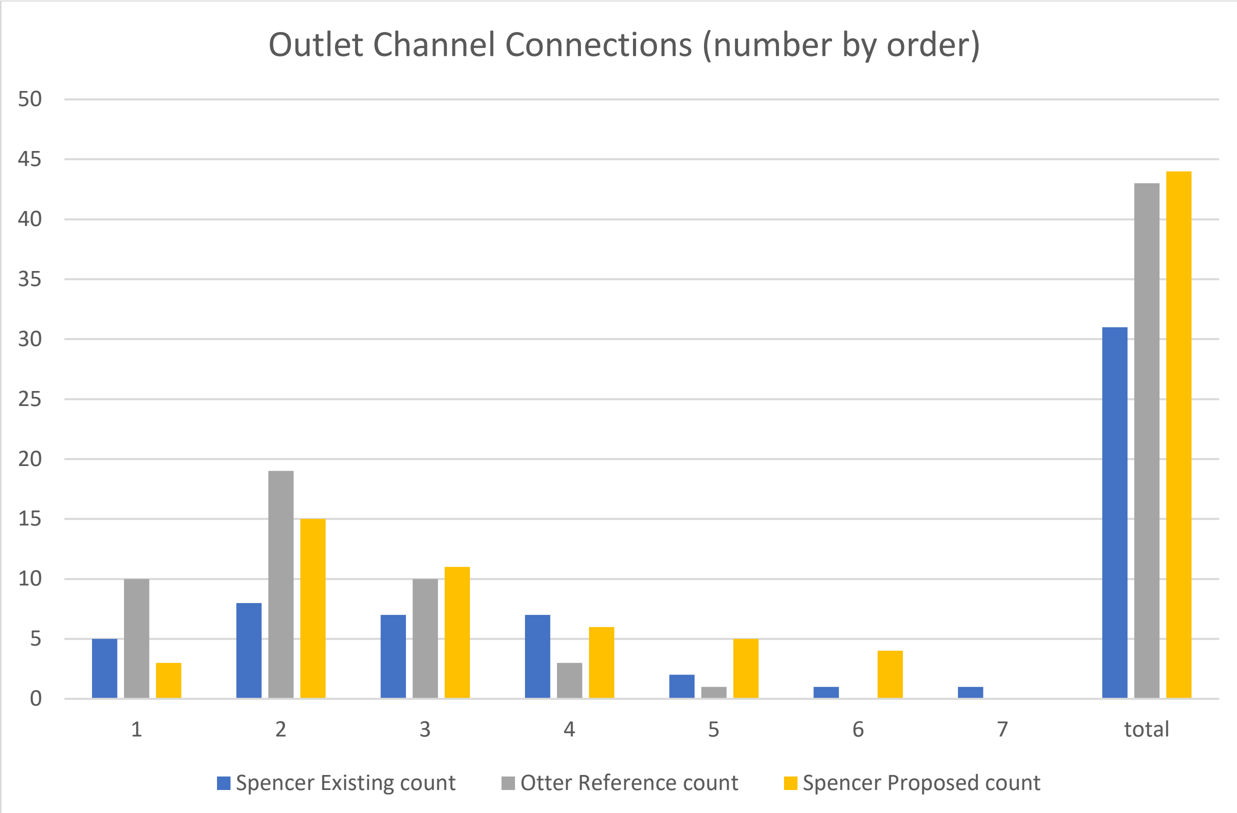

Figure 41. Count of outlet channels by Strahler order for Spencer Island existing conditions, proposed conditions, and Otter Island reference site

The largest channel draining the site by length is the ditch that runs west to east and south to north to the levee breach channel. This ditch and the ditch draining the northern half of the site south to the breach channel are 6th order channels also draining watershed ID 28. Under existing conditions the 5th order channel draining the south portion of the island to Steamboat Slough becomes a 6th order channel when water levels are above the pedestrian bridge riprap sill elevation. Removal of the sill under proposed conditions will reverse the existing flow direction at ebb tide (from north to south) and combine two 5th order channels into a 6th order channel that will then be connected to Steamboat Slough at the east end of the south cross dike.

The PSNERP Conceptual design calls out these ditches as 3rd order channels, which likely is a byproduct of the incomplete development of the marsh channel network (in response to the unexpected levee breaches) at the time the conceptual design was developed. Since that time, the reed canary grass pasture lands and open water areas have converted to tide flats and cattail marsh, allowing for a dense dendritic network to form, increasing the stream order.

The 4th order channel called out in the PSNERP full restoration plan that extends 2/3 of the restoration site is proposed to be excavated to elevation -4. This channel connects to a proposed 164 feet wide levee breach constructed to elevation -8 where it connects to Union

Slough. The levee is breached already at this location in three places, with a total width of roughly 60 feet at low tide, and 330 feet at high tide. Due to the existing drainage network, it is unclear if this channel could be sustained without significant alterations to the adjacent ditches as the established drainage network redirects flow away from this outlet to the main breach channel and the outlet to Union Slough where the existing tide gate is located. The existing drainage area tributary to this breach at low tide is only 10 acres, however at high flow the acreage contributing water to Union Slough at this location is at least an order of magnitude greater.

Shoreline crest topographic analysis

The crest (high point) elevation of the island shorelines was profiled in GIS to better understand the spatial extents of remnant natural shoreline and the extents of modified shoreline to help identify target top elevations for degraded levees. Review of the profiles indicated that unmodified shoreline areas have a south to north dip in elevation from about elevation 12 to 9.5 feet NAVD 88 (WSE ref line in Figure 41 and Figure 42). Ground elevations within 1 foot of this reference line are assumed to be under tidal influence (blue dots) and ground elevations above this reference line are assumed to be upland/riparian (grey dots). MLLW and MHHW tidal datums were plotted for reference.

The island wetted perimeter measured at the mean tide elevation is 24,456 feet. The total shoreline length along Union Slough (measured from the south to north tip of the island) is 11,942 feet. Because the ground elevation along the shoreline crest is very uneven, the undulating crest has a total length of 17,500 feet. The average shoreline crest elevations in the upland zone along Union Slough is 16.4 feet. In the intertidal zone the average shoreline crest elevation is 9.3 feet along the Union Slough. Along the shoreline crest 8 breach channels are present, with 5 located in the project footprint. 22% of the shoreline along Union Slough is within the intertidal zone, the remainder (78%) in the upland zone.

The total shoreline length along Steamboat Slough Is 12,514 feet. Because the ground elevation along the shoreline crest is very uneven, this results in an undulating crest with a total length of 18,300 feet. Average upland elevations along Steamboat Slough are 15.2 feet. In the tidal zone average elevations are 9.3 feet along the Steamboat Slough shoreline crest. A total of 7 distinct breaches are present. 35% of the shoreline along Steamboat Slough is within the apparent intertidal zone, the remainder (65%) in the upland zone.

The Otter Island (reference site) shoreline crest profile, measured starting at the south end, and clockwise along the island perimeter, is shown below in Figure 43. Elevations that are less than the tidal MHHW datum but greater than the tidal mean tide are highlighted in blue. Data that are less than MTL are highlighted in orange. Data that are higher than MHHW are highlighted in grey. Statistics for all the data greater than MHHW (presumably upland) indicate the average shoreline height is 9.6 feet (roughly 0.5 feet higher than MHHW). This elevation is a good target for levee lowering height at the north end of Spencer Island and should grade upstream to reflect the influence of the increasing hydraulic grade line elevation. The average elevation of the non-channel portions of the island is slightly higher than the average crest elevation that includes portions of the tidal channels (9.3 feet). Approximately 85% of Otter Island perimeter is above the MHHW elevation (9.0 feet) but only slightly, which suggests that the natural crest elevation of the island is strongly tied to the MHHW elevation., Notably if a 9.5 foot reference plane is used to delineate tidal from upland, 68% of the island is below elevation 9.5, and 32% above. Otter Island has about twice the shoreline length as Spencer Island below the tidal reference plane along Steamboat Slough, and 3 times the length along Union Slough, which is an indicator of impairment for channel connectivity during high tide and fluvial flooding.

The frequency of channels bisecting the crest of Otter Island (more than 30) is approximately three times higher than at Spencer Island (roughly 10). Most channels along the perimeter of Otter Island have invert elevations above mean tide level which suggests that fish use would be concentrated during high tides. The largest tidal channel present has an invert elevation about equal to the MLLW datum plane which indicates fish use is likely continual. The significantly higher average crest elevation (6 to 7 feet) and reduced frequency of channels that connect the island interior are indicators of impairment (limited fish access, hydrologic disconnection). It should be noted that Steamboat slough shoreline crest elevations along the north end of Spencer Island are very similar to those observed at Otter Island indicating this portion of Spencer Island does not appear to have undergone significant subsidence.

Another significant difference between the Spencer Island channels and Otter channels is the higher overall invert elevation (for Otter Island). This is likely due to the greater frequency of channels to disperse flow, and has resulted in a higher overall island elevation (reduced tidal prism). This suggests that island deposition at Spencer Island and inclusion of multiple levee breaches will result in gradual infill of constructed channels and increasing island elevation with time, until an equilibrium condition is reached.

There is substantial variability in the shoreline crest elevation along Otter Island, likely a result of woody material deposition and vegetation influence. This suggests a hummocky surface should be considered in grading plans for degraded levees and disposal areas.

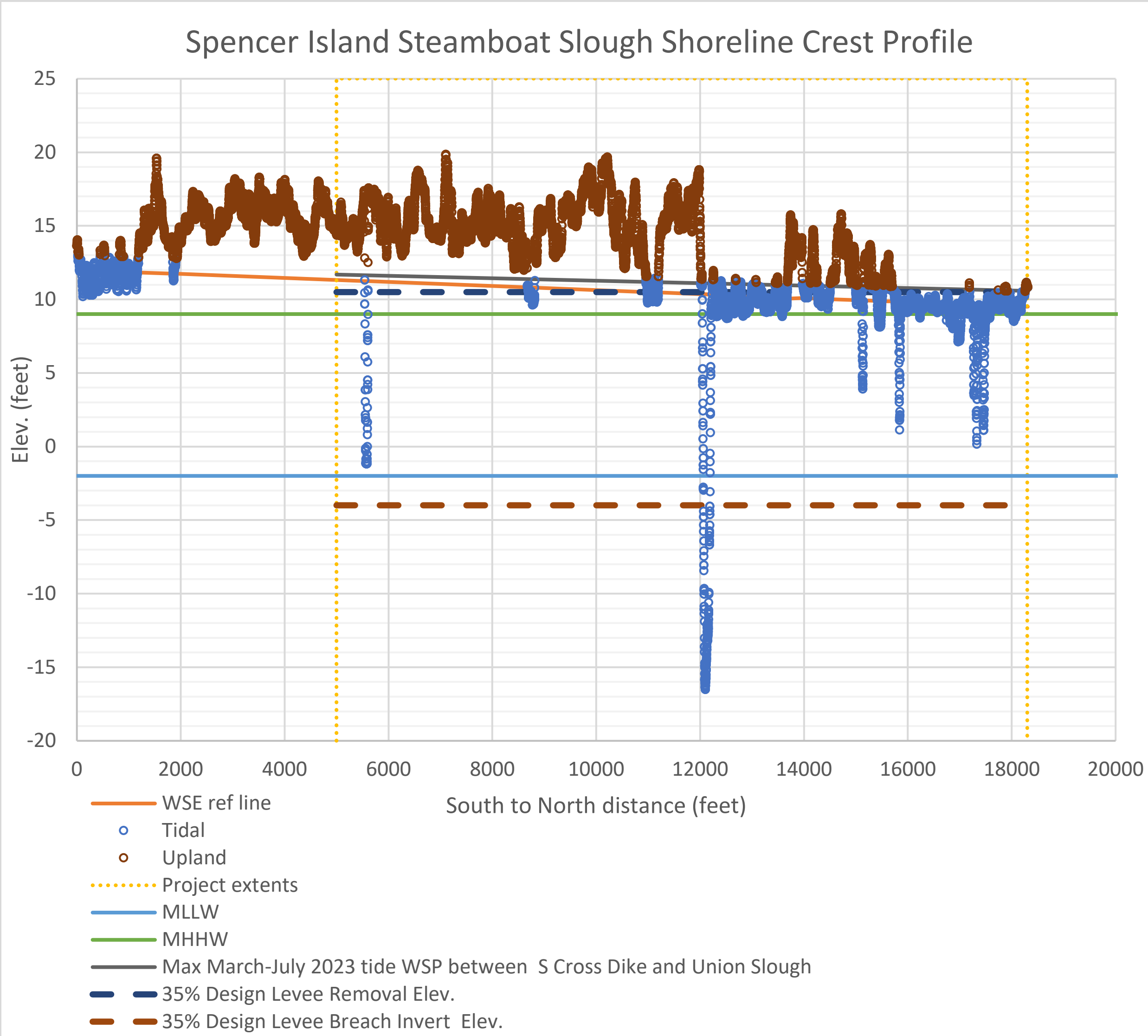

Figure 42. Spencer Island shoreline crest elevation profiles south to north along Union Slough

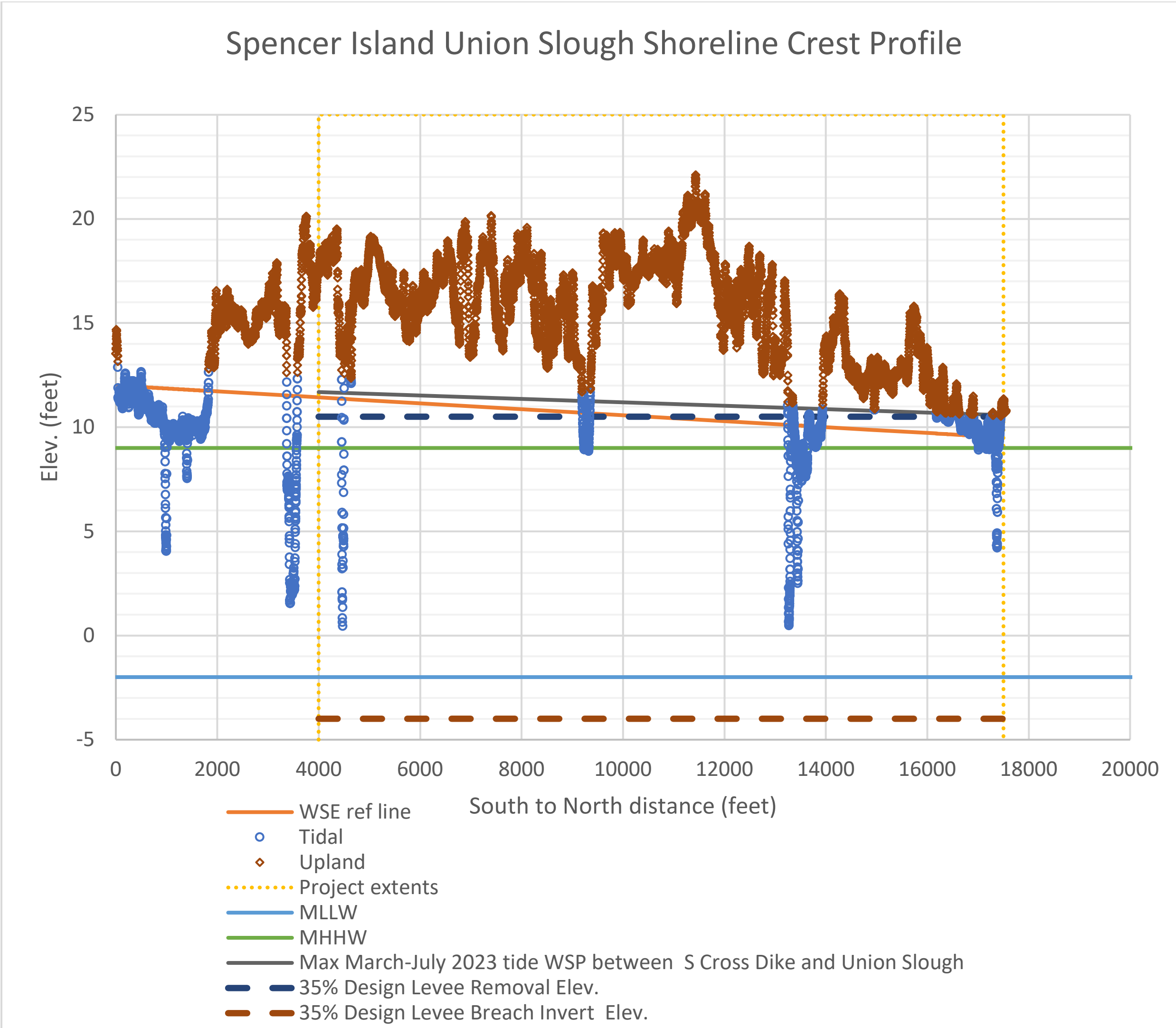

Figure 43. Spencer Island shoreline crest elevation profiles south to north along Union Slough (top) and along Steamboat Slough

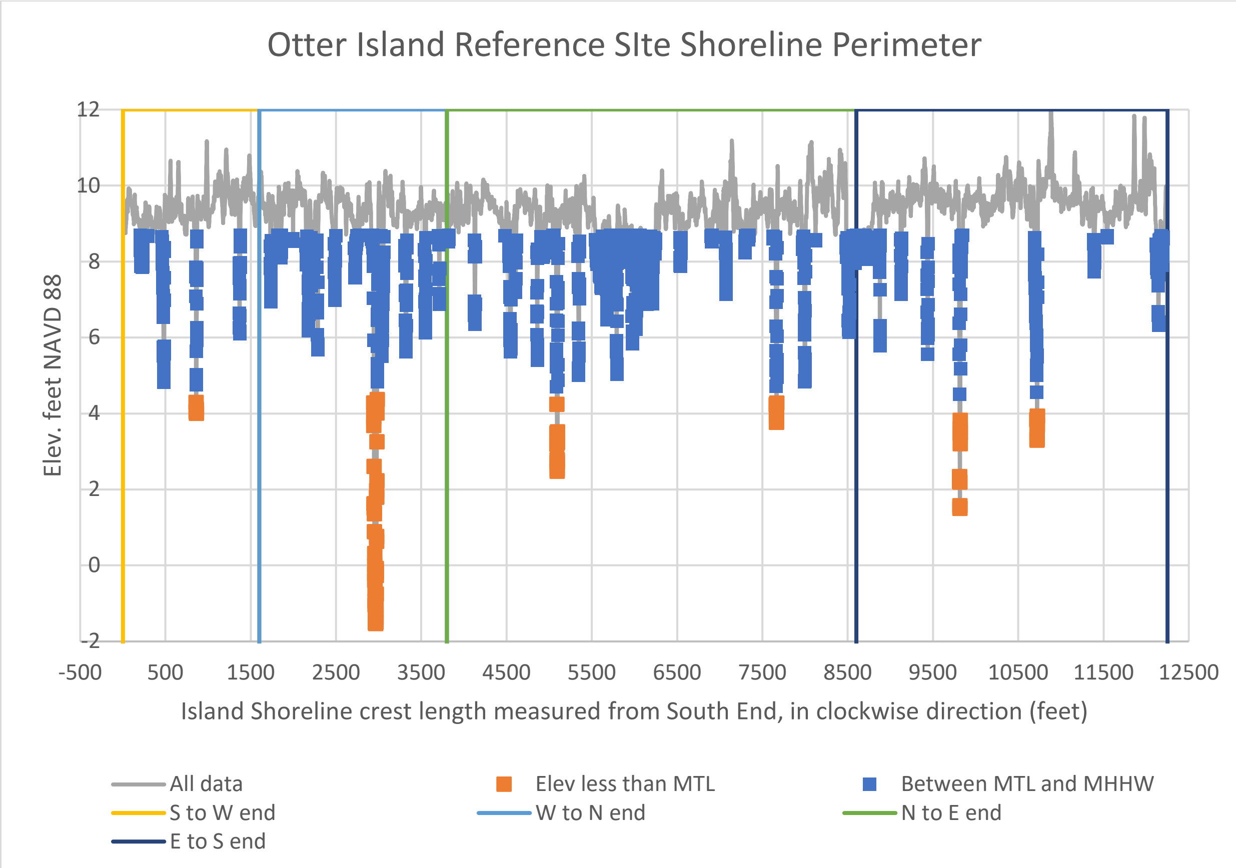

Figure 44. Otter Island shoreline crest elevation profile

Bare earth and first return lidar interpretations

First return lidar (digital surface model) and bare earth lidar (digital elevation model) were compared to understand the potential bias in lidar elevations caused by vegetation (influences accuracy of grading plans), to understand vegetation heights and cover in various locations at Otter Island and Spencer Island (influence of elevation on plant community).

From inspection of the Otter Island site, heights of vegetation are generally greater than 1 foot above the bare earth (derived) surface. Many shrubs and trees on Otter Island exceed 20 feet in height. Open water areas generally have very small differences in elevation between the first return and bare earth DEMs. Open water areas on Otter Island represent a small portion of the island area.

From inspection of the Spencer Island relative height map and lidar DEM (Figure 46), heights of vegetation are generally less than 1 foot above the bare earth (derived) surface. Few shrubs and trees on Spencer Island exceed 20 feet in height. Those that do are located on levees or the shoreline. Open water areas generally have very small differences in elevation between the first return and bare earth DEMs. Open water areas on Spencer Island are extensive and represent a much larger portion of the overall island area as compared with the reference site. The lower overall vegetation height and greater proportion of open water areas are attributed to historical agricultural practices and island subsidence which increases inundation frequency and suppresses vegetation growth.

Inspection of the bare earth lidar and aerial imagery indicates an abrupt transition in land cover above and below elevation 5.5 feet. Below elevation 5.5 feet the bare earth lidar is smooth and subject to erosion from tidal flux and fluvial flooding, vegetation is sparse to nonexistent, and elevations closely match the first return lidar data, confirming an absence of vegetation visible in air photos. Above elevation 5.5 first return data are higher and the surface of the bare earth data is rough due to the presence of vegetation. The areas that are vegetated but subject to daily tidal inundation are dominated by cattails or inundation tolerant grasses. The island area below elevation 5.5 feet is 140 acres, or 33% of the total island area. The Otter Island site has an average elevation above MHHW and is dominated by upland/riparian/scrub shrub vegetation, with less than 10% of the island below elev. 5.5 feet. The difference in land cover between Spencer Island and the reference site is due to historical land use (farming and subsidence), and higher tidal inundation frequency and depth. This is evident from the similarity in elevation and land cover of the north and south tips of Spencer Island to Otter Island. The north and south tips of Spencer Island are outboard of historical levees, and do not appear to have undergone substantial subsidence. Thus, a potential restoration approach would be to increase the average elevation of Spencer Island through natural deposition over time as a result of diverting more sediment laden floodwaters into the site, or through direct sediment placement to force a transition of the landcover from open water/tideflat/cattail marsh to a more upland dominated, scrub/shrub/riparian wetlands. Another notable takeaway from Figure 46 is the widespread subsidence present throughout developed areas of Smith Island and Ebey Island.

Relict channels are present within the developed portion of Spencer Island however ditch construction, historical disturbance, and vegetation growth prevent use of the available topo data to inform restoration metrics such as constructed side slopes and widths for proposed tidal channels, degraded levees, or disposal areas. From available lidar data (Figure 46) it is evident that that the entire shoreline of Spencer Island (where levees are not present) is higher than the island interior suggesting either natural levees are present along the island perimeter, or there has been differential settlement. Several nearby relict tidal channels are present on Ebey Island that appear to have natural levees formed by sediment deposition and vegetation growth along the lengths of the channels, with the height of the natural levee directly correlated with proximity to the distributary connection and width of the relict tidal channel.

Ebey Island, like all other developed islands in the estuary, has undergone subsidence of several feet in elevation. Assuming the subsidence experienced at Ebey Island is uniform, the landward slopes of natural levees along the relict channels provide a convenient analog for designing finished slopes for degraded levees and disposal areas constructed at Spencer Island. The average slope for six locations along two transects is +/- 0.011 feet per foot (1.1%). Natural levee heights generally range between 1 and 5 feet, which also provides a range for heights of constructed disposal areas at Spencer Island.

During feasibility design development, the perimeter ditches along levees were assumed to have high enough habitat quality or utility for conveying flow into the island interior that preservation of the ditches would be preferable to filling them with levee spoils. This tradeoff is being evaluated by the PDT and sponsor and may result in a shift in design approach from building discrete disposal areas (habitat islands) toward building up natural levees along the island shoreline and constructed channels.

Note that relict streambank slopes at the profiled channels range from 1.67 H:V to 5.75 H:V with an average of about 3H:1V. Proposed breach side slopes are 4H:1V which suggests constructed channels could be narrowed.

Sinuosity, depth, and width characteristics for relict channels on Ebey Island could be used to refine the proposed breaches and constructed channels at Spencer Island, however Ebey Island is substantially larger than Spencer Island, the developed conditions of Ebey Island obscure locations of historical lower order channels. This implys that the channel order of relict channels may not be analogous, which limits the value of directly applying measured channel characteristics. Other locations in the estuary could be better for developing analog data to help refine designs. USACE will consult the project sponsor and TAG on best available guidance for refining the design of constructed channels in PED.

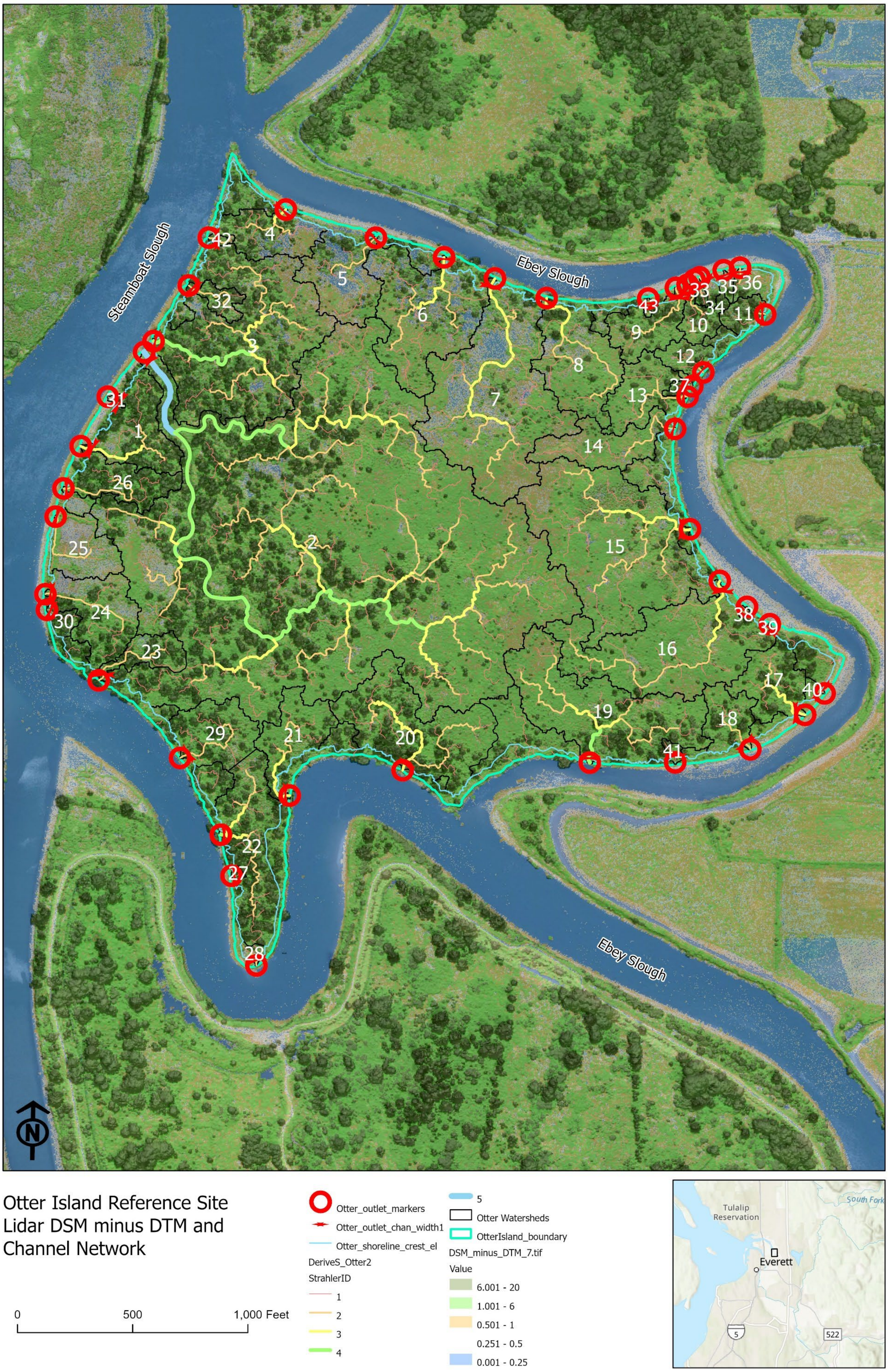

Figure 45. Otter Island reference site, relative height map (shows difference between first return and bare earth lidar) which gives indication of vegetation height above bare earth Lidar

Figure 46. Spencer Island existing conditions relative height map (shows difference between first return and bare earth lidar) which gives indication of vegetation height above bare earth Lidar

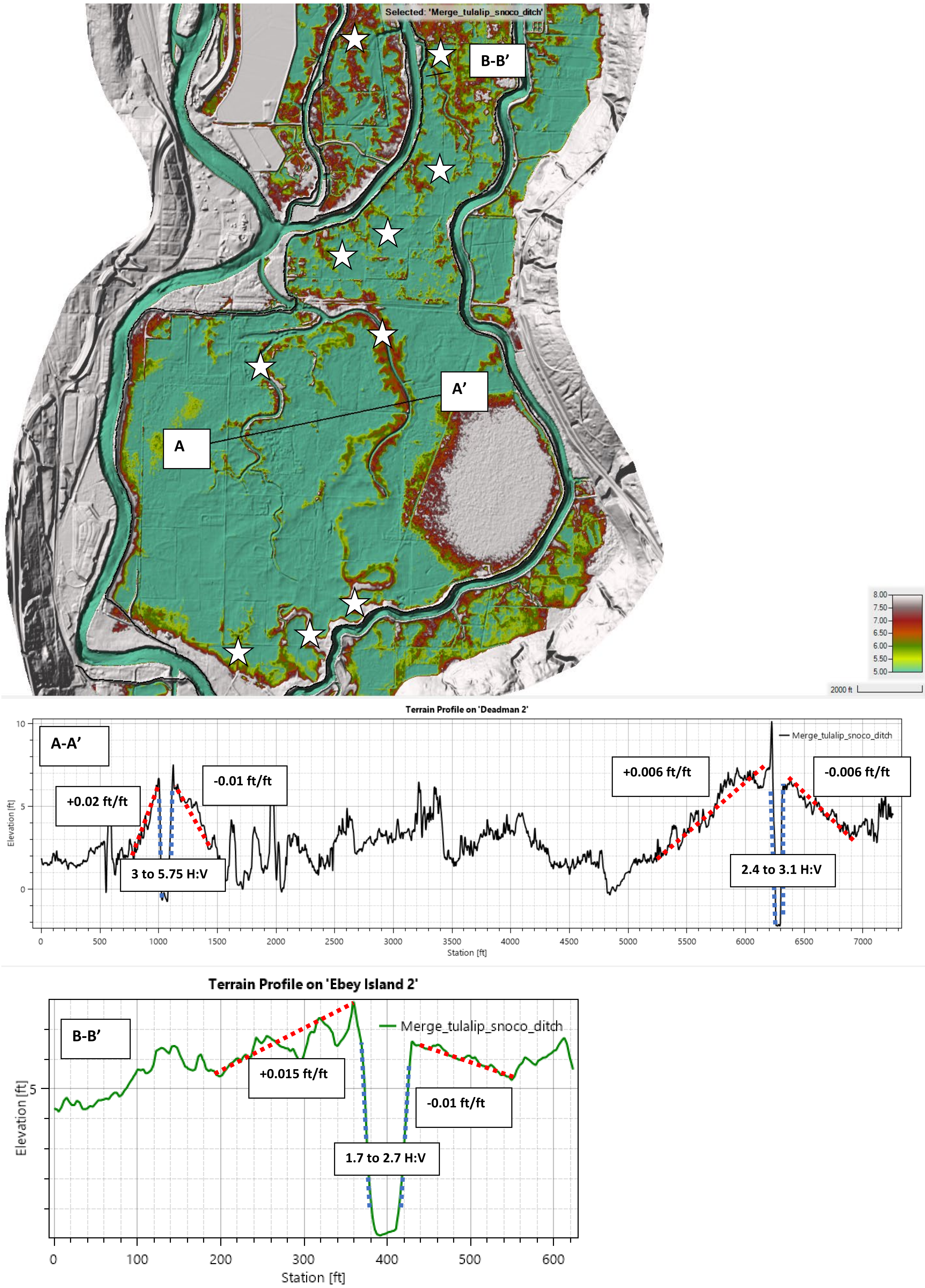

Figure 47. Evaluation of relict tidal channel and natural levee slopes on Ebey Island

Note that starred locations represent relict channel locations.

5. Spencer Island Tidal Marsh Allometry Analysis

Overview

Scientific research on Puget Sound tidal marshes focused on providing guidance for restoration (Hood 2015A, 2015B, 2022) has documented scaling of tidal channels (number and size) contained within tidal marshes based on the island area connected to delta distributary channels as well as the role (or lack thereof) of large wood in tidal delta marshes. The scaling relationships identified by Hood (allometry) vary between estuaries due to tidal range and other factors (waves, fluvial flows, sediment). Tidal channel size scales positively with marsh area and negatively with wave energy. As part of this work river deltas in Puget Sound including the Snohomish were evaluated providing a valuable local data set.

Using data for river delta tidal marshes throughout Puget Sound, Hood developed allometric models through multiple linear regression that predict the most likely number and size of tidal channels that could develop following salt marsh restoration through dike removal and reconnection with the adjacent distributary channels. This approach is a significant improvement over previous San Francisco Bay regression-based approaches that were extended to Puget Sound in the late 1990s. This approach utilized single large breaches to drain the tidal flux of entire tidal marshes. Experience gained at Union Slough and Qwulloolt marsh restoration projects (based on this previous restoration approach) and based on current conditions at Spencer Island highlight the impaired conditions resulting from connecting subsided marshlands to distributaries through an insufficient number of outlet channels. This feedback was relayed by members of the project Technical Advisory Group (TAG) to USACE and the Corps in the fact-finding phase of the project, which led to the shift to the Hood approach for identifying marsh restoration metrics.

Restoration metrics that utilize allometry data include the potential dimensions of the primary connection (largest marsh island channel connected to a distributary) and the total number of channel outlets based on marsh island area. Projects that reconnect marsh island to distributaries should do so in a way that is restorative for the biota that are present. For tidal marshes in Puget Sound, tidal marshes are essential for sustaining the food web and healthy populations of a plethora of species. Juvenile salmon present in the Snohomish River delta that use the marsh channels are expected to be one of the primary beneficiaries of restoration.

Restoration of the Snohomish River delta and estuary is focused on removal of existing infrastructure that directly displaces tidal marsh habitat and disconnects the tidal channel and river distributary channel network, degrading natural processes and associated habitats.

Tidal channel allometric analysis

The Spencer Island remnant levees (dikes) fill in what was historically tidal marsh/palustrine (freshwater tidal) wetlands. The combination of subsided tidal marsh within the middle of the island, the well-developed dike breach along Steamboat Slough and the remnant levees, portions of which are several feet above the high tide line, limit tidal exchange to a few channels, resulting in unnaturally high velocities, and significantly limiting the exchange of sediment wood and nutrients with the island during major floods. Removal of the dikes and addition of additional breaches and channels will help accelerate reconnection of the degraded marsh island to the distributary channels and estuary and restore associated natural processes.

The Hood (2015A) allometric regression parameters and equations for the Snohomish delta were used for the entire island area (426 acres, 144 hectares). The mean prediction (Y) for outlet counts is 50 channels, with a 95% confidence limit of 9 to 271 connections, with the largest channel having a predicted outlet width of 29 meters (roughly 100 feet) and a length (wetted perimeter at mean tide elevation divided by 2) of 8,890 m. The predicted wetted inundation area of the largest outlet channel is 2.2 ha, with the total island channel inundation area of 7.2 ha. The total connected island channel length is estimated to be 38,650 m, comprising 331 first order channels (and the remainder of the higher order network).

Table 10. Hood regression allometric predictors for Spencer Island

		Regression parameters			**Outputs**				
Metric	**Reference Site**	**a**	**b**	**X**	**Y**	**upper 95% CL**	**lower 95% CL**	**Existing**	**Proposed (35%)**
Outlet count	Snohomish	0.394	0.61	138.7	**50**	271	9	**31**	**44**
Total length (m)	Snohomish	1.931	1.24	138.7	**38647**	382306	3907	**27408**	**29560**
Total area (ha)	Snohomish	-2.398	1.52	138.7	**7**	99	0.5	**34**	**35**
Largest length (m)	Snohomish	1.657	1.07	138.7	**8891**	139506	567	**160**	**1909**
Largest area (ha)	Snohomish	-2.66	1.4	138.7	**2**	23	0.2	**0.6**	**8.5**
Largest outlet width (m)	Snohomish	-0.33	0.84	138.7	**29**	174	5.0	**44**	**44**

The existing island has at least 31 connections, however, only 12 of the 31 identified connected channels extend through the island crest into the interior of the island, the remainder are draining small catchments present between the existing levees and the adjacent sloughs. The proposed (35%) design adds 13 new outlets, getting the island much closer to Hood's linear regression prediction for outlet number. The total length of channels on Spencer Island is less than the regression prediction, possibly due to presence of ditches that short circuit the marsh drainage network, loss of historical channels, and incomplete development of the marsh channel network post-levee breach. The total area (wetted, measured at mean tide) represents 24% of the island area - this is nearly 5 times greater than the regression prediction (5%) due to several feet of subsidence, which has resulted in substantial inundation at low tide. Restoration does not significantly alter this condition but provides substantially more opportunity for sediment and large woody material to deposit within the island. Combined with side casting of spoils along constructed channels the site will more closely resemble reference conditions after construction.

The largest connection for existing conditions is formed by a 7th order channel that drains 277 acres, more than half of the island area, which explains the extremely deep scour hole at its connection with Steamboat Slough. This channel is very short (160 m), wider than the regression prediction by about 50% and is fed by two long 6th order channels that span the north and south ends of the island. Restoration breaks up the existing drainage network, resulting in a single large 6th order channel draining to the location where the 7th order channel is presently located. This is expected to redistribute daily tidal flux to reduce excessive velocities near the outlets believed to be hindering fish use. Reordering of the network results in a the largest channel becoming much larger than the existing 7th order channel, but still about 4 times less than the regression.

Channel outlet data for Spencer Island existing conditions (Table 7), Proposed conditions (Table 8), and the Otter Island reference site (Table 9) were evaluated using a similar allometric approach as Hood to investigate how restoration metrics like outlet channel width, outlet invert elevation, connected channel length can be predicted by drainage area or outlet channel order.

Figure 48 below compares outlet width to the upstream drainage area and Figure 49 provides ranges for measured or estimated channel widths vs. the outlet channel stream order. Channel width increases exponentially with stream order (a surrogate for geometric increases in the flow conveyed in the channel network) with the strongest regression associated with the project area. Widths vary considerably for the same order channel suggesting that stream order is not strongly predictive metric but is useful as a check on reasonableness of restoration channel widths. Variations in channel size within the same channel order reflect the stochastic influences of Inclusion of nearby reference sites could increase the strength of this regression and provide better insights on equilibrium conditions for channel design. Note that widths of channels at junctions within the marsh can be measured to increase the size of the data set and improve the regression. Note that the width measurements are obscured by the presence of vegetation and the DEM resolution, especially for small channels. Estimated error in width estimates is ± 6 feet.

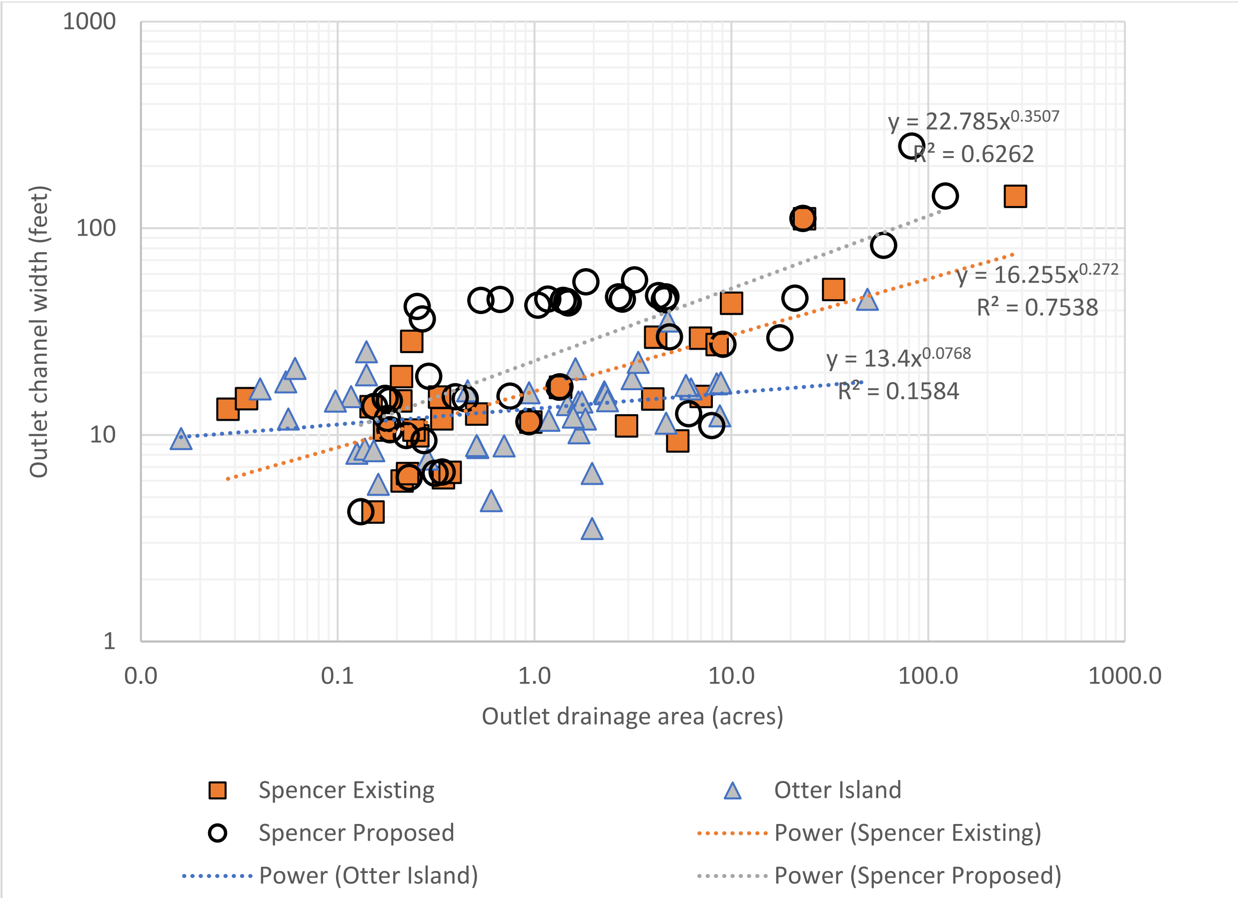

Figure 48. Spencer Island and Otter Island outlet watershed area at low tide vs. outlet channel width

The above plot shows the connection outlet width vs. the drainage area tributary to the outlet. The linear relationship between drainage area and outlet width is consistent with the regression with stream order. From inspection it does appear that the project site has more small channels (in area) relative to the north or south ends of the site, due to the presence of levees and small number of levee breaches. The widths of these channels are highly variable suggesting that several of these are disconnected higher order channels. Note that the disconnection can be a result of the levees and/or the short circuiting of the drainage network caused by the ditches. Note that the reference site regression line (r^2 = 0.15) does not appear to provide useful data for design of the restoration site. The scatter in the width and marsh area could be a result of natural processes such as channel abandonment.

While use of GIS delineations of marsh drainage area could provide some rationale for sizing down the levee breaches, these channels also convey tidal flux and river flow across the island which suggests that they should be oversized to accommodate uncertainties in how much flow will be conveyed (to prevent hindering connectivity due to undersized channels).

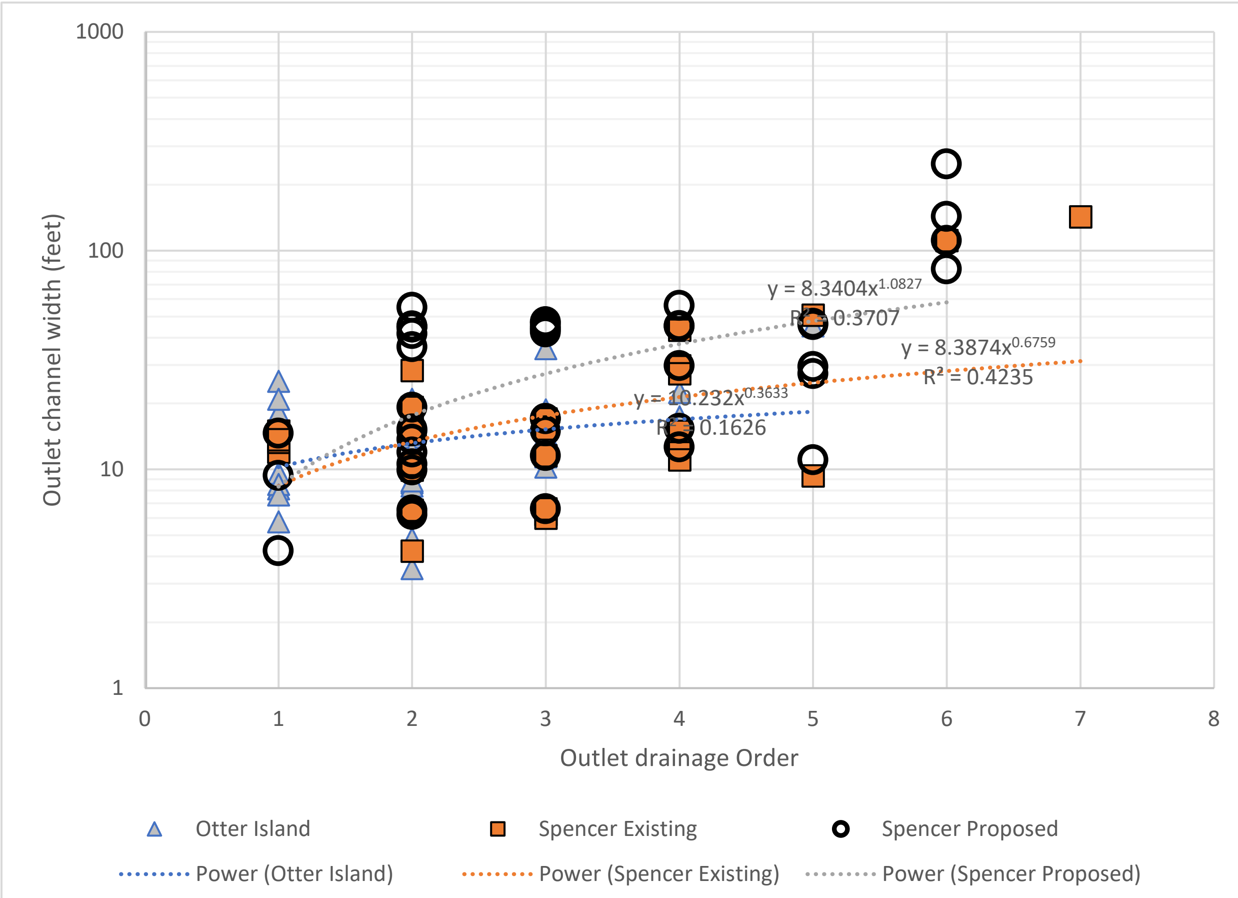

Figure 49. Spencer Island and Otter Island outlet channel stream order vs. width at mean tide

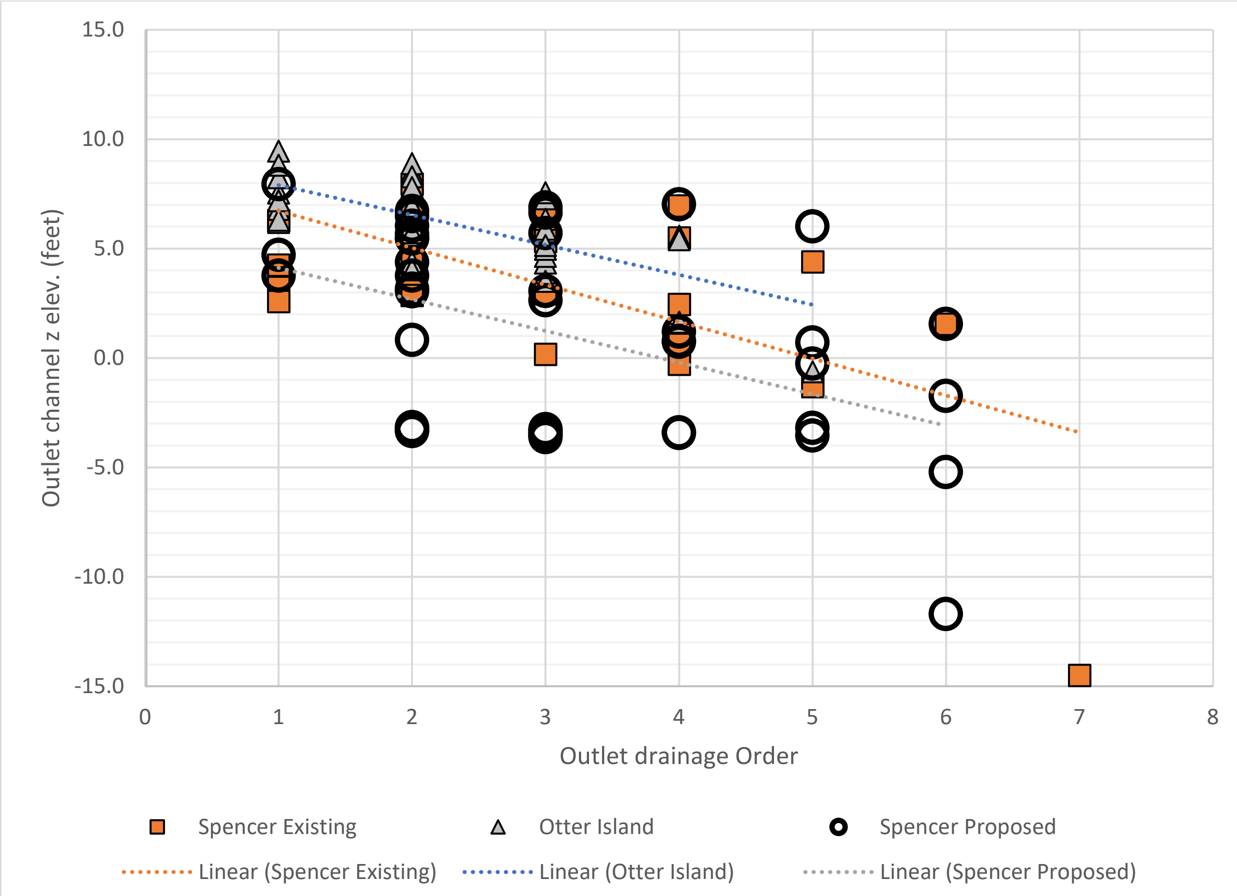

Figure 50 Spencer Island and Otter Island outlet channel stream order vs. outlet channel elevation

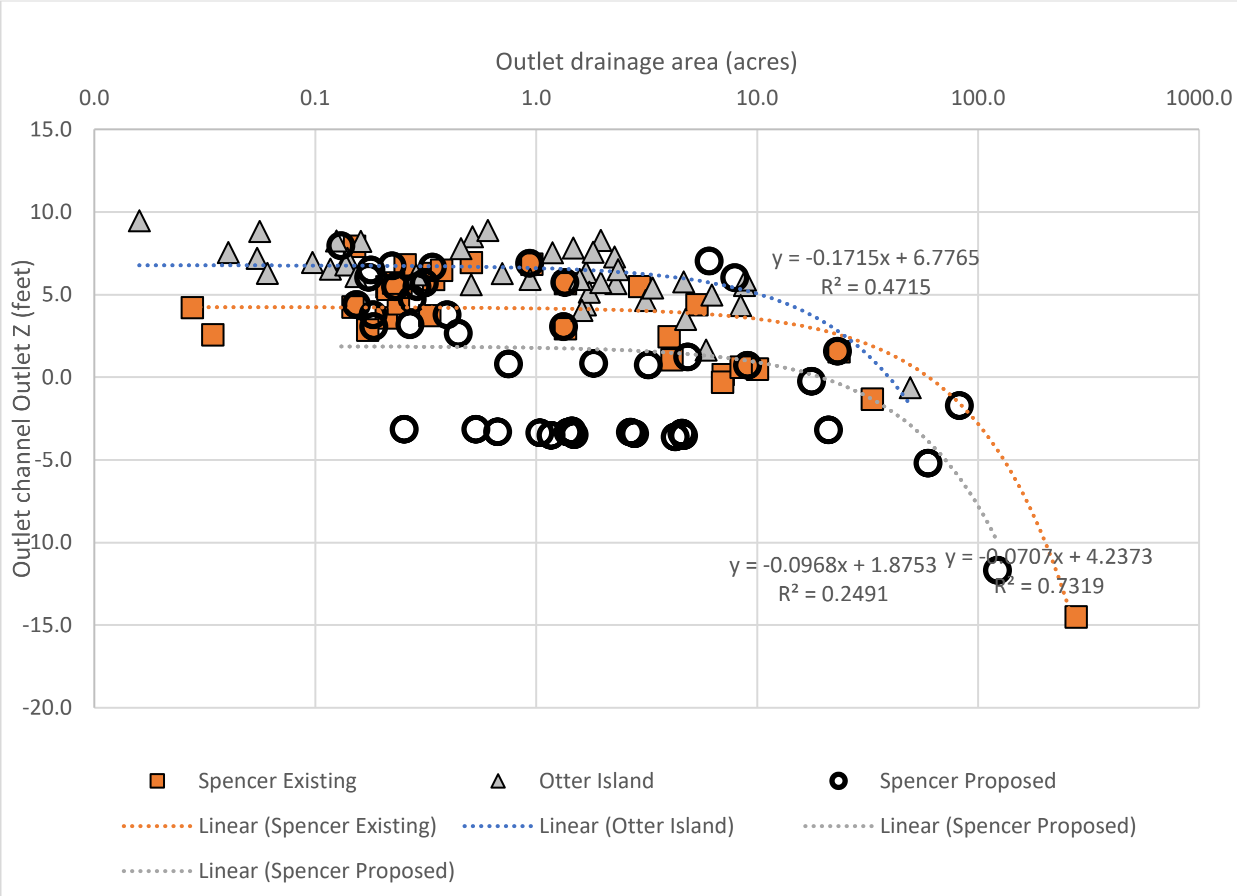

Figure 51. Spencer Island and Otter Island outlet drainage area vs. outlet channel elevation

The above plot provides ranges for channel outlet elevations based on the stream order of the channel draining the marsh. Channel outlet invert elevation decreases with increasing stream order (a surrogate for geometric increases in the flow conveyed in the channel network) with the strongest relationship associated with the project area. Invert elevations vary considerably for the same order channel suggesting that stream order is not strongly predictive metric but is useful as a check on reasonableness of restoration channel invert elevations. Note that the lower depths for second order channels in the project area are likely a result of disconnection of what were higher order channels prior to levee construction. Inclusion of nearby reference sites could increase the strength of this regression and provide better insights on equilibrium conditions for channel design. Note that the above elevations are extracted where the width was measured, invert elevations drop off riverward of this transect.

The largest channel draining the project site has a width that is 1.3 times wider than the next largest channel draining the island despite the fact that the drainage area is 8.4 times greater. This is a result of the engineered channel at the south end of the island that is connected to Union Slough being over-sized. As-built elevations for this channel are – 4 feet. Current bed elevations are several feet higher (1.5 feet).

Adding more breach connections along Steamboat and Union Sloughs in association with ditch blocking would redistribute tidal prism (flux) into more outlet channels and reduce the area tributary to the largest outlet, helping normalize velocities and hydraulic conditions at that location. The above curves can be used to check reasonableness of sizes for new breach channels.

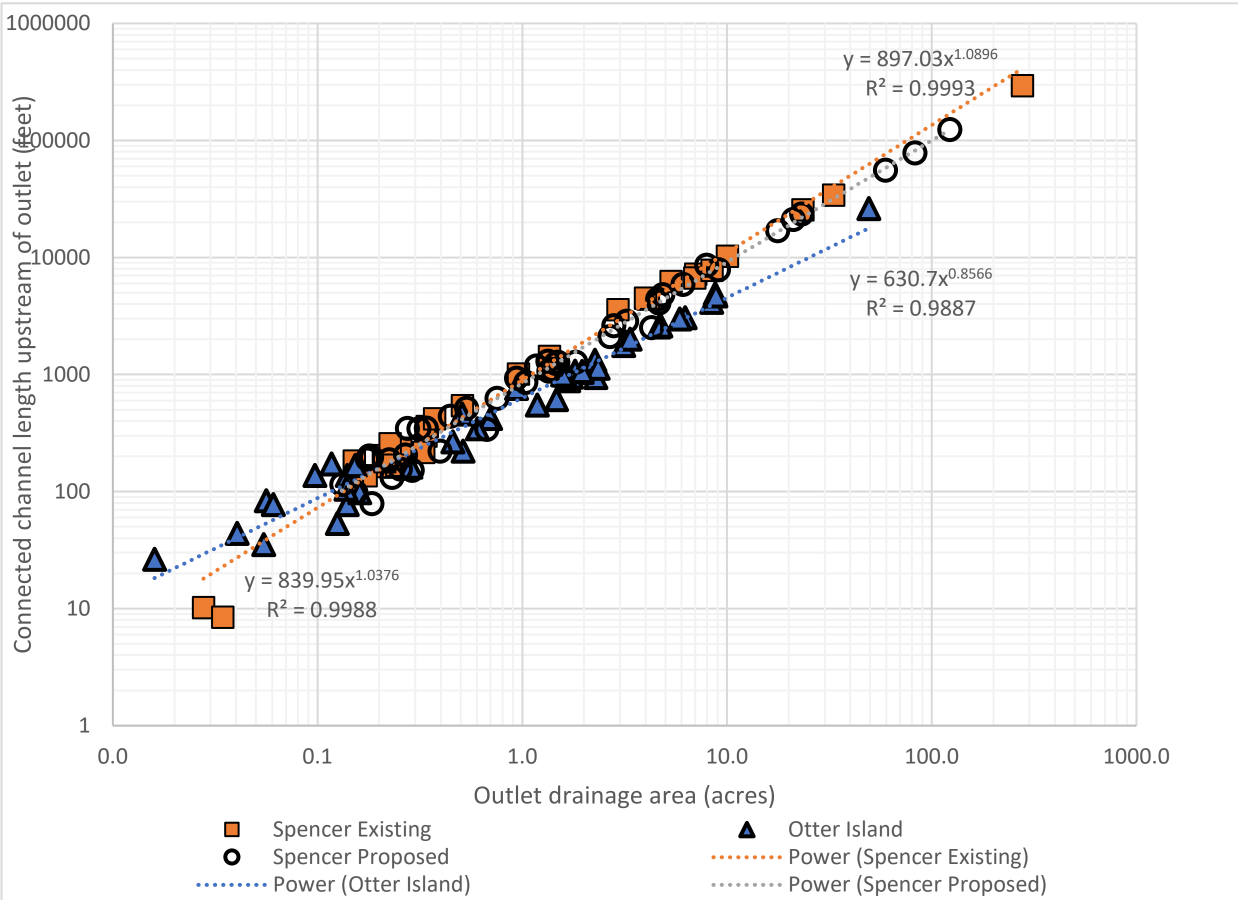

Figure 52. Spencer Island and Otter Island outlet watershed area at low tide vs. total length of all channels connected to outlet

The above plot shows the total connected channel length upstream of an outlet vs. the drainage area tributary to the outlet. The strongly linear relationship between area and connected channel length indicates that marsh channel network is very well established and that the density of channels within a watershed area does not vary significantly across the island. From inspection it does appear that the project site has more small channels (in length and area) relative to the north or south ends of the site, due to the presence of levees and small number of levee breaches.

The largest channel draining the project site has 8.6 times more tributary channel length at low tide than the next largest channel draining the island and 8.4 times the drainage area. It is likely this outlet channel is an outlier relative to other marshes in the estuary and also suggests flows are overly concentrated in the primary breach, which could explain widespread ongoing erosion in the vicinity.

Adding more breach connections along Steamboat and Union Sloughs in association with ditch blocking would redistribute tidal prism (flux) into more channels (increasing length and drainage area of connected channels) and reduce the channel length and area tributary to the largest outlet, helping normalize velocities and hydraulic conditions at that location.

Outlet spacing analysis

Hood's paper (2015B) on number, orientation and spacing of dike breaches for Puget Sound tidal marshes was prepared to provide guidance for designing tidal marsh restoration projects and includes Snohomish specific data which can be compared to data for existing and proposed conditions at Spencer Island. As shown in Table 11 the total shoreline length for this portion of the site is 24,456 ft which results in an outlet channel spacing of 789 ft (241 m) between outlets. Outlet spacing is greater along Steamboat Slough (1,38 feet, 347 m) than Union Slough (878 ft, 268 m). With restoration this spacing would decrease to 521 ft (159 m) along Steamboat Slough, and 878 ft (268 m) along Union Slough. The Otter Island reference site has an outlet spacing of 285 ft (87 m) about half that of the restored conditions at Spencer Island. While these data suggest the outlet spacing is less than desired, plotting these data on top of Hood's suggests the restored outlet spacing would fall along the upper best fit line.

Table 11. Shoreline outlet spacing data

Shoreline	Configuration	Shoreline Length (lf)	# Connections	Spacing (lf/outlet)	Spacing (m/outlet)
Steamboat Slough	Existing	12,514	11	1,138	347
	35% Design	12,514	24	521	159
Union Slough	Existing	11,942	20	878	268
	35% Design	11,942	20	878	268
Entire Island	Existing	24,456	31	789	241
	35% Design	24,456	44	556	170
Otter Island	Existing	12,250	43	285	87

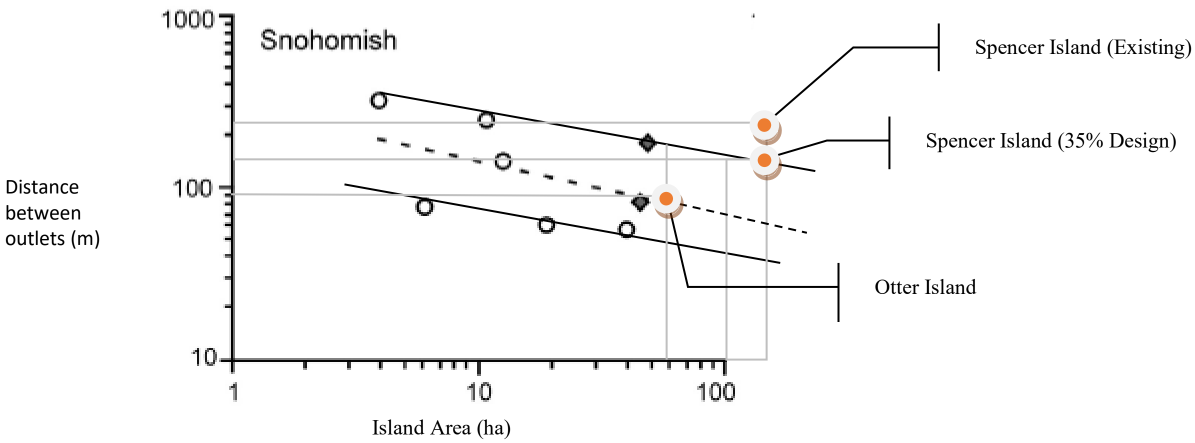

Figure 53. Excerpt from Hood (2015B) mean distance between outlet data for Snohomish delta overlaid with Spencer and Otter Island data.

6. USACE Hydrodynamic Modeling Results Discussion

Modeled inundation, water surface profiles, and velocities are shown in Annex D-2. To understand changes in velocities, and the potential for influence on geomorphic conditions, the present day 50% AEP (2-year), 10% AEP (10-year), and 1% AEP (100-year) river flood events were analyzed and discussed below.

As shown in Table 12 restoration does not significantly alter the flow distribution in the estuary during large river flows and as such is not likely to significantly alter geomorphic conditions and trends. There is a modeled 2.8% to 4.1% increase in peak flow in Union Slough, Steamboat Slough, and Ebey Slough for the 50% AEP and 10% AEP events, and a decrease of about 2% on the mainstem. Note that the mainstem conveys about 10 times the flow of Ebey Slough, 8 times the flow of Union Slough, and twice the flow of Steamboat Slough through the I-5 corridor for typical high flow events (or about 60% of all the flow in the river). When widespread levee overtopping occurs, more flow is conveyed across Ebey Island away from the mainstem and the flow distribution becomes more equal (mainstem conveys about 45% of all flow in the river). Restoration of Spencer Island appears to redirect about 2% of the flow in the mainstem for typical flood events to the other distributaries, and for very large (1%AEP and higher) about 1% or less. Based on these small changes in flood discharge, widespread or large scale changes in bed and bank conditions along the distributary channels is not expected but it appears possible that more sediment will be transported Union Slough and Steamboat Slough than presently occurs, and less on the mainstem.

Table 12. Snohomish River Peak flood magnitude and changes through the I-5 corridor

Scenario	50% AEP Peak Flow (cfs)			10% AEP Peak Flow (cfs)			1% AEP Peak Flow (cfs)		
Reach/Area	Proposed	Existing	% Difference	Proposed	Existing	% Difference	Proposed	Existing	% Difference
Snohomish Mainstem	42,440	43,370	-2.1%	50,160	51,150	-1.9%	92,740	93,590	-0.9%
Overland	-	-	N/A	-	-	N/A	620	420	47.6%
Union Slough	5,260	5,060	4.0%	6,310	6,060	4.1%	23,450	22,870	2.5%
Steamboat Slough	20,960	20,340	3.0%	24,910	24,150	3.1%	72,520	72,440	0.1%
Ebey Slough	4,350	4,230	2.8%	5,220	5,060	3.2%	17,420	17,430	-0.1%
Total Flow	73,010	73,000	0.0%	86,600	86,420	0.2%	206,750	206,750	0.0%

Changes in maximum computed velocity are shown in Figure 53 through Figure 55 below.

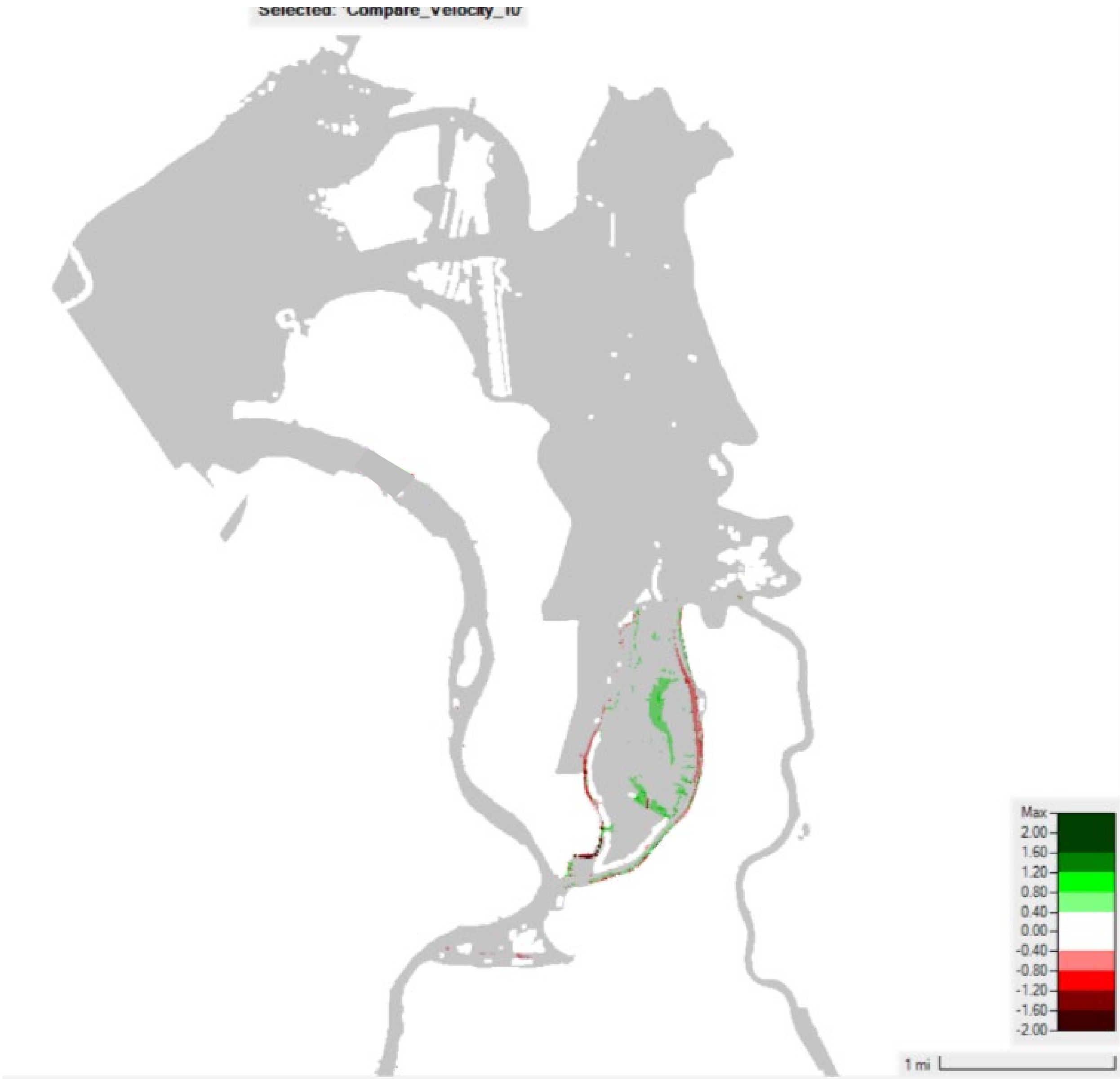

Figure 54. Modeled 50% AEP event velocity differences

In Figure 54 the major changes are a decrease in velocity in the upper portion of Union Slough (> 1ft/s), likely due to backwater effects from flow crossing Spencer Island to Smith Island. A small (< 1ft/s) increase in velocity in the upstream end of Steamboat Slough and increase across the island (~1 ft/s), and a decrease in velocities in Steamboat Slough in the middle of Spencer Island (< 1 ft/s). Velocity changes in excess of +/- 0.4 ft/s are restricted to the project footprint and immediate vicinity. Changes less this amount are shaded grey. The changes downstream at I-5 are likely spurious and related to small differences in the existing and with project model meshes, as flows in this location are decreased. This will be checked/refined in PED.

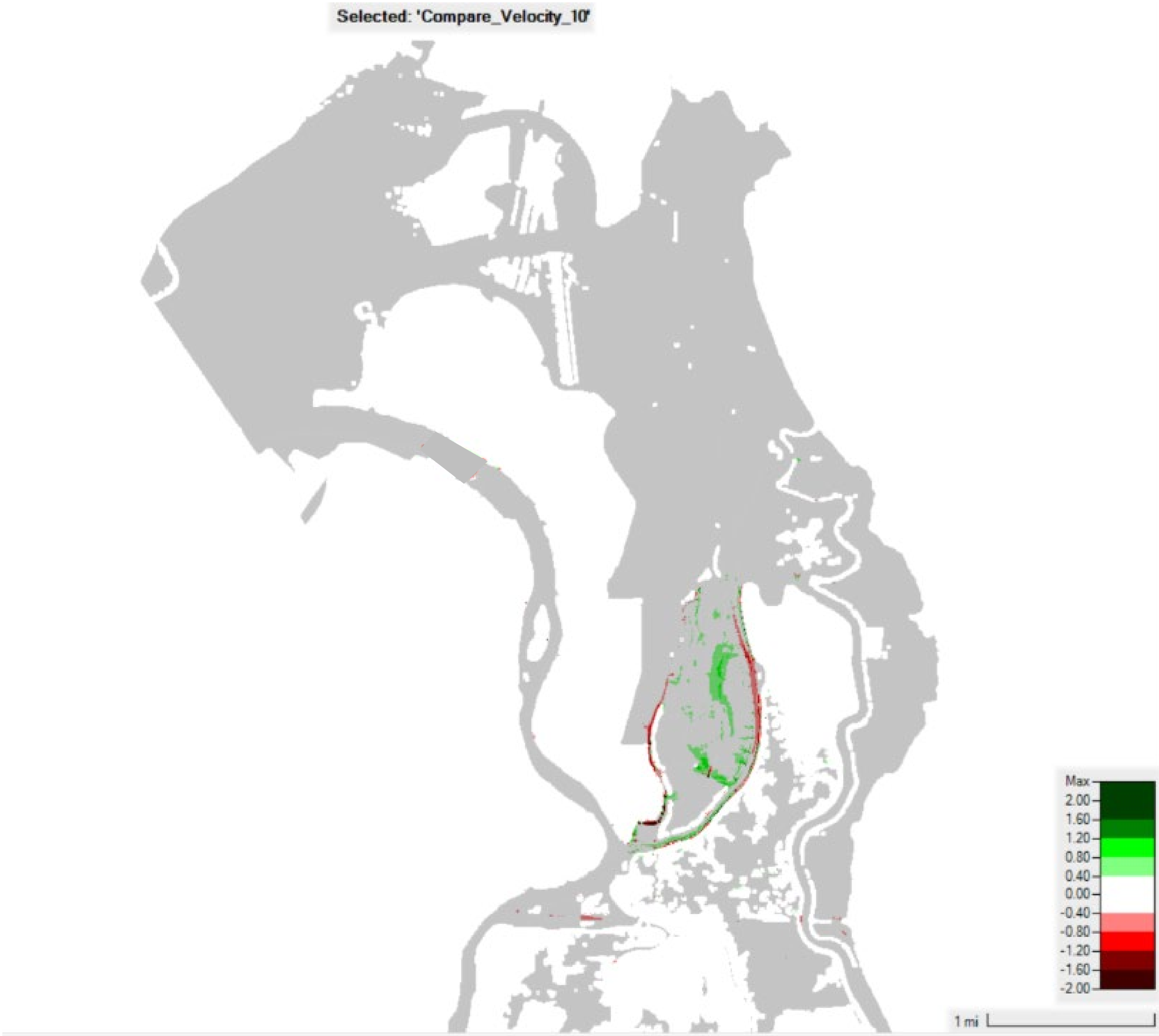

Figure 55. Modeled 10% AEP event velocity differences

In Figure 55 the major changes are a decrease in velocity in the upper portion of Union Slough (> 1.6 ft/s in places), likely due to backwater effects from flow crossing Spencer Island to Smith Island. A modest (~ 1ft/s) increase in velocity in the upstream end of Steamboat Slough (due to diversion of flow from the mainstem) and increase across the island (~1 ft/s), and a decrease in velocities in Steamboat Slough in the middle of Spencer Island (~ 1 ft/s). Velocity changes in excess of +/- 0.4 ft/s are restricted to the project footprint and immediate vicinity. The changes downstream at I-5 are likely spurious and related to small differences in the existing and with project model meshes, as flows in this location are decreased. This will be checked/refined in PED.

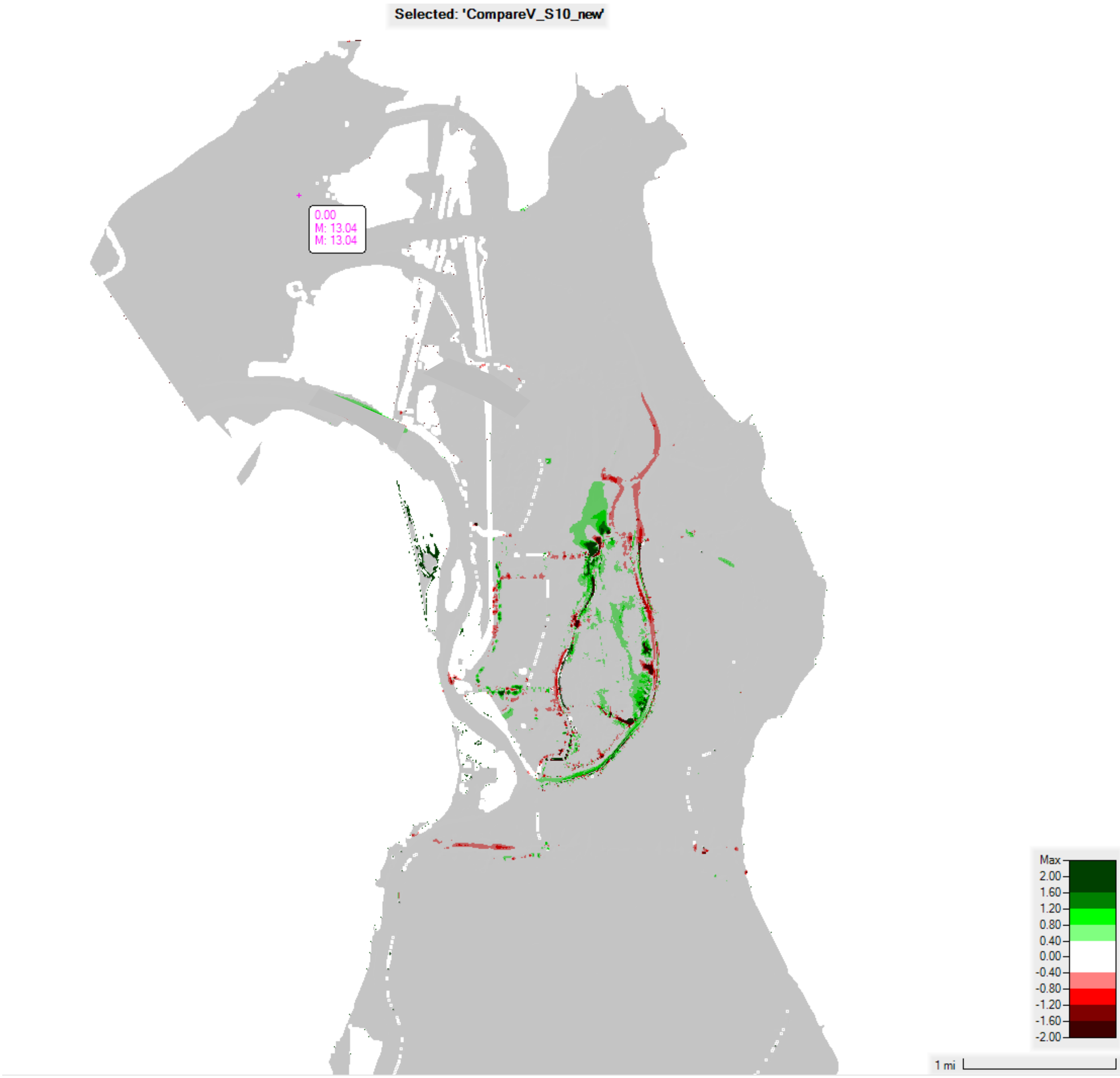

Figure 56. Modeled 1% AEP event velocity differences

In Figure 56 the major changes are a decrease in velocity in the upper portion of Union Slough (> 1.6 ft/s in places), likely due to backwater effects from flow crossing Spencer Island to Smith Island. A larger (> 1ft/s) increase in velocity is predicted for the upstream end of Steamboat Slough (due to diversion of flow from the mainstem) and increase across the island (>1 ft/s), and a decrease in velocities in Steamboat Slough near the middle of Spencer Island (> 2 ft/s). The largest change (increase > 2/ft/s) occurs on Smith Island at the entrance to the City of Everett ecosystem restoration project where an existing levee breach will be expanded to allow for floodwaters to pass unrestricted into the constructed wetland. While the increase is relatively large, the increase is a result of removal of high ground and conversion to flowage area. Note the expansion of the breach also reduces (normalizes) velocities at the entrance to the main tidal channel, which is beneficial for ecosystem processes. Velocity changes in excess of +/- 0.4 ft/s are largely restricted to the project footprint and immediate vicinity; however more widespread changes are observed than with smaller events.

There are lesser changes elsewhere which are due to local changes in the flow direction and conversion of high ground to floodplain, rather than a result of major changes in hydraulic conditions. suggests that deconstructed levees and channels at the southwest and northwest corners of the island could be more dynamic than those elsewhere.

Levees on Smith Island overtop at the same frequency and velocity under with and without project conditions. The Union Slough 1135 setback levee is expected to overtop during very large floods under with and without project conditions. The 1135 levee is armored on the interior and exterior sides and well vegetated and maintained by the City of Everett. On Ebey Island water levels decrease due to reduced stages on Steamboat Slough. Dikes there may be overtopped less frequently from the Steamboat Slough side.

As noted in Section 2 above, there is a buried gas pipeline that traverses the Snohomish County Smith Island Phase 1 restoration project near the City of Everett mitigation wetland levee breach on Smith Island that will be enlarged by the Corps to increase flood conveyance (to offset induced flood impacts). This gas pipeline is 800 feet from the levee breach and is protected from erosion and scour by an trench burial, covered with a revegetated engineered embankment, which is flanked on both sides for its full length by buried rock revetments (see Figure 11 above). Ground elevations above the pipeline are 7 to 10 feet higher than the top of the pipeline. This pipeline was protected as part of the Phase 1 of the Smith Island ecosystem restoration project by Snohomish County. Quarry spall revetments (2-ft thick, 2H:1V side slopes) are buried 7 feet below ground (windrows) to elev. 0 on both sides of the pipeline to protect the pipeline in the event of channel migration.

As shown in Figure 57 below, under existing conditions, the ground near the pipeline experiences a maximum velocity during the 1% annual chance flood of 1.8 ft/s, which will likely increase modestly to 2.5 ft/s. These velocities are lower than those needed to begin to erode the well-developed vegetated marsh on top of the pipeline (roughly 4-ft/s). Research indicates that vegetated tidal marsh is robust and able to withstand high velocity flow for extended periods (van den Berg M 2024, Fischenich 2001). In the event of channel migration (which is unlikely given the geomorphic stability of the distributary channels), the maximum tidal channel velocities in the vicinity of the pipeline (4-ft/s) would be far too low to pose erosion risks for the windrow revetments. Computed safety factors for a fully exposed windrow revetment exceed 5.0. The area of highest velocity is presently 800 feet away from the pipeline, providing ample time for monitoring and maintenance actions should channel migration become a concern in the future. In summary restoration risks for the gas pipeline on Smith Island remain very low, as these risks are presently addressed by the pipeline protection work completed previously by Snohomish County in anticipation of tidal marsh restoration.

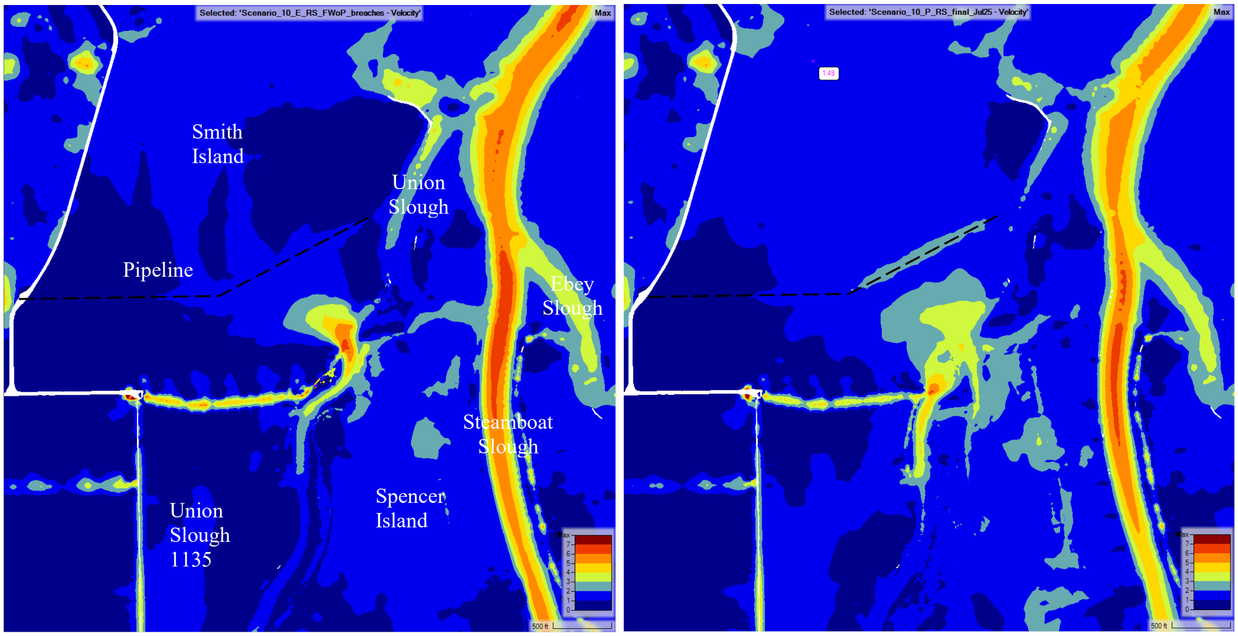

Figure 57. Max velocity for 1% AEP flood event pre (left) and post (right) restoration near Smith Island conveyance improvement

7. Discussion of existing data, observed trends, and implications for design of the Spencer Island Ecosystem Restoration Project

Review of overlays of existing Lidar data and 1938 air photos (Figure 2) indicates that shoreline positions (and channel widths) of the lower Snohomish River distributary channel network are remarkably consistent around Spencer Island and adjacent distributary channels suggesting there has not been large enough changes in the tidal, streamflow or sediment transport characteristics to initiate dynamic behavior such as bar building, active erosion, avulsion, etc., which are processes present on upstream tributaries.

Levee and dike construction reportedly began in the late 1800s and was largely complete by the 1930s. Levees and revetments are present along both banks of Union and Steamboat Slough in the project footprint, as well as adjacent distributaries and the mainstem Snohomish. Historical air photo review indicates channel positions are remarkably consistent over time, in the tidally influenced portion of the river (from Snohomish to Puget Sound), where bars are largely absent, and banks are relatively high.

Two observable changes to the distributary channel shoreline that have occurred since 1938 include the “Buse Cut” between Steamboat Slough and Union Slough (dividing Spencer Island in two) and northward migration of a small portion of Otter Island where Ebey Slough first connects with Steamboat Slough, likely in response to the effects of the cut. Large scale changes to topography in the vicinity of the project include construction of Interstate 5 in the

1960s and construction of the City of Everett wastewater treatment plant lagoon dikes. These projects filled tidal channels and disconnected flood and sheet flows across Smith Island.

Arguably the largest topographic and hydrologic changes that have occurred in the last 20 years are construction of Ebey Slough (Qwulloolt), Spencer Island, Union Slough, and Smith Island restoration projects. These projects breached portions of existing dikes and constructed starter channels to reconnect marshes to distributary sloughs. Refer to Figure 1for a complete list of restoration projects completed and proposed for the estuary.

Vertical land motion data suggest the mouth of the river is stable vertically (constant base level) which likely contributes to observed stability. Sedimentation is present in the form of sand dunes and small bars, primarily along the mouths of sloughs (tide flats), within the channel of the mainstem Snohomish, Steamboat Slough, and Union Slough, and along the lower portion of Ebey Slough. Upstream of Otter Island Ebey Slough is generally deeper than the mainstem and Steamboat Slough.

Multibeam data show that thick deposits of sand are present on top of smooth erosion resistant bed materials in deep scour pools. Pool depths exceed 25 feet in many locations. Scour pools are most common at the downstream confluences of major distributaries, tight bends, at armored obstructions, and at the confluence with major tidal channels. Sediment budget data derived from repeat cross section surveys suggest a slow rate of vertical aggradation on the mainstem, Union Slough, and Steamboat Slough in the vicinity of Spencer Island.

Natural levees are widespread along the banks of the mainstem Snohomish, all sloughs, and most tidal channels. Scrub shrub and water tolerant trees are present along these elevated ridges, likely enhancing sedimentation. Scarps and slumps of emergent and herbaceous marsh vegetation are common along banks however the presence of vegetation rootmats appears to limit erosion. Ongoing dredging of the mouth of the river and the upstream navigation channel has an unknown effect on conditions near Spencer Island, presumably small as they are located downstream of the split with Steamboat Slough.

Design of nearby Snohomish estuary marsh restoration projects has typically been focused on creation of a small number of large breaches through levees often but not always at the locations of historical channels. Starter channels and ditch blocks are also included within the interior of the site to aid in reestablishment of a dendritic tidal channel network.

Common changes observed including restoration of daily tidal flux, die-off of upland vegetation and non-native wetland herbaceous plants, formation of tidal flats, erosion, sedimentation and establishment of tidal channel networks, reestablishment of wetland plant communities tolerate on tidal inundation and salinity, deposition of large wood within channels and shorelines.

At some of the restoration sites (Qwulloolt, Smith Island) reconnection has resulted in evolution of constructed channels in response to daily tidal flux. In the case of the Qwulloolt project the primary breach channel was undersized initially, but erosion and scour enlarged the channel to the point where equilibrium conditions were reached within a few years. Some channels within the site were constructed at elevations higher than the equilibrium channel elevation and headcutting is occurring. The erosion is confined to the tidal channels. Headcutting is also observed at some of the tidal channels at Smith Island. This erosion is difficult to predict but is a desirable outcome as it helps redistribute sediment within the site and promotes reestablishment of a dendritic channel network.

The accidental dike breach at Spencer Island in 2005 has initiated the same change in vegetation conditions. The presence of narrow, deep ditches throughout the site however has hindered reestablishment of the dendritic channel network, as the ditches cut across natural drainage divides, and the straight deep channels short circuit relicts of natural channels. The remnant levees along Steamboat and Union Slough limit tidal exchange with Steamboat Slough to one very large channel and to Union Slough with one medium sized channel. This condition concentrates flow in the ditches connected to these channels as there are no other pathways to disperse tidal flow. At very low outgoing tides it is possible that velocities in portions of these ditches present barriers for fish that might otherwise want to enter the marsh. Presumably natural erosion and sedimentation will adjust these ditches to an equilibrium condition that resolves this issue, however the lack of perceptible changes to these ditches since the dike breach occurred suggests this process is likely to span several decades, if not longer.

Inspection of aerial photos of recently restored marshes adjacent to Spencer Island indicates that these marshes have not experienced large scale post-construction geomorphic changes (other than vegetation die off and reestablishment) implying that levee lowering and breaching around Spencer Island is not going to result in dramatic alteration of local geomorphic conditions, and that constructed features within the island are not likely to be highly dynamic.

8. PED Phase Design Refinement Recommendations

The evaluated feasibility phase design is focused on maximizing hydraulic connectivity and restoration of associated natural processes. The feasibility design presented herein is based primarily on a 10% concept developed when less information was available to inform the design, specifically the GIS evaluation of the marsh island drainage networks and seasonal water level data. In light of that information, the following changes in the proposed feasibility design should be evaluated in PED. Note that these changes maintain or modestly decrease the current scope, cost, and complexity while maintaining the intended benefits, so they do not impact feasibility decisions.

- Reconnect more of the small catchments to the marsh interior by inclusion of additional small levee breaches within the proposed project footprint. This could add about a half dozen additional channel outlets, primarily along Union slough, and result in the total number of connections better matching allometric regression predictions. These channels should utilize a higher average elevation given their small size.
- The width and depth of the proposed breaches is likely larger than needed in some locations. This is partly due to uncertainty over how the restored site will respond to

sediment and large woody material deposition and vegetation establishment. The large channels will help redistribute tidal flux from the main breach channel to other locations along the restored shoreline reducing velocities hindering fish access. There is an opportunity to fine-tune the width and depth of these channels consideration of the likely drainage area tributary to the breach channel after grading is complete. Note that the higher average elevation of Otter Island results in less tidal exchange which reduces the erosion of the outlet channel.

- After a tree survey is completed, refine the levee removal grading plan to avoid significant trees. Identify trees to remove and count large wood pieces that are likely to need to be repositioned to see if there are opportunities to incorporate large woody material into channels and fill features. Use of steeper side slopes may be warranted (see Mid Spencer as-built memo).
- Refine the grading plan for disposal areas – prioritize placement along perimeter ditches and gradually feather disposal areas from the degraded levees into the marsh. Add disposal areas along constructed channels as side cast if the cut quantity exceeds the adjacent ditch fill volume. This will naturalize the appearance of the finished grading plan by prioritizing fill placement along banks where sediment would naturally deposit.
- Evaluate lowering the levee degrade elevation slightly to better match Otter Island crest elevations (from 10.5 feet to 9.5 feet) or to the site average OHW elevation based on additional surveys.
- Refine the grading plan to target desired plant communities and successional processes.
- Update the 2D hydrodynamic model based on the above terrain changes and reassess impacts to flood levels and geomorphic response. Confirm expected water quality changes by including the revised terrain in the 3D FVCOM model.

9. Future Without Project Conditions

Recent trends detected by others related to altered estuarine hydrodynamics and salinities (Hall 2024, Nugraha and Khangaonkar 2024) are likely to continue. Preserving status quo conditions at Spencer Island would result in intermittent breaching of levees and slow conversion of a degraded tidal wetlands back to more natural conditions. Existing undersized channels and ditches will continue to erode, deepen, and enlarge, and slowly evolve to more natural channels, however anecdotal observations from Spencer Island and other Snohomish estuary restoration sites (Qwulloolt marsh) indicate ditches tend to remain in a degraded state even after tidal hydrology is restored.

Existing tidal channels will enlarge, and some will silt in or close off entirely. Hydrodynamic patterns during daily tide cycles as well as major floods will not be significantly modified until large portions of existing dikes are eroded down to more natural elevations or breach entirely. Flood flows in Steamboat Slough will be isolated by dikes from the island interior and will remain higher than those in Union Slough due to the much greater depth/conveyance.

Sediment and large wood will primarily flow down the sloughs. Large wood accumulates on the island now, washed into the island on the incoming tide or when the south cross dike is overtopped. Because of the presence of the Union Slough dike, the volume of woody material stored on Spencer Island will increase over time, helping build up the marsh plain elevation, and promoting more dynamic conditions within the marsh tidal channel network. Flow will continue to favor the large breach hindering reconnection of other potential breach channels within the island. In the absence of sea level rise the island would slowly naturalize as the perimeter levees became increasingly degraded by floods, however given the slow rate of change present on the site, due to extensive ditch network, low topographic gradient and consolidated soils, the process could take many decades. Thus, degraded habitat conditions are expected to persist for several decades or more, unless the perimeter dikes are removed to reestablish natural processes and fish access.

Because geomorphic and habitat conditions are strongly influenced by the presence and character of wetlands the NOAA Sea Level Rise viewer was used to evaluate the combined effects of future sea level rise, vertical land movement, and accretion (relative sea level rise) on existing coastal and riparian wetlands. Because the Corps planning window is 50-years, and construction is not likely to be complete until 2027, 2080 was used as the end point in the analysis. Accretion was varied from 0 mm/year to 6 mm/year and the intermediate low, intermediate, intermediate high and high sea level change scenarios were used to estimate how wetlands could change over time.

From review of the Marsh Migration maps (Figure 56 through Figure 64), it is evident that the Snohomish Estuary will experience dramatic alteration in the coming decades. The trajectory and end point is essentially the same for all scenarios, however the rate of change depends on the emissions scenario and vertical land movement rate, which is heavily influenced by the rate of sediment accretion. Higher emissions increase rate of sea level rise, which converts the island to tide flats more quickly, while higher rates of sediment accretion offset some of the relative sea level rise.

The viewer properly classifies existing conditions at Spencer Island as freshwater tidal marsh, and correctly maps tideflats, however adjacent areas on Smith Island are incorrectly mapped as developed.

From inspection of Figure 57 through Figure 62, Spencer Island would remain vegetated in all but the high emissions scenario and would remain one of the few vegetated areas of the lower valley, much of which would convert to tideflats or open water. Many of the areas up-valley that are projected to convert to open water are agricultural lands protected by levees. Levee and interior drainage improvements could forestall some of these changes for several decades. Similarly, placement of dredged materials obtained from the mainstem Snohomish could forestall conversion of freshwater marsh to salt marsh and from salt marsh to tideflat or tideflat to open water. The feasibility of beneficial use of dredge materials in the estuary is being evaluated by others, separate from this project.

The NOAA high accretion rate was evaluated because increased freshwater runoff during the winter and spring if coupled with increased upland erosion, could increase sediment loading. The high accretion rate does not appear to significantly offset changes except for the intermediate-low scenario, which is unlikely given current greenhouse gas emissions.

Other changes that are possible include higher temperatures, drought stress, resulting in changes in plant communities, and alteration of streambank conditions and stability. Given the very low rates of channel migration present in the lower Snohomish it seems unlikely that conditions will change dramatically or quickly. If headwater erosion rates increase, large wood loading and logjam frequency could also increase.

The evaluation does not consider the movement of the depositional fan at the mouth of the river upvalley, which could initiate localized bank erosion and channel migration. Landowners occupying developed properties subject to repeated flooding will likely abandon the floodplain prior to this condition materializing, which could be beneficial if infrastructure impairing natural processes is also removed. The heavily developed valley walls are dominated by dense glacial tills and are generally erosion resistant, and typically 100's of feet above the valley floor. Thus, changes are expected to be localized within the flood-prone valley floor, sparing developed uplands.

Upgrades to infrastructure such as roads, bridges, levees, and pumps that alter channel and floodplain conditions are not considered in this evaluation but should be assumed to counteract and degrade natural processes and habitats.

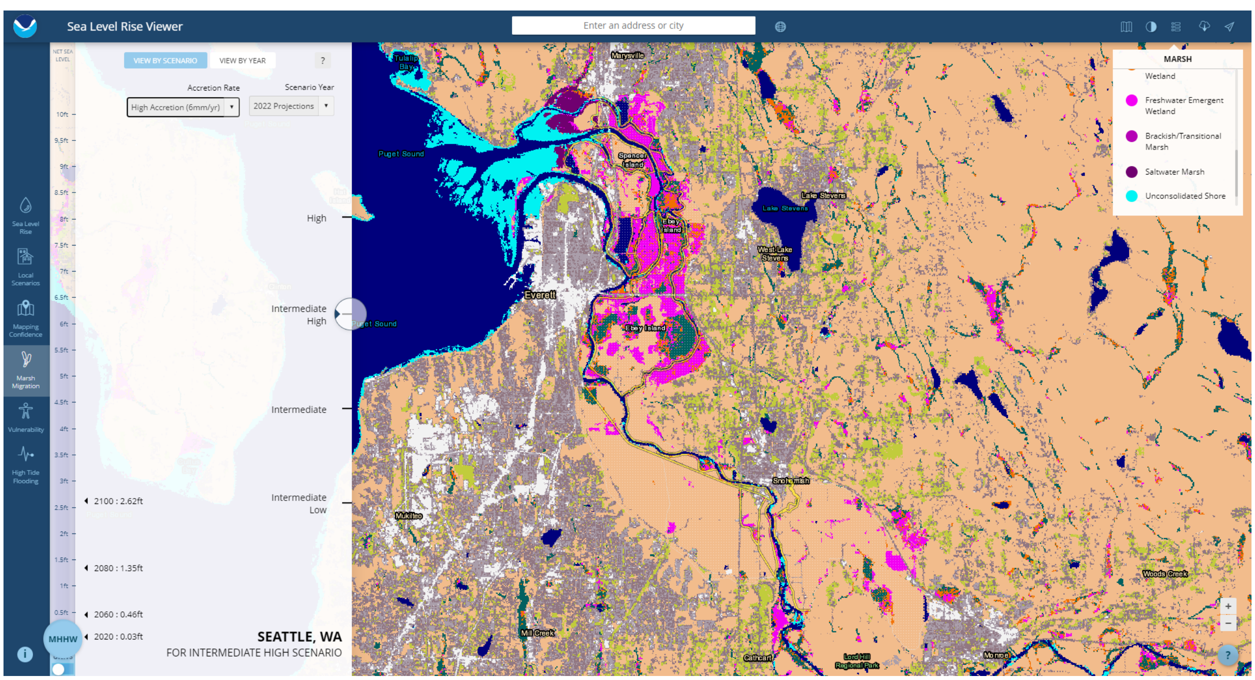

Figure 58. Marsh wetlands, existing conditions baseline, Spencer Island is mapped as freshwater emergent marsh

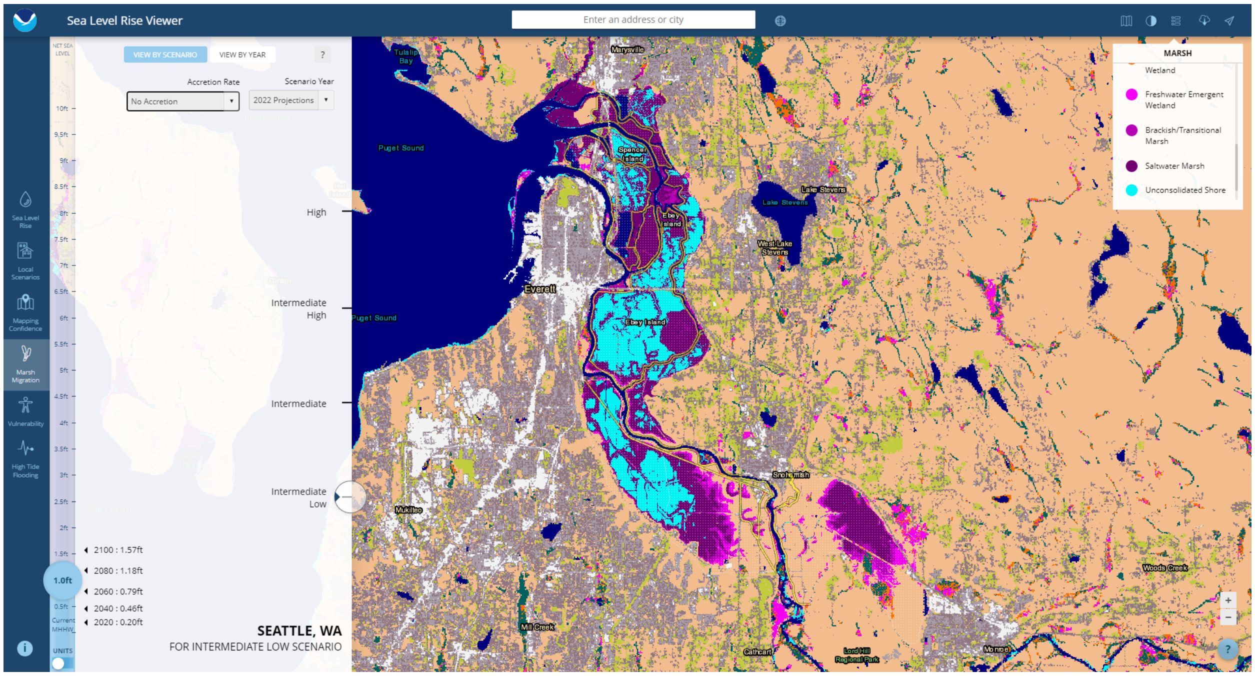

*Figure 59. 2080 Intermediate-low emissions scenario + **no accretion**. Island converts to salt marsh.*

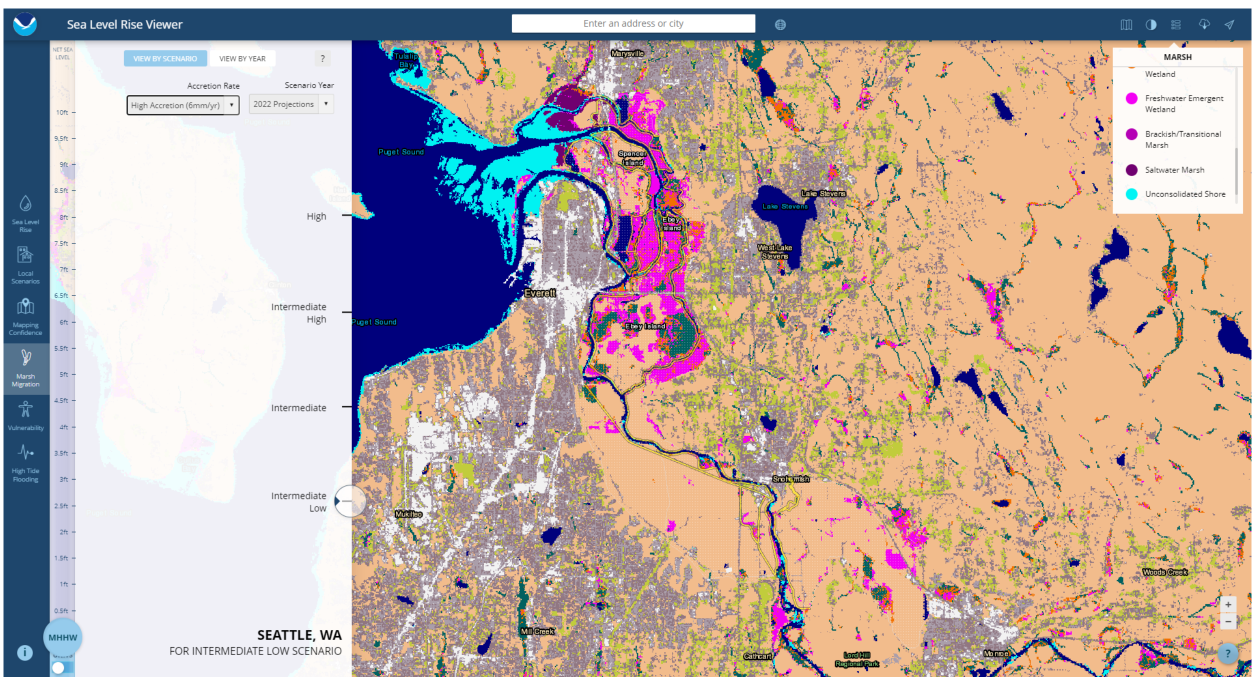

*Figure 60. 2080 Intermediate-low emissions scenario + **high accretion**. Island maintains status quo.*

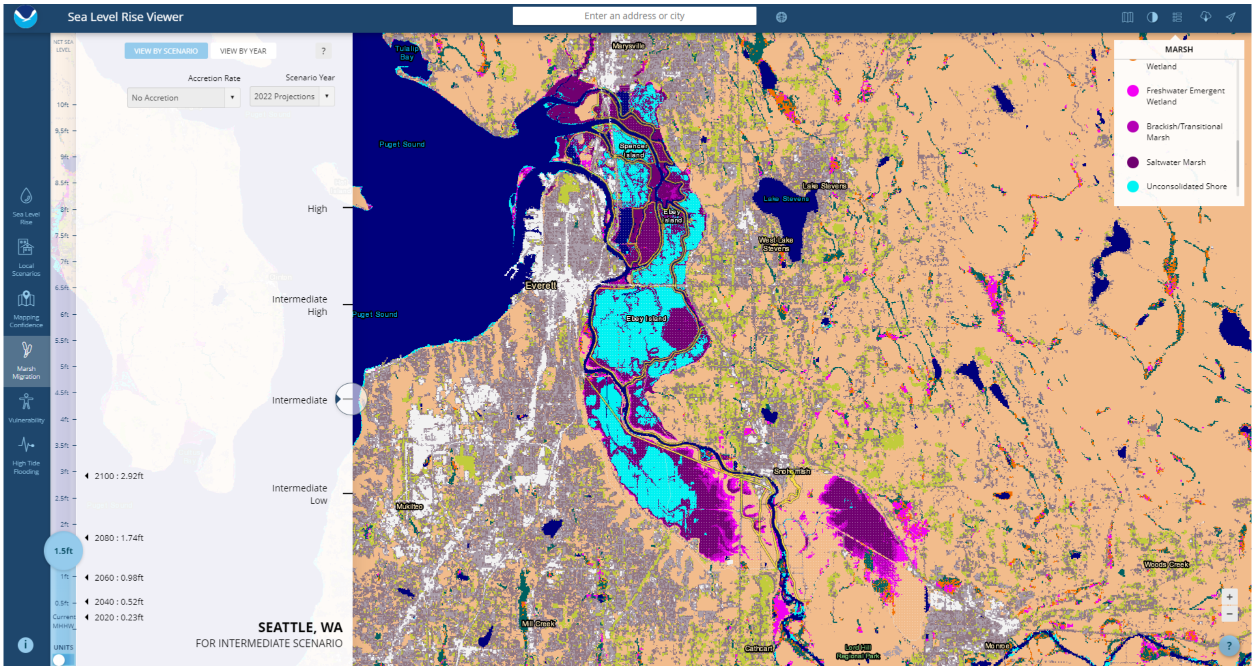

*Figure 61. 2080 Intermediate emissions scenario + **no accretion**. Island converts to salt marsh.*

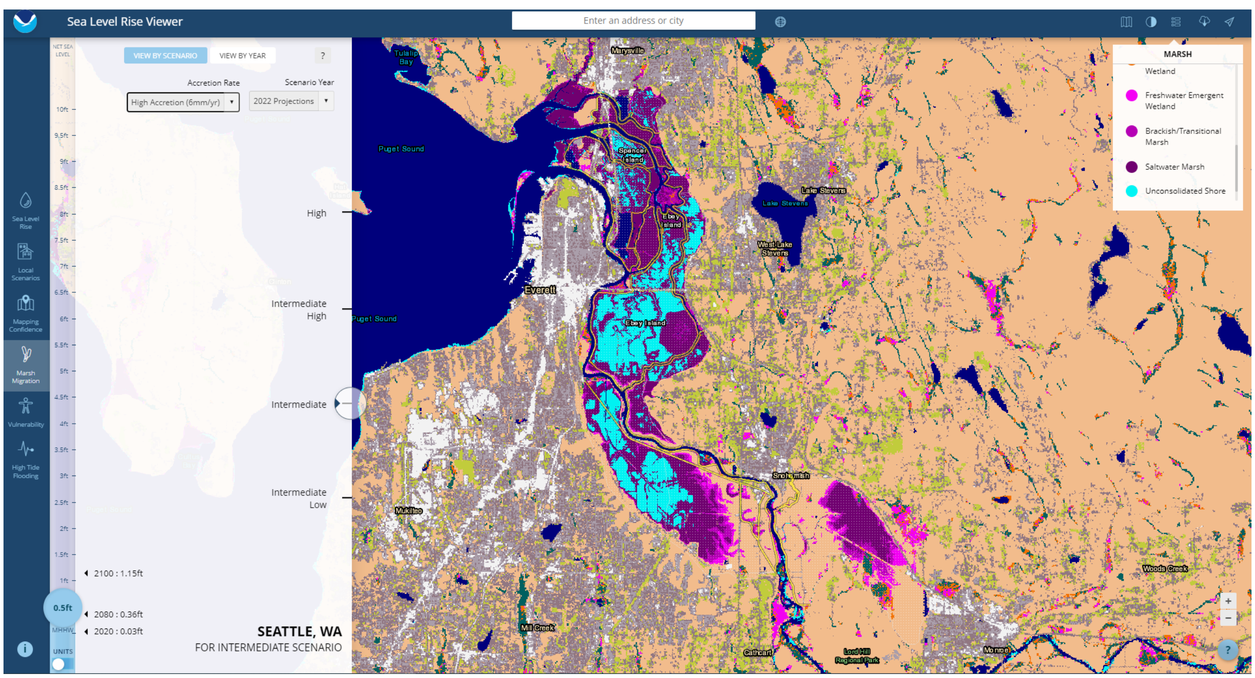

*Figure 62. 2080 Intermediate emissions scenario + **high accretion**. Island converts to salt marsh.*

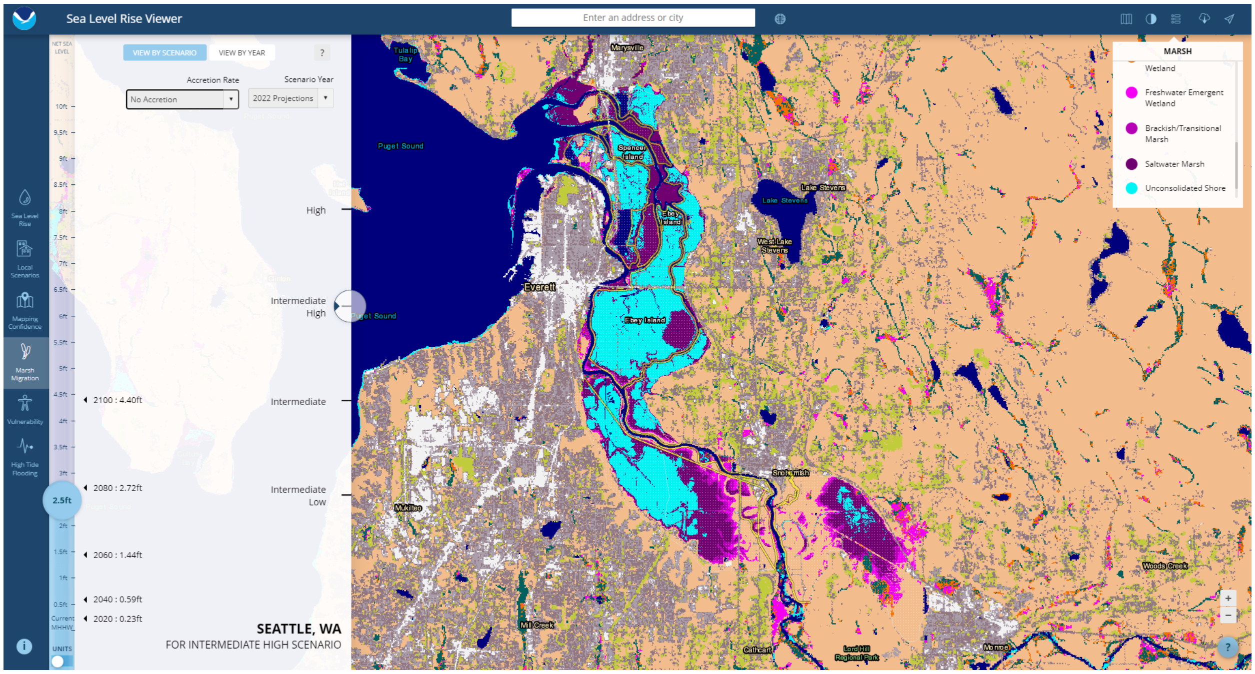

Figure 63. 2080 Int-high emissions scenario + no accretion. Island converts to salt marsh with some tide flats.

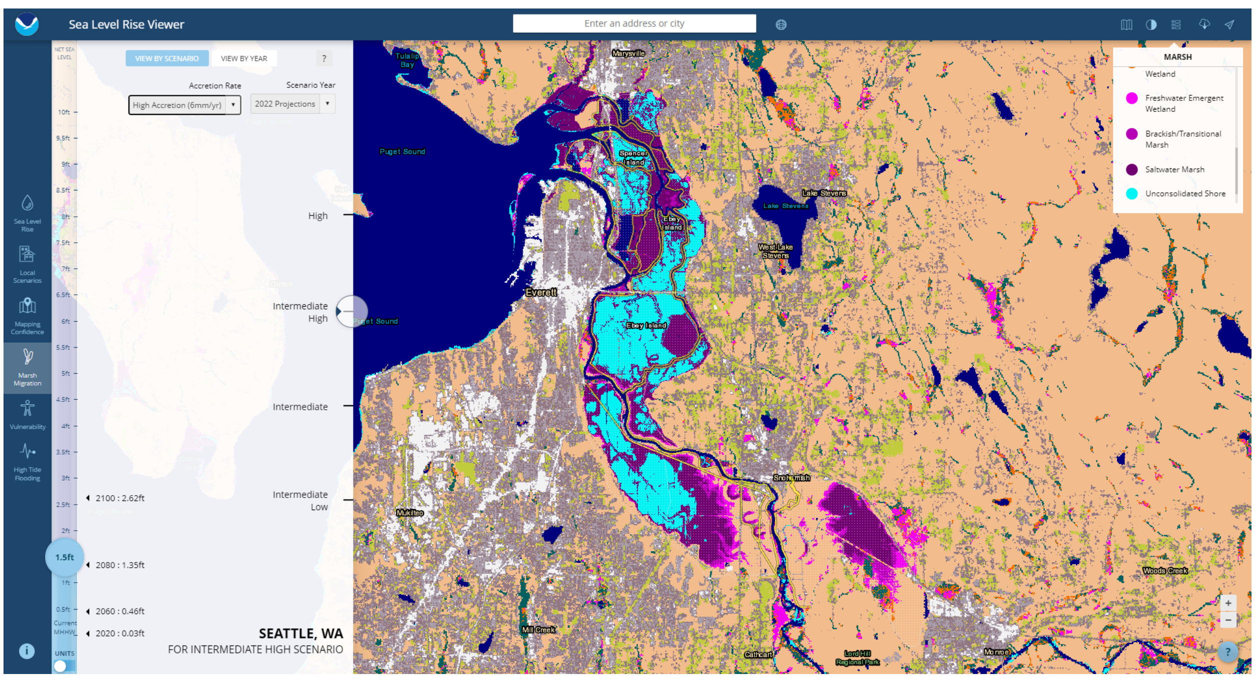

Figure 64. 2080 Int-high emissions scenario + high rate of accretion. Island converts to salt marsh.

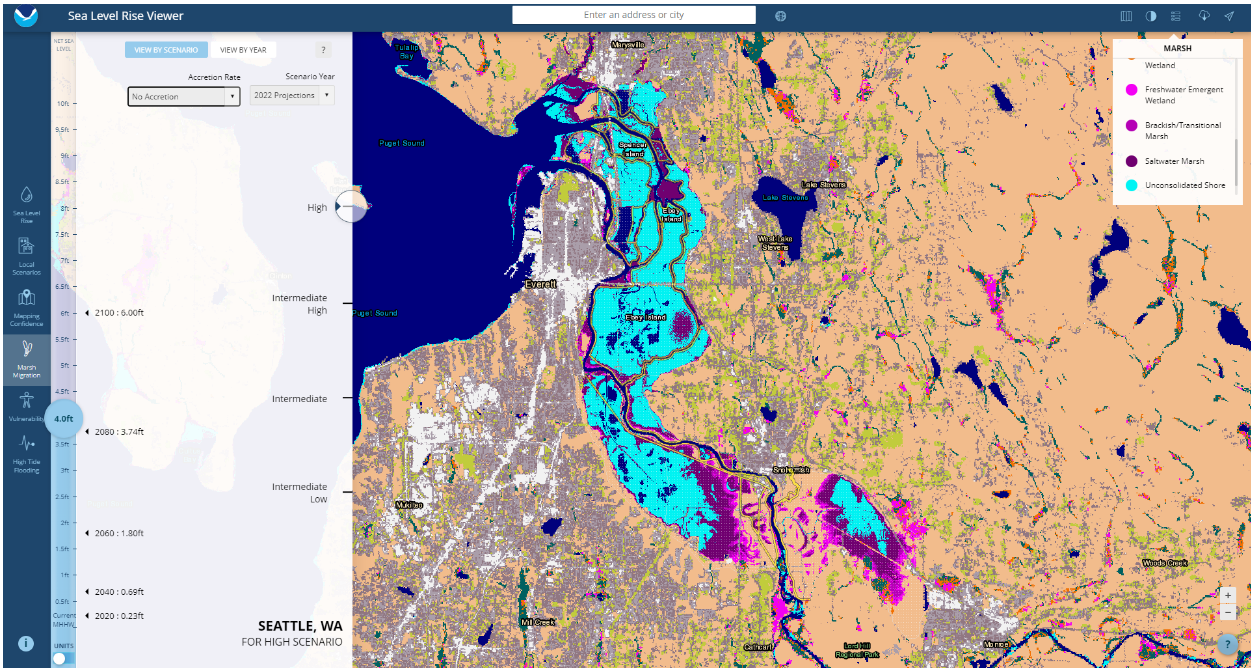

Figure 65. 2080 High emissions scenario + no accretion. Island converts to tide flats.

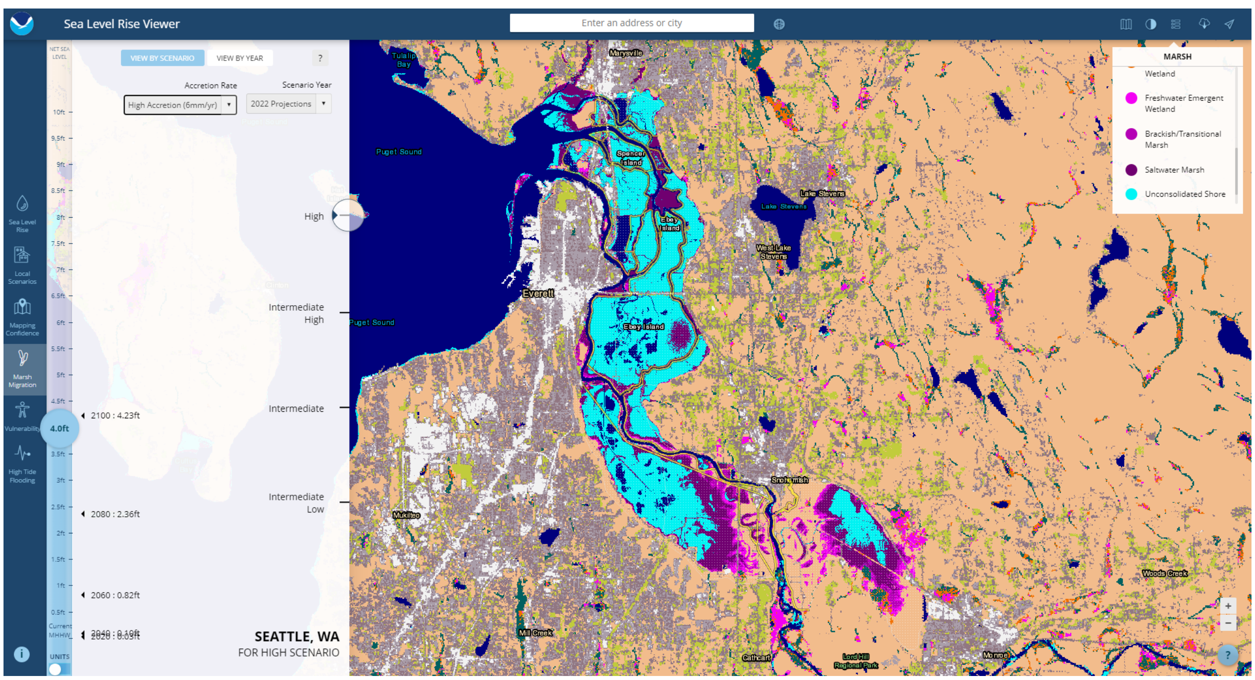

Figure 66. 2080 High emissions scenario + high accretion. Island converts to tide flats.

10. Future With Project Conditions

Recent trends related to altered estuarine hydrodynamics and salinities (Hall 2024, Nugraha and Khangaonkar 2024) are likely to continue. Removal of levees and construction of tidal channels in locations where historic disconnected channels are present in conjunction with removal of hydraulic barriers is expected to permanently reestablish dynamic tidal channels in these locations and associated natural processes. Slow changes to the width, depth, cross sectional shape, and planform of all constructed channels is a desired and expected outcome. Some channels will enlarge, and some will silt in or close off entirely. Because of the depth of the constructed channels through levee breaches, erosion of small channels draining the marsh into the new channels is likely, which could hasten dendritic channel network and microtopography formation near the breaches. Levee breaching and spoils placement areas that have appropriate elevation (9.5 feet or higher) will revegetate and convert what is largely cattail marsh to riparian forested wetlands.

Near term hydrodynamic patterns during daily tide cycles as well as major floods will be modified. Tides will come into and flow out of the island at a flowrate and velocity consistent with well connected tidal marsh and the current erosional conditions present on site should diminish. Hydraulic connection with adjacent marshes on Union Slough will improve significantly.

Flood flows will cross the island from Steamboat Slough to Union Slough relatively unhindered, which should increase the amount of water, sediment and large wood flowing across the island toward Union Slough and Smith Island. Large wood accumulates on Spencer Island now, the volume of material stored may decrease as the Union Slough dike lowering could allow some of the trapped material to flow downstream toward Union Slough and Smith Island. This may be counteracted by the removal of dikes on Steamboat Slough that could increase the amount of woody material entering Spencer Island. If there is an increase in woody material deposited on the island this will help reestablish the marsh plain elevation, and promoting more dynamic conditions within the marsh tidal channel network. Portions of connected sloughs will likely deepen in some areas where tidal flux into the island is enhanced, and shallow in others. The density and length and complexity of marsh channels will increase due to the construction of new outlets and filling of ditches that presently cause short circuiting.

Given that Spencer Island is already connected to Steamboat and Union Slough, many of the environmental and hydrologic changes expected under existing conditions should be expected to materialize under future with project conditions. This primarily includes altered hydrodynamic patterns and flooding, since the unmaintained perimeter dikes will continue to settle, breach and erode over time. One characteristic that is unlikely to be modified (without intervention) is low flow connectivity to the tidal marsh and the detrimental influence of ditches on juvenile fish. This is due to the presence of consolidated soils and slow erosion rates.

The wetlands present on site would still convert to salt marsh due to sea level change in the 50-year planning period, however, it is reasonable to assume that the island wetland vegetative community would remain in its present state for a longer period of time, due to the greater connectivity provided by the levee removal and breaches. This would promote dispersion and deposition of sediment and large wood that is presently bypassing the island interior along the sloughs. Thus, the resiliency of the low-salinity (oligohaline) tidal marsh (i.e. longevity) could be enhanced as a result of the project.

Given that current salinities are low (oligohaline), and that the tidal prism of the site is not going to be affected significantly by restoration, inclusion of more connection points along distributaries should provide more opportunities for fish to access what should be high quality habitat (in terms of wetted usable area, water temperatures, and salinities). While sea level change could increase salinity, this will not occur for several decades, so reconnecting with this large oligohaline wetland should be highly beneficial if it occurs as scheduled.

If dredge disposal material is placed within the island the rate of conversion of freshwater to saltwater wetlands could be delayed further. The conversation of expansive vegetated wetland areas to unvegetated tideflats could reduce forage opportunities for salmonids, so projects such as Spencer Island that preserve or enhance the longevity of wetlands accessible to salmonids should remain beneficial for decades.

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Feasibility Report Engineering Appendix

Spencer Island Ecosystem Restoration HH&C Annex D4: Conceptual Alternatives Analysis

Snohomish County, WA

January 2026 35% ATR

Prepared by

US Army Corps of Engineers®
Seattle District

CENWS-ENH-H 4-January 2024

TECHNICAL MEMORANDUM: Updated Hydraulic Analysis of Spencer Island Ecosystem Restoration Feasibility Study Alternatives

BLUF

This Technical Memorandum transmits the results of a hydraulic analysis (modeling) for 5 action alternatives analyzed for the Spencer Island Ecosystem Restoration Project (project) and the no-action alternative (NAA). See Reference 3 for alternative descriptions and work quantities. See Tables 2 through 4 for habitat quality score and quantity data. See Reference 4 for descriptions of the metrics and scoring methods. Since completion of the draft technical memorandum in June 2023 discussions between WDFW and Snohomish County resulted in a determination that Alternatives 4A, 5A, 6A, 6B and 7 are not viable (due to pedestrian access impacts). In addition a new alternative was developed (Alternative 8) by WDFW based on input from Snohomish County. This memorandum presents data for the remaining viable alternatives (Alt. 2, 3, 4B, 5B, 8) and supersedes data presented in the June 2023 draft memorandum and is the basis for benefits calculations used in plan formulation.

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BACKGROUND

1. The updated analysis presents inundation areas and velocities associated with each alternative including the no action alternative (NAA, Alternative 1) for a representative June spring tide series spanning two weeks that bound the maximum astronomic tide range (Figure 1). June is typically the period where juvenile salmonids are out-migrating to the estuary and beginning to forage in tidal marshes before entering Puget Sound (Nancy Gleason, pers. communication).
2. Refer to the June technical memorandum (Ref. 6) for details of the modeling discussed below.
3. The analysis was conducted with a modified version of the Snohomish County HEC-RAS 2D model developed by Watershed Science and Engineering (Ref. 1). The original WSE model spans

the entire Snohomish River and floodplain and extends upstream the Snoqualmie River to the Carnation gage and the Skykomish River to the Gold Bar gage and requires 24 hours of computation time to analyze a single flood event. For practical reasons, Seattle District Hydraulic Engineering Section truncated this model by deleting the portions upstream of the Snohomish mainstem Monroe USGS gage and running it with observed flows at the USGS gage and tides from the NOAA Seattle gage.

4. The Modified WSE model was run for two weeks in June 2022 based on observed flows and tides. This model was then truncated near the Spencer Island project site and the underlying model mesh refined to provide reliable computations of depth and velocity in breach channels and around levees. Model outputs (time series of stage and flows) from the larger modified model are then used as boundary conditions for the Spencer Island project site 2D HEC-RAS models.
5. The models are not presently calibrated to conditions local to Spencer Island, however the larger model by WSE is calibrated to recent floods and is wholly adequate for a 10% plan evaluation.
6. Eleven unique terrain, geometry and plan files were created, one for each alternative. All plans use the same two-week tide and flow boundary conditions. Where grading work occurs Manning's roughness value overrides are used. See Reference 3 for plan views of the various alternatives.
7. Modeling indicates that inundation at the site is never static – there are always portions of the island that are filling or draining in a tide cycle, even if the tide in the distributaries is slack (flood or ebb). For this reason, the water surface elevations in the marsh can differ from those in adjacent distributaries by a foot or more in elevation at the same point in time, which confounds computation of inundation area associated with a particular tidal datum (such as mean tide, mean low water, etc.).
8. To simplify quantification of restoration metric inundation acreages a steady state HEC-RAS model was created to compute inundation associated with a steady tide associated with a particular metric and restoration alternative grading plan. In this model the stage in the distributaries is held constant until steady state inundation is achieved. This forces all areas within the restoration site to inundate to the same tide elevation for a given condition and thus reduces the uncertainties associated with how many acres could be wetted for a particular grading plan and tide.
9. Output data presented here are for final 10% alternatives that will be evaluated in the incremental cost incremental benefits analysis. The output data are nearly identical to data previously presented in the draft technical memorandum. Refer to the June technical memorandum (Ref. 6) for details of model input, boundary conditions, and stage and velocity variations between alternatives.
10. The impacts to connectivity were evaluated by the PDT (Ref. 4) based on the physical impairments present (to habitat and natural processes), associated with a range of tidal elevations.
11. Because astronomic tides vary throughout the year based on the relative positions of the earth, sun, and moon, the lowest and highest tides occur in December and June (spring tides). Because of the presence of the Snohomish River tidal datums are higher within the distributary channels and connected tidal channels near Spencer Island. In general daily low tides are more effected

by fresh water. For example, during June the lowest tides in Puget sound can fall below – 4 feet NAVD 88 but generally do not fall below -2 feet at Spencer Island, while the highest tide in June is only about a half foot higher at Spencer Island than Puget Sound.

12. At the lowest tides, tidal flows become slack, and all water is concentrated in the deepest areas of the site. Velocities can be amenable to fish passage however the available habitat is limited by the narrow ditches. At the south cross dike a riprap sill is present that creates a velocity barrier during most tide levels, and at low tides completely blocks any flow (or fish passage) between the south end of the island and middle of the island. Where ditches connect to the primary breach channel the bottoms of the ditches are perched several feet above the water level in the breach channel creating waterfalls (physical barriers).
13. Tidal channels evolve in size over time in response to daily tidal flux until the velocities and shear stresses within the channels fall below thresholds for further erosion. Spencer Island has a series of deep linear ditches that are connected to a very deep breach channel, connected to a large distributary channel (Steamboat Slough). Daily tidal flux through the primary breach can exceed several thousand cubic feet per second due to the large island size and low average elevation of the island caused by nearly a century of agricultural use. The ditches connected to the breach are too small to accommodate this influx/efflux and are slowly eroding in response. The erosion of the island vegetation throughout the site was relatively rapid however the erosion of the ditches to larger more natural tidal channels is progressing slowly, and at current rates may continue for several decades.
14. When the tides drop below the elevation of the marsh vegetation fish are concentrated in deep linear ditches that provide few opportunities for forage or refuge from predators. The slow rate of evolution of the site into a more natural condition is believed to be due to the excessive consolidation of the island soils caused by the dikes, ditches and pumps formerly present when the island was used for agriculture. If the marsh soils were eroding at a faster rate, and incoming sediment loads were high enough, the site would be more likely to evolve to a state that would not be problematic. Without intervention degraded conditions, caused by both the perimeter levees, undersized deep ditches, and consolidated marsh soils, will continue to hinder access for fish to the island (i.e. connectivity) at all tide levels.
15. During river floods, maximum water levels can be several feet above the high tide elevation. Connectivity of the island to the distributary channels during river floods is important for ecosystem health as this is the primary way the site recruits sediment and organic materials, vital for vertical accretion of the consolidated marsh island. Perimeter levees are several feet above the king tide elevations and limit connection of much of the island perimeter to distributaries during only the largest (infrequent) river floods. For convenience, the highest June tide used in the modeling as a surrogate for king tides and periods when high river flows are occurring.

HABITAT QUALITY & QUANTITY SCORES

1. **Metric 1: Channel Connectivity (Tables 1 and 2)**
    a. From a fish use standpoint, excessive tidal flux and velocities into the site are not considered problematic, however if these fish are then washed out in subsequent ebb tide, or hindered from foraging when they are in the ditches, or become more exposed to predators, conditions then become problematic. For this reason, the velocity data at the hotspots were extracted and filtered to exclude flood tides, and then the ebb tide data were analyzed to determine the frequency during the simulation that the hot spot velocity exceeds an impact threshold of 1.5 feet per second (Reference 4).
    b. Table 1 presents ebb tide velocity data for each alternative which is the basis for the Metric 1 scores shown in Table 2. Fortunately, the average velocity at the three hot spots is less than the impact threshold, however the maximum well exceeds this value at all hot spots for all three locations analyzed for the NAA, Alt. 2, Alt. 3. For Alt 4B the ditch exit near the main breach drops below the impact threshold, however the main breach and cross dike remain above. Max velocities for Alt. 5B and Alt. 8 drop below the impact threshold at 2 of the three hot spots.
    c. The Metric 1 Habitat Quality Score (HQS) is the average frequency in time below the impact threshold for the three hot spots during ebb tides in June. Alternatives that reduce the frequency of excessive velocities have higher HQSs (maximum of 1, or 100% of the time) than those that do not.
    d. See Table 2 for a summary of Alternative HQS and quantities.
    e. From inspection the average % time below the impact threshold at the three hot spots varies by 69% for the NAA, to 95% for Alt 8. The NAA has conditions impactful for fish 31% of the time during ebb tides based on this metric, which seems considerable. Alt 2 does not have significantly better performance (70%, increase of 1%). The habitat quality scores for Alt. 3 (78%, +9%), Alt. 4B (82%, + 13%) are better than the NAA and Alt 2. Alt. 5B and Alt. 8 have the most improved HQS (91%, +22%), (95%, +26%) respectively.
    f. Only Alt. 5B and Alt. 8 directly address the cross-dike sill, which is a one of the major physical barriers to connectivity. The scale of the problems created by the main breach and subsided island are apparent in the fact that the main breach would still exceed the 1.5 ft/s threshold 16% of the time. Note that, Alt. 4B and Alt. 8 reslope the banks of the main breach channel creating lower velocity zones that could be used by fish to bypass the high velocity areas. Alt 2 (the PSNERP approved design) performs marginally better than the NAA and significantly worse than all other action alternatives indicating the reformulation requested by NWD has helped identify superior courses of action.
    g. Removal of the cross-dike bridge and sill is the common element for alternatives that have the highest HQSs for this metric. The HQS approaches or reaches 100% for the ditch exit (Alt. 4B, Alt. 8) and cross dike (Alt. 5B, Alt. 8) which indicates conditions are significantly improved for fish. However, the reduction in time below threshold for Alt 4B at the cross dike (worsened conditions relative to NAA) suggests this measure should not be implemented without inclusion of additional breaches or levee lowering.
    h. The June two-week average daily low tide at the confluence with Steamboat Slough (4.6 ft NAVD 88) is representative of conditions when peak ebb tide velocities occur. This

stage is exceeded about 67% of the time during the June simulation and would be well within the banks of natural tidal channels but due to subsidence at Spencer Island results in inundation outside of the extents of the existing ditch network. At the daily low-low tide, slack water conditions are approached, and velocities are infrequently above the impact threshold. Inundation maps associated with this condition used in the quantity scoring are shown in Figure 2 through Figure 7.

i. The usable wetted habitat area under for this metric for the NAA is 83 acres which increases by as much as 3.5 acres for Alt. 8. Inundation area (usable habitat) for the alternatives that create more channels and breaches (Alt. 3, 4B, 5B, 8) is greater than those that just remove levees (Alt 2). The TSP preferred alternative (Alt. 2) would increase habitat for this metric by 1 acre.

j. The estimated Habitat Units (HU) (quantity x quality) for Metric 1 vary from 56.9 for the NAA to 82 for Alt. 8 (increase of 44% from NAA). Alt. 2 (TSP preferred) has the lowest HU (59.0, increase of 4%) of the action alternatives.

2. **Metric 2: Marsh Connectivity Habitat Quality (Table 3)**

   a. One of the primary objectives of Puget Sound restoration is to increase the availability of tidal marsh habitat which is critical for survival and recovery of threatened and endangered salmonids.

   b. Research by Dr. Greg Hood (Ref. 5) documented the “allometry” or recurring geomorphic patterns of existing Puget Sound river delta tidal marsh islands with the specific purpose if identifying natural trends and variabilities on island blind tidal channel frequency and size to aid in design of ecosystem restoration projects such as Spencer Island. The regression analysis relates marsh island area to the number of connections, the largest connecting channel size, the total length of the channel network, and many other variables.

   c. The frequency (or number) of blind tidal channel connections between a marsh island and adjacent distributary channel network is an important output variable from the regression analysis as it directly correlates to the opportunities for fish to access a marsh island during the outmigration to the estuary.

   d. Using Lidar data and air photos, we estimated that there are at least 31 connections between Spencer Island and Union and Steamboat Sloughs at present. Note that many of these occur along levees and the connected channels are truncated significantly reducing tidal flux and size. The highest frequency (and quality) of channels occurs at the north and south ends of the island where levees are absent or purposely breached.

   e. Using the Hood regression equations, the median estimate for the total number of blind channel connections is 51, which indicates a potential restoration goal should be to add as much as 20 new connections to adjacent sloughs. Given the infrequency of connections along existing levees the PDT elected to focus on those areas.

   f. Table 3 summarizes the number of existing and new breach channels by alternative that are connected to distributaries. Internal channels are not counted in this analysis. The Metric 2 HQS is simply the ratio of the total number of existing and new breach channel connections to the regression prediction.

g. The NAA alternative has the lowest HQS (0.61), which is negligibly increased to 0.63 by Alt. 2 (PSNERP approved plan). The highest HQS (0.94 and 0.96) are associated with Alt. 5B and Alt. 8 that add more breaches along both Steamboat and Union Slough.
h. Quantity scores for this metric were based in the average tidal elevation during the June 2022 simulation period. This stage (5.5 feet) corresponds to an elevation that is about equal to the zone of perennial vegetation and represents areas where fish would be able to access marsh vegetation for foraging or shelter. This elevation is exceeded about 50% of the time in the June simulation.
i. Inundation maps associated with this condition used in the quantity scoring are shown in Figure 2 through Figure 7.
j. The usable wetted habitat area under for this metric for the NAA is 130 acres which increases by as much as 3.5 acres for Alt. 8. The alternatives that create more channels and breaches (Alt. 3, 4B, 5B, 8) increase habitat by a greater amount than those that just remove levees (Alt 2). The TSP preferred alternative (Alt. 2) would increase habitat for this metric by less than 1 acre.
k. The estimated Habitat Units (HU) (quantity x quality) for Metric 2 vary from 79.1 for the NAA to 128.6 for Alt. 8 (increase of 62% from NAA). Alt. 2 (TSP preferred) has the lowest HU (82.2, increase of 4%) of the action alternatives.

3. **Metric 3: Floodplain Connectivity (Table 4)**:
   a. Removal of stressors such as roads, dikes, levees, and revetments that are degrading estuarine habitat is a primary goal of the PSNERP project and Puget Sound recovery efforts.
   b. Spencer Island has a total shoreline length of 24,455 feet (4.6 miles). The island has been a focus of dike construction since the late 1800s. As shown in Table 4 The total length of actively maintained and remnant dikes (levees) higher in elevation than the maximum June tide (elevation 11 feet) is 19,510 feet (3.7 miles) for existing conditions, which represents a total dike to shoreline length ratio of 80%. In a sense 80% of the island has dikes that interrupt the fluvial and coastal processes associated with flooding.
   c. Presumably removal of all dikes and levees from the island that disrupt natural processes associated with flooding would represent the largest potential restoration benefit when ranking alternatives.
   d. Alternatives developed for this 10% analysis lowered levees consistent with the locations of the PSNERP conceptual report, but to increase connectivity to Union Slough and adjacent restoration sites, alternatives were developed by the PDT that remove portions of the Union Slough levee and south cross dike.
   e. Target lowering elevations for all levees are 10.5 feet NAVD 88. This elevation corresponds to an elevation that corresponds to the average shoreline elevation along the undisturbed Otter Island, located just downstream of Spencer Island and is exceeded 3% of the time during the June simulation.
   f. The peak June tide (modeled) exceeded 11 feet NAVD 88. This is an astronomic spring tide, not a flood, but is about 2 feet above the MHHW elevation of 9 feet and is exceeded a few times a year (not accounting for river flooding). Inundation maps

associated with this condition used in the quantity scoring are shown Figure 2 through Figure 7.

g. Inundation area (usable habitat) is maximized for the alternatives that remove levees and increase channels and breaches (Alt. 5B and Alt. 8). Note that the usable wetted habitat area under the NAA is 392 acres, which increases by as much as 16.5 acres for Alt. 8. The TSP preferred alternative (Alt. 2) would only increase habitat for this metric by about 11 acres.
h. GIS was used to delete the portion of existing levee polylines that became inundated for the maximum June tide in the model to determine the total length of levee remaining on site that would likely continue to impair natural processes.
i. From inspection of Table 4 Alt. 2, Alt. 3 and Alt. 4B would more than double the NAA HQS, indicating they are highly beneficial from the standpoint of this metric. Alternative 5B has about 3 times higher HQS than the NAA. The alternatives that remove the most amount of levee length (5B and 8) have 2.8 to 3.2 times the HQS of the NAA for Metric 3.
j. The estimated Habitat Units (HU) (quantity x quality) for Metric 3 vary from 79.2 for the NAA to 260.9 for Alt. 8 (increase of 229% from NAA). Alt. 2 (TSP preferred) has the lowest HU (183.6, increase of 132%) of the action alternatives.
k. Metric 3 (floodplain connectivity) is the largest driver of increases in HU, followed by Metric 2 (marsh / distributary channel connections), and Metric 1 (normalized velocity in tidal channels). Separately these actions are beneficial, however removing levees without also adding new connections to distributary channels would perpetuate degraded conditions within the marsh channel network and unnecessarily delay (or hinder) restoration.

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TABLES

FIGURES

Table 1. Ebb tide velocity data for June tide series for three primary velocity barrier locations

Location	Statistic		Ex Cond	Alt 2	Alt 3	Alt 4B	Alt 5B	Alt 8
Main breach	Avg		1.13	1.09	0.77	0.76	0.74	0.72
	Min		0.01	0.01	0.00	0.01	0.00	0.00
	Max		3.37	3.52	2.44	2.55	2.37	2.53
	% change from existing conditions	Avg		-3%	-32%	-33%	-34%	-37%
		Max		5%	-27%	-24%	-29%	-25%
Ditch Exit	Avg		1.06	1.02	0.93	0.48	0.72	0.46
	Min		0.02	0.03	0.03	0.00	0.00	0.00
	Max		3.25	3.07	3.02	1.35	2.14	1.37
	% change from existing conditions	Avg		-4%	-12%	-55%	-32%	-56%
		Max		-6%	-7%	-58%	-34%	-58%
Cross Dike	Avg		1.41	1.35	1.07	1.47	0.31	0.28
	Min		0.01	0.01	0.01	0.01	0.00	0.01
	Max		4.40	4.36	3.90	4.61	1.33	1.05
	% change from existing conditions	Avg		-4%	-24%	5%	-78%	-80%
		Max		-1%	-11%	5%	-70%	-76%

Table 2. Metric 1 (Channel Connectivity) quality and quantity results

Alternative	Metric 1 HQS @ Barrier Locations				Metric 1 Quantity	Metric 1 Habitat Units (Quality x Quantity)
	Main Breach	Main Ditch Outlet	Cross Dike Bridge	Average	Acres Inundated at "Mean June Low Tide" (A1)	
No Action	67%	73%	65%	69%	83.1	56.9
Alt 2	69%	75%	67%	70%	84.1	59.0
Alt 3	81%	79%	74%	78%	85.4	66.9
Alt 4B	83%	100%	64%	82%	84.5	69.6
Alt 5B	83%	90%	100%	91%	86.4	78.7

Alt 8	84%	100%	100%	95%	86.6	82.0

Note: percentages reflect

Table 3. Metric 2 (Marsh Connectivity) quality and quantity results

Alternative	Blind tidal channel connections between Marsh Island and Distributary Network			Metric 2 HQS	Metric 2 Quantity	Metric 2 Habitat Units (Quality x Quantity)
	Existing #	# New	Hood 2014 Restoration Target	(Existing + New)/Target	Acres Inundated at "Mean June Tide" (A2)	
No Action	31	0	51	0.61	130.2	79.1
Alt 2	31	1	51	0.63	131.1	82.2
Alt 3	31	10	51	0.80	132.6	106.6
Alt 4B	31	12	51	0.84	131.5	110.9
Alt 5B	31	17	51	0.94	133.7	125.9
Alt 8	31	18	51	0.96	133.8	128.6

Note: # New connections excludes interior connections at North Cross Dike and South Cross Dike. Removal of existing south cross dike bridge at Steamboat Slough including bank resloping counted as a breach

Table 4. Metric 3 (Floodplain Connectivity) quality and quantity results

Alternative	Shoreline length data (see note 1)		Metric 3 HQS	Metric 3 Quantity	Metric 3 Habitat Units (Quality x Quantity)
	Total Length Levee (TLL)	Total Island Shoreline Length (TSL)	HQS 3 = (TSL-TLL)/TSL	Acres Inundated at "Max June Tide" (A3)	
No Action	19510	24455	0.20	391.7	79.2
Alt 2	13303	24455	0.46	402.7	183.6
Alt 3	13271	24455	0.46	402.7	184.2
Alt 4B	13087	24455	0.46	403.0	187.3
Alt 5B	10483	24455	0.57	407.2	232.7
Alt 8	8832	24455	0.64	408.3	260.9

Note 1: Length of levee is length of all levee segments on island that are not inundated during max tide condition (i.e. are still impacting connectivity)

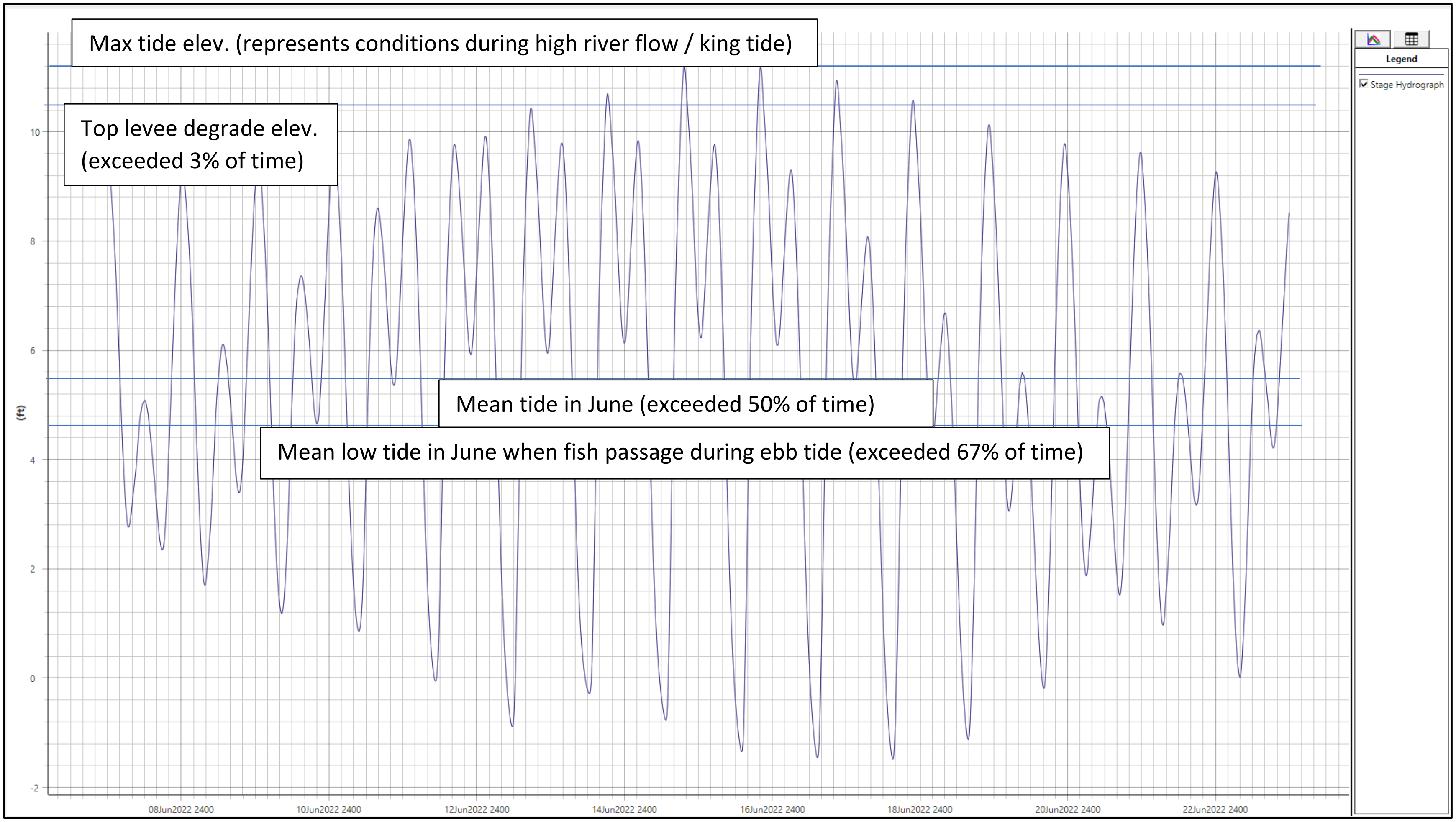

Figure 1. June king tide series used in model for benefits calculation in Steamboat Slough near north end of Spencer Island showing reference elevations

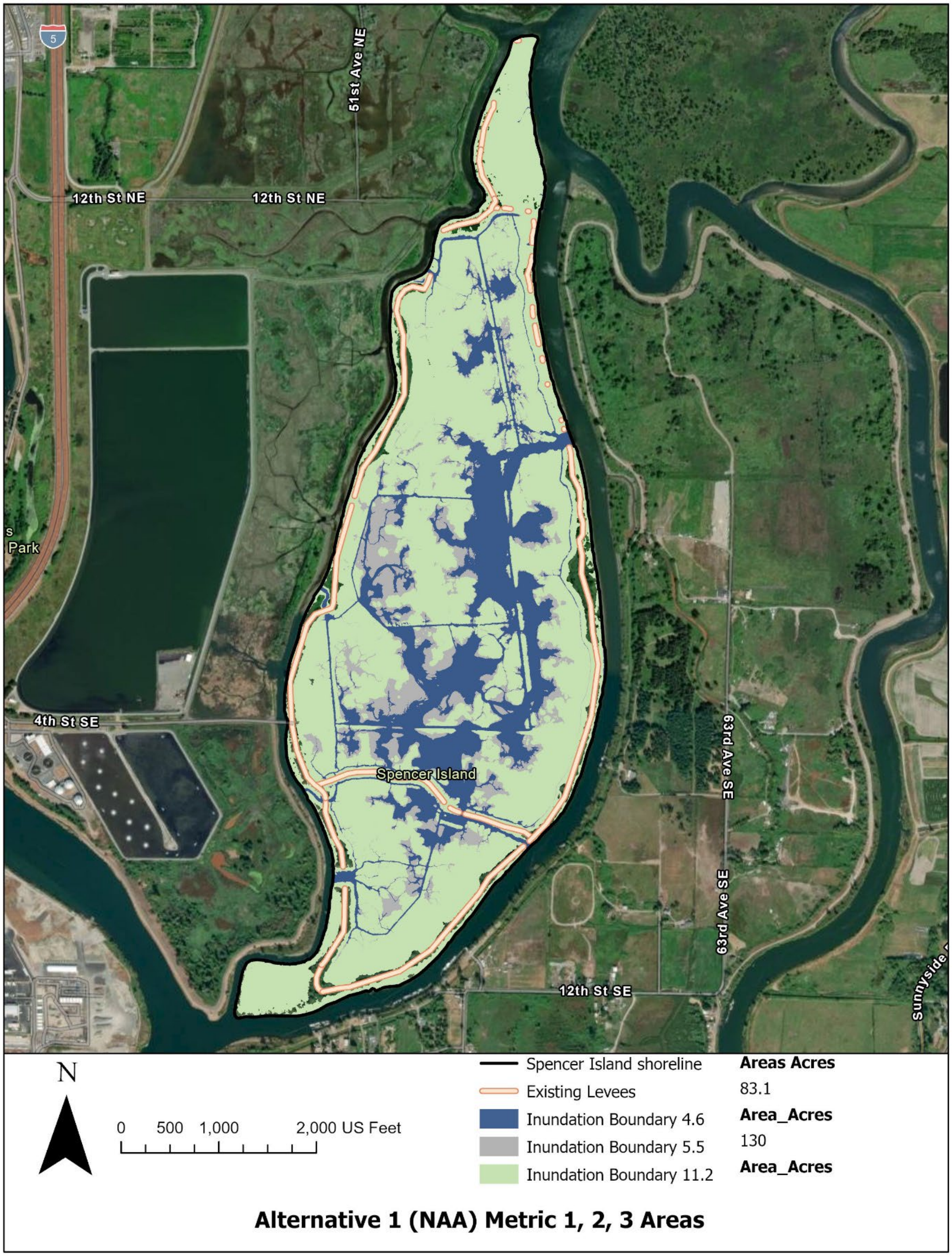

Figure 2. Alternative 1 (No Action) inundation limits for Metrics 1, 2, 3

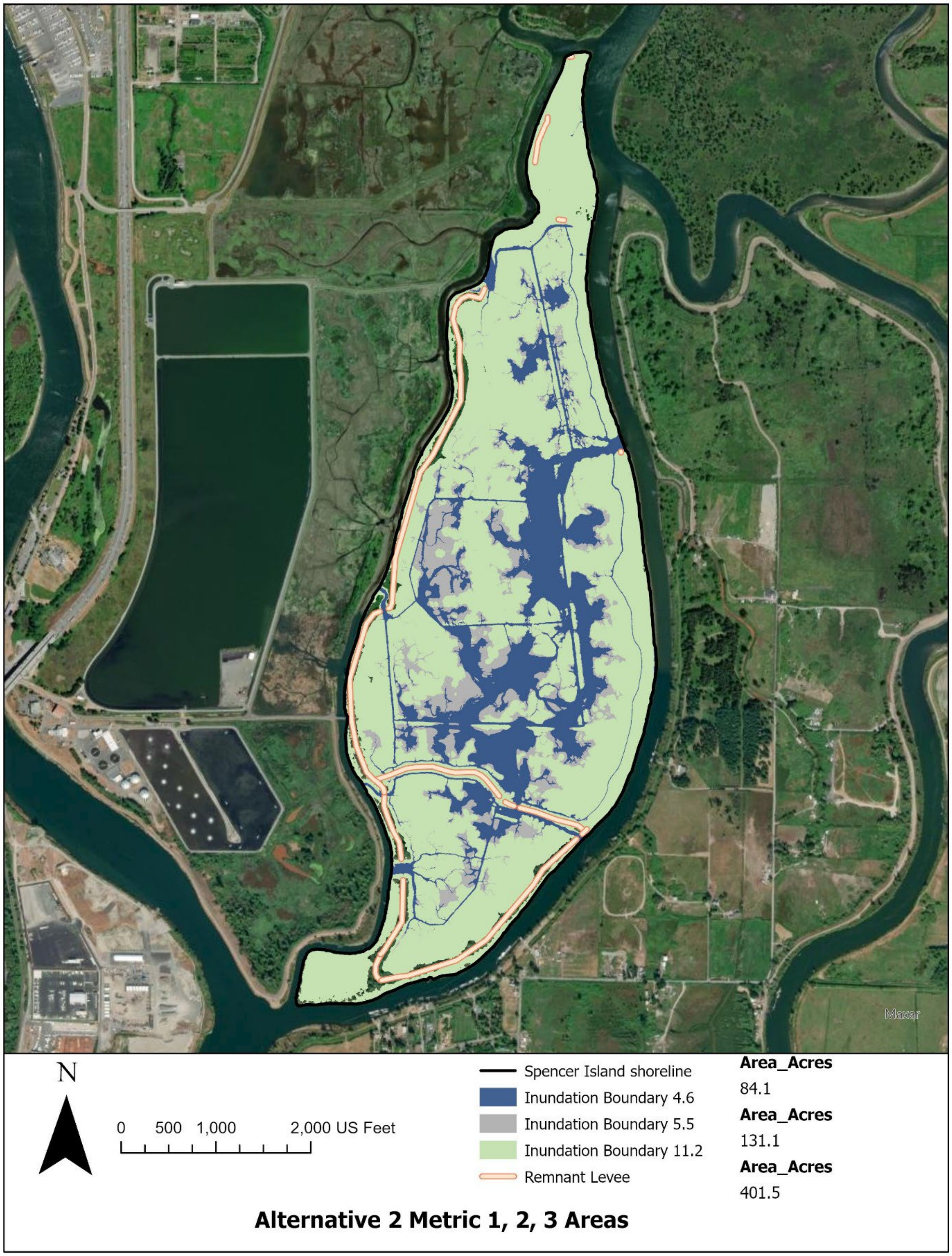

Figure 3. Alternative 2 inundation limits for Metrics 1, 2, 3

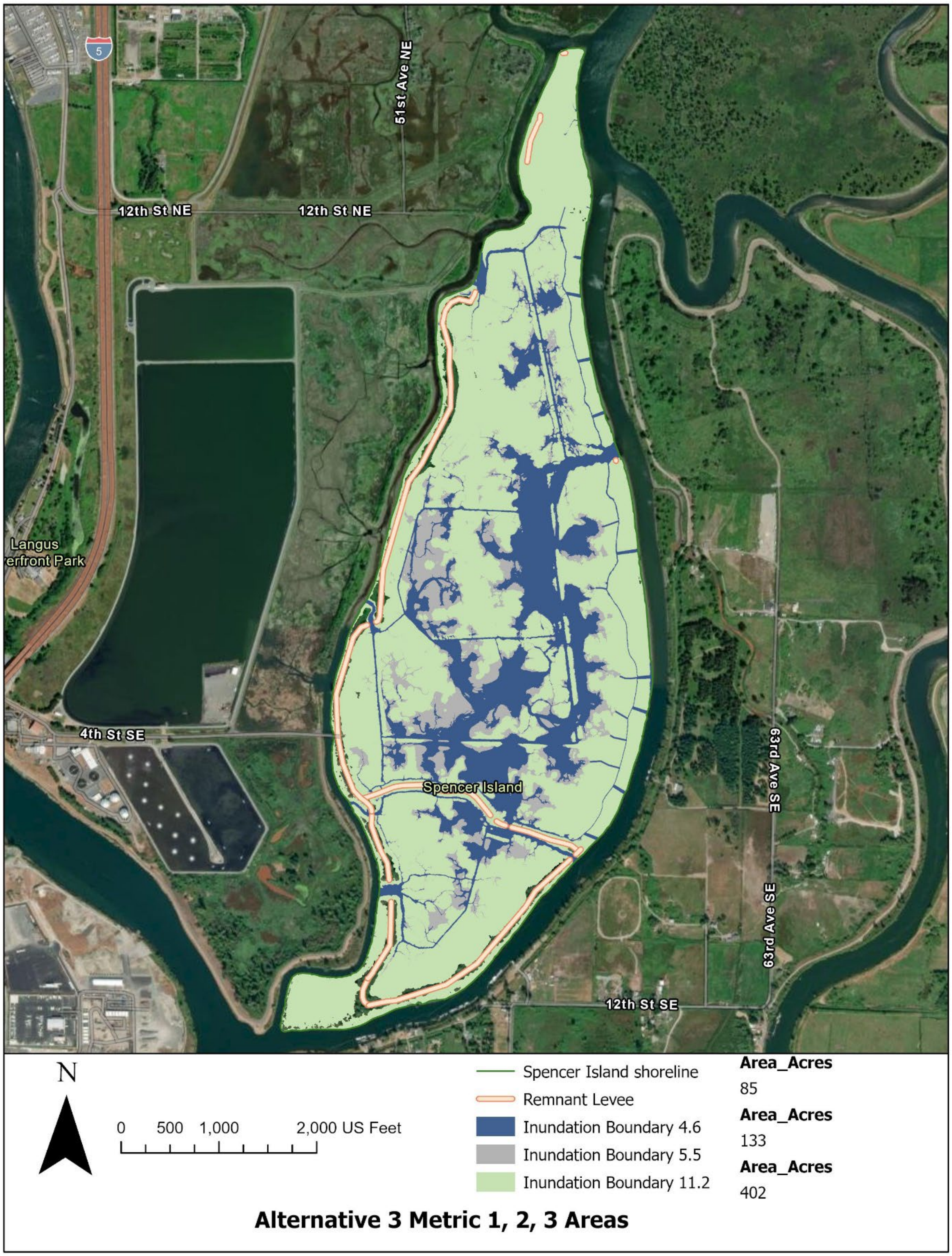

Figure 4. Alternative 3 inundation limits for Metrics 1, 2, 3

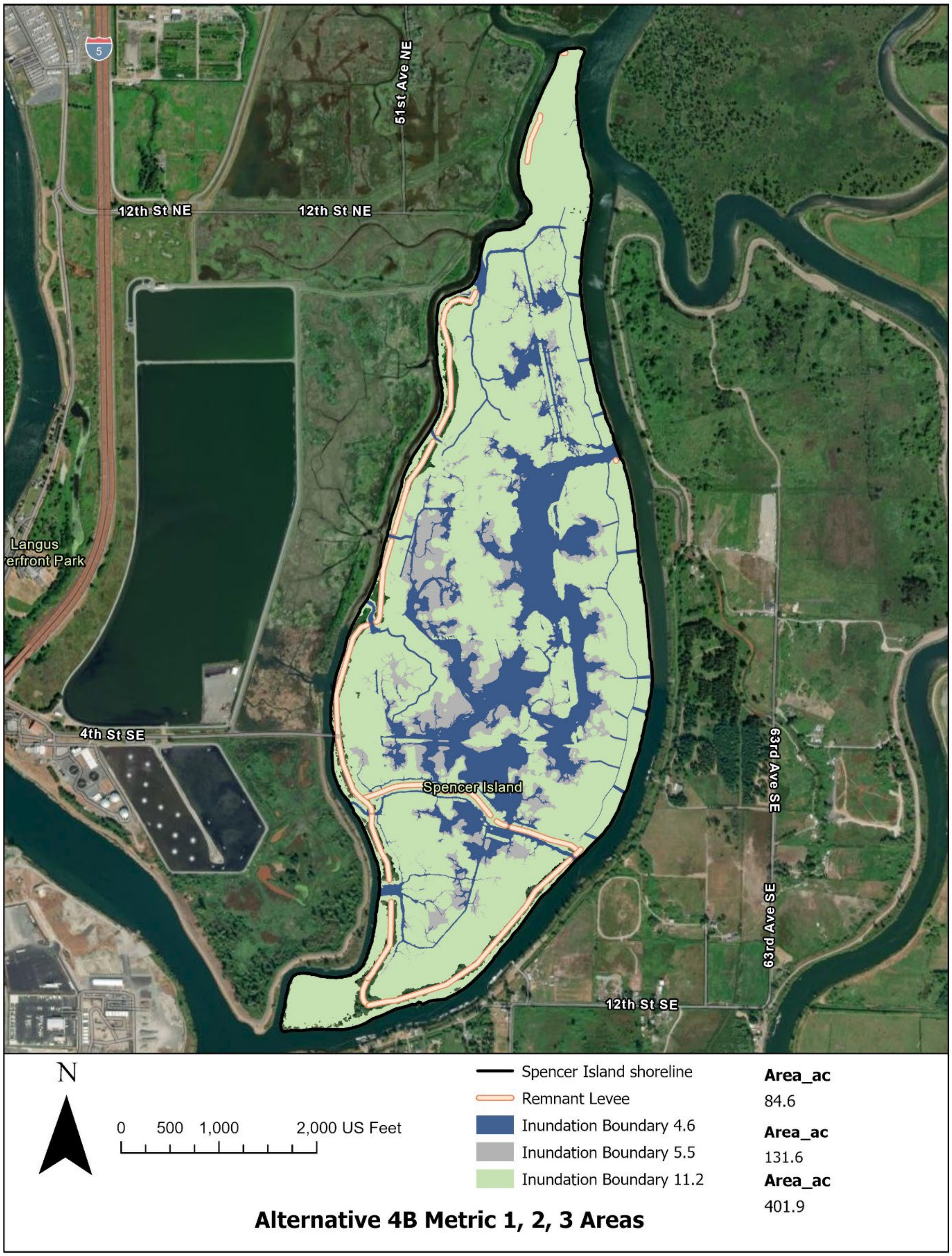

Figure 5. Alternative 4B inundation limits for Metrics 1, 2, 3

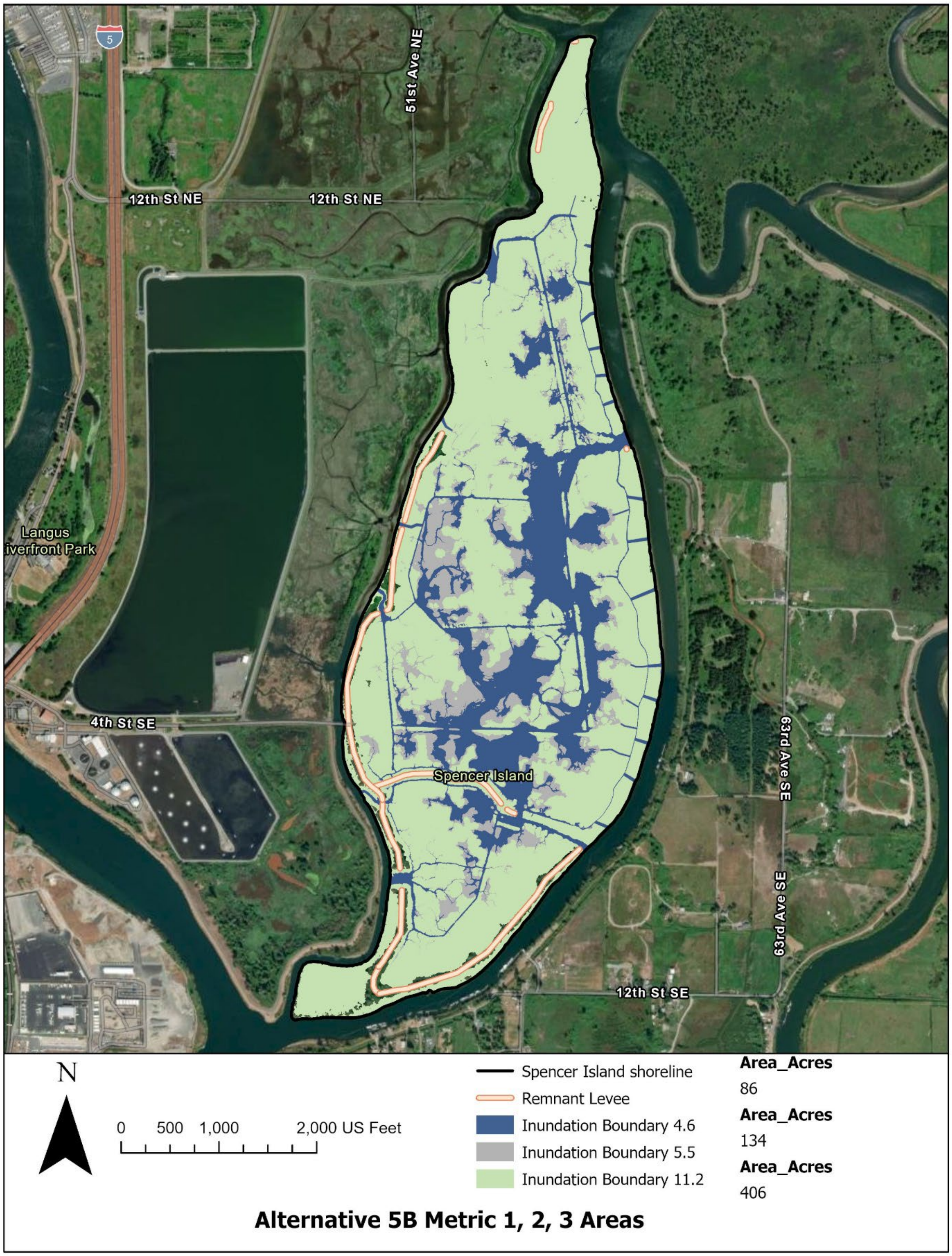

Figure 6. Alternative 5B inundation limits for Metrics 1, 2, 3

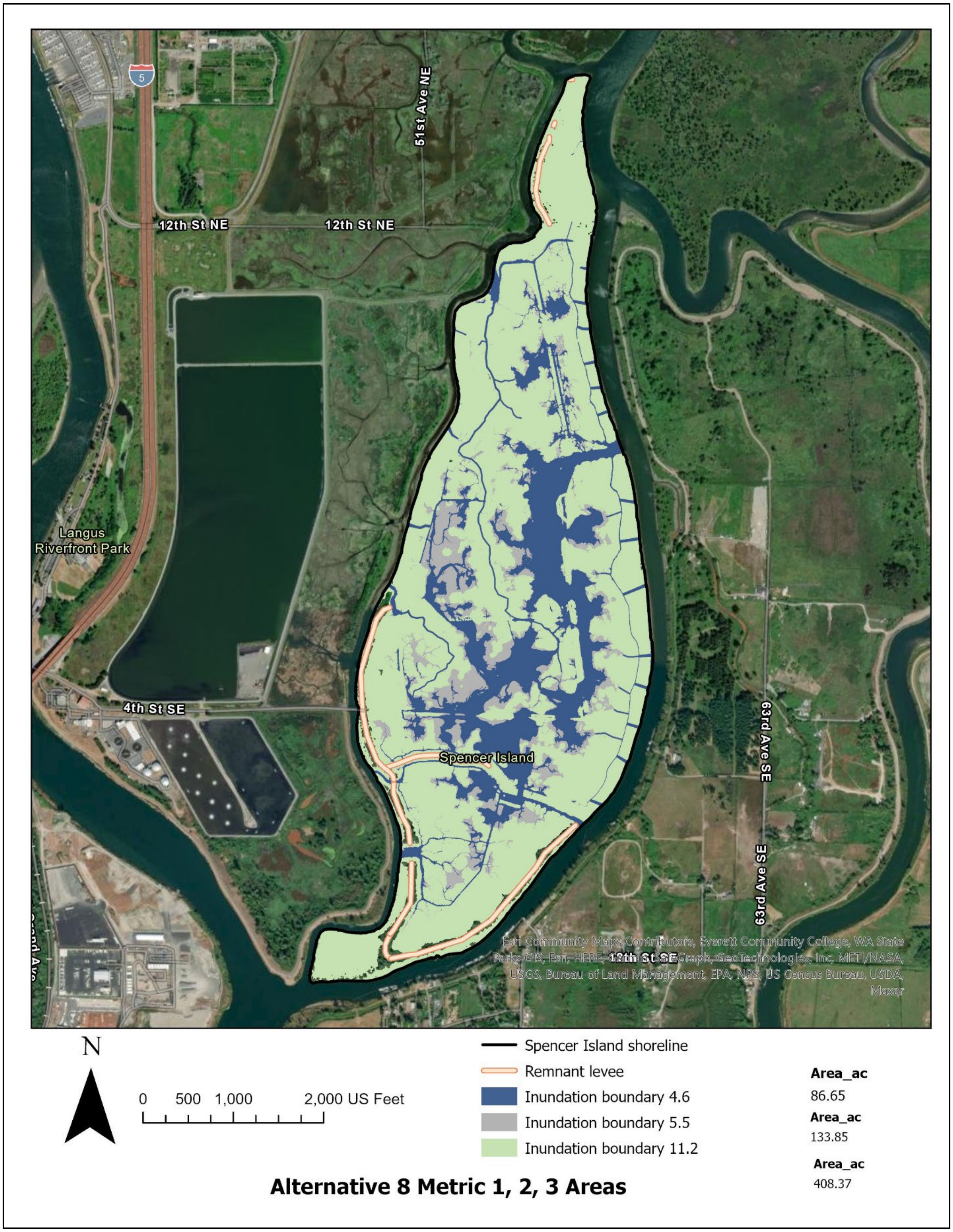

Figure 7. Alternative 8 inundation limits for Metrics 1, 2, 3

CENWS-ENH-H 2-JUNE 2023

TECHNICAL MEMORANDUM: Hydraulic Analysis of Spencer Island Ecosystem Restoration Feasibility Study Alternatives (DRAFT FOR REVIEW)

BLUF

This memorandum transmits the results of a hydraulic analysis (modeling) for 10 alternatives analyzed for the Spencer Island Ecosystem Restoration Project (project). See Reference 3 for alternative descriptions and work quantities. See Tables 2 through 4 for habitat quality score and quantity data. See Reference 4 for descriptions of the metrics and scoring methods.

REFERENCES

1. WSE 2021. Hydraulic & Hydrologic Modeling in the Snohomish Watershed. Prepared by Watershed Science and Engineering (WSE) for Snohomish County Public Works Surface Water Management Division, April 2021.
2. USACE 2023a. Documentation of 10-March 2023 recon survey of Spencer Island ecosystem restoration project. Memorandum prepared by Zac Corum, CENWS-ENH-H. 14-Mar. 2023.
3. USACE 2023b. Spencer Island Ecosystem Restoration Project Quantity Take Offs. Memorandum prepared by Alicia Rothery, CENWS-END-C. 31-May 2023.
4. USACE 2023c. Ecosystem Output Calculator for CAP and CAP-like River Delta Ecosystem Restoration in Puget Sound (draft, 6/2/2023). CENWS-PMP-P. June 2023.
5. W. Gregory Hood, Geographic variation in Puget Sound tidal channel planform geometry, Geomorphology, Volume 230, 2015, Pages 98-108. https://doi.org/10.1016/j.geomorph.2014.11.009

MODEL SETUP

1. The analysis computes inundation areas and velocities associated with each alternative including the no action alternative (NAA, Alternative 1) for a representative June spring tide series spanning two weeks that bound the maximum astronomic tide range. June is typically the period where juvenile salmonids are out-migrating to the estuary and beginning to forage in tidal marshes before entering Puget Sound (Nancy Gleason, pers. communication).
2. The analysis was conducted with a modified version of the Snohomish County HEC-RAS 2D model developed by Watershed Science and Engineering (Ref. 1). The original WSE model spans the entire Snohomish River and floodplain and extends upstream the Snoqualmie River to the Carnation gage and the Skykomish River to the Gold Bar gage and requires 24 hours of computation time to analyze a single flood event. For practical reasons, Seattle District Hydraulic Engineering Section truncated this model by deleting the portions upstream of the Snohomish mainstem Monroe USGS gage and running it with observed flows at the USGS gage and tides from the NOAA Seattle gage. See Figure 1.
3. The underlying data for the model are a combination of bare earth topo-bathymetric Lidar merged with single beam bathymetric surveys of the mainstem and sloughs (Ref. 1). Hydraulic Engineering Section supplemented the bathymetric data with a survey of the Spencer Island ditches and main breach channel using a consumer grade depth sounder combined with RTK GPS (Ref. 2).

4. The Modified WSE model was run for two weeks in June 2022 based on observed flows and tides. This model was then truncated near the Spencer Island project site and the underlying model mesh refined to provide reliable computations of depth and velocity in breach channels and around levees. Model outputs (time series of stage and flows) from the larger modified model are then used as boundary conditions for the Spencer Island project site 2D HEC-RAS models. See Figure 2 for the Puget Sound tide series data, Figure 3 for the flow data used in the
5. Modified WSE model used to derive boundary conditions for the detailed models presented in this memorandum. Local flows are ignored in the analysis as the focus of the modeling is tidal flux and inundation associated with salmon use, not flooding.
6. The models are not presently calibrated to conditions local to Spencer Island, however the larger model by WSE is calibrated to recent floods and is wholly adequate for a 10% plan evaluation.
7. Ten unique terrain, geometry and plan files were created, one for each alternative. All plans use the same two-week tide and flow boundary conditions. Where grading work occurs Manning's roughness value overrides are used. See Reference 3 for plan views of the various alternatives.
8. Modeling indicates that inundation at the site is never static – there are always portions of the island that are filling or draining in a tide cycle, even if the tide in the distributaries is slack (flood or ebb). For this reason, the water surface elevations in the marsh can differ from those in adjacent distributaries by a foot or more in elevation at the same point in time, which confounds computation of inundation area associated with a particular tidal datum (such as mean tide, mean low water, etc.).
9. To simplify quantification of restoration metric inundation acreages a steady state HEC-RAS model was created to compute inundation associated with a steady tide associated with a particular metric and restoration alternative grading plan. In this model the stage in the distributaries is held constant until steady state inundation is achieved. This forces all areas within the restoration site to inundate to the same tide elevation for a given condition and thus reduces the uncertainties associated with how many acres could be wetted for a particular grading plan and tide.

MODEL RESULTS

Tides

1. Tidal fluctuation in response to the June tide series (Figure 3) at the confluence of the main breach channel and Steamboat Slough is shown in Figure 5. No detectable differences in stage are observed suggesting that the changes within the site topography are not resulting in impacts to the adjacent distributary channels for the non-flood June simulation period. Once a preferred alternative is selected, the 35% hydraulic analysis will be conducted to verify any off site impacts are within tolerable ranges for flood conditions.
2. At the south cross dike bridge the channel goes dry once the stage on both sides of the bridge drops below elevation 2.0 ft NAVD 88 due to an existing riprap sill. This sill is both a physical barrier preventing natural ingress and egress to the restoration site and a velocity barrier when stages are higher than the sill. As shown in Figure 5, stages associated with high tides are unaffected, however stages at low tides are significantly reduced for alternatives that remove the existing bridge and riprap sill and replace them with a natural channel. Alternatives 5A, 5B,

6A, 6B, and 7 are clearly more restorative than alternatives 1, 2, 3, 4A and 4B as the stages follow the low tide down without "flatlining" at the sill. This indicates water is present in the channel connecting the restoration sites throughout the tide cycle, rather than going dry for a good portion of the tide cycle.

Flows

1. The existing levees around Spencer Island are generally too high to be eroded by high flows, concentrating tidal exchange to three locations where the levee has failed previously or been intentionally breached. One tide gate is present along Union Slough that would be removed in all alternatives and replaced with a breach or a breach and bridge. The tide gate was installed prior to the main levee breach and has a flap gate that drains the site but does not allow back flow. Another breach constructed by Ducks Unlimited was constructed at the north end of the site, connecting it to Union Slough. Both the tide gate and breach convey only a small portion of the daily tidal exchange relative to the other breaches connected to Steamboat Slough.
2. Velocity barriers are present because of excessive tidal flux and incomplete erosion of adjacent marshlands following unanticipated natural levee breaches. These "hot spots" are the focus of the analysis as they are located at the primary ingress and egress points connecting the restoration site to the adjacent sloughs.
3. The variation in tidal flux (flow) within the site is partially illustrated in Figure 5 that shows the flow into the site (negative discharge) from the connected distributary and out of the site (positive discharge) at the main breach connecting the site to Steamboat Slough and at the south cross dike, the two connection points that experience the largest daily tidal exchange. Changes in flux are a desirable outcome of restoration actions. Due to the subsided topography the existing breach has widened and deepened in response to excessive tidal flux, and likely river flows as well. The modeling indicates flux is highest on the flood tide phase of the daily tide cycle, with the peak flood flow about twice the peak ebb flow.
4. All alternatives that increase the number of connection points along the levee between the site and adjacent distributary channels spread out the daily tidal flux into the site and reduce flow and velocity at the primary breach channel. The scale of the effect depends on the number and size of the breach connections.
5. At the south cross dike (Figure 6) the removal of the existing bridge and sill significantly increases flux on both the ebb tide, but much less so on the flood tide. Since the ebb tide is the portion of the tide cycle that fish trying to enter the site would have to swim against, increases in ebb tide velocities associated with increased flow could be problematic. Fortunately, as shown in the velocity discussion, if a natural channel is used to replace the bridge, velocities can remain below a threshold of impact despite the much higher flow in the channel.

Velocities:

1. For determination of habitat quality scores, the existing conditions model results were scrutinized to identify velocity hot spots within the Spencer Island site at primary ingress and egress locations for fish that are likely to pose barriers for unrestricted juvenile fish movement (velocities exceed sustained swimming speeds). Three locations were identified that are

representative of challenges fish face trying to reside within the site during the ebb (outgoing) tide. All are associated with remnant or existing infrastructure (dikes, culverts, bridges).

2. The largest hot spot is located at the main breach channel connecting the site to Steamboat Slough. This breach formed around 2005 in response to river flooding at the location of a tide gate installed in the 1990s. The breach has grown progressively and is almost 200 feet wide and more than 25 feet deep in places. The breach can convey several thousand cubic feet per second during a single tide cycle. This has resulted in deep scouring of the channel and ongoing erosion of the adjacent banks and marsh plain. Velocities at this location can exceed 5 feet per second on a flood tide (incoming) and 3 feet per second on an outgoing tide (Figure 7).
3. Another important hot spot is the northern connection point of the ditch draining the southern portion (two thirds of the site area) to the main breach channel. The ditch is significantly undersized for existing tidal flux, which has resulted in widespread erosion of the marsh nearby.
4. At the south end of the site WDFW and Snohomish County constructed a cross dike. This dike breached in around the same time that the main breach along Steamboat Slough formed (2005). In response to the breach a new bridge was installed to maintain cross dike access. This bridge includes a riprap sill at elevation 2 ft NAVD 88. This location is a physical barrier, erosion hot spot and velocity barrier for fish that attempt to avoid being flushed out with the tide.
5. The highest modeled velocities are associated with peak flood tide conditions, when the distributary channels are rising from the lower low to the higher high tide, followed by peak ebb tide conditions when the distributaries are falling from the higher high to lower low tide. As shown in Figure 7 and Figure 8 and summarized in Table 1, average ebb tide velocities in the main breach channel decrease between 4% (Alt 2) and 35% (Alt 7). All alternatives that include small breaches along Steamboat Slough reduce average velocities at the main breach by 25% (Alt 3) to 35% (Alt 7) and maximum velocities by 19% (Alt 4A) and 26% (Alt 5B). Expansion of the existing breach along Union Slough in concert with levee lowering (Alt 2) does not appear effective at reducing velocities at the primary hot spot.
6. At the main ditch confluence with the main breach, which is an area of ongoing erosion, average ebb tide velocities in the June spring tide series are reduced by as little as 4% (Alt 2) to as much as 56% (Alt 7). Modification of the ditch by converting portions to a sinuous tidal channel appears to be the most effective way to address undersized conditions responsible for excessive velocities (Alts 4A, 4B, 7), however adding breaches without modifying ditches provides substantial benefit as well (Alts 3, 5A-B, 6A-B). Maximum velocities at this location are potentially reduced by 5% (Alt 2) to as much as 58% for Alt 4B and Alt 7.
7. At the south cross dike bridge sill which has the highest velocities of all hot spots average ebb tide velocities in the June spring tide series are decreased by -4% (Alt 2) to -80% (Alts 6A, 6B). Two alternatives (4A, 4B) that do not modify the sill but block and rechannelize ditches near the cross dike potentially increase velocities at the hot spot by 2% (Alt 4A) to 5% (Alt 4B). Maximum velocities at this location are potentially increased by as much as 8% (Alt 4A) and decreased by as much as 78% (Alts 6A, 6B). Significant reductions are also seen for Alt 3, 5A, and 5B, and 7. It is notable that addition of breaches along Steamboat Slough even without modification of the cross dike (Alt 3) is beneficial at this location, however removal of the bridge, sill and laying the banks back to accommodate a natural channel appears to be the most effective strategy to address velocity barrier concerns at this location

8. The time series of velocity data described above were analyzed as part of the Metric 1 channel connectivity evaluation, described below.

Habitat Quality & Quantity Scores

1. **Metric 1: Channel Connectivity:**
    a. From a fish use standpoint, excessive flows and velocities into the site are not considered problematic, however if these fish are then washed out in subsequent ebb tide, conditions then become problematic. For this reason, the velocity data at the hotspots were extracted and filtered to exclude flood tides, and then the ebb tide data were analyzed to determine the frequency during the simulation that the hot spot velocity exceeds an impact threshold of 1.5 feet per second (Reference 4).
    b. The Metric 1 Habitat Quality Score (HQS) is the average frequency in time below the impact threshold for the three hot spots during ebb tides in June. Alternatives that reduce the frequency of excessive velocities have higher HQSs (maximum of 1, or 100% of the time) than those that do not.
    c. See Table 2 for a summary of Alternative HQS and quantities.
    d. From inspection the average % time below the impact threshold at the three hot spots varies by 64% for the NAA, to 91% for Alt 7. The NAA has conditions impactful for fish 36% of the time during ebb tides based on this metric, which seems considerable. Alts 3 through 4B are significantly better than the NAA. Alts 5A-B, 6A-B, and 7 are all quite similar in HQS. Alt 2 (the PSNERP approved design) performs marginally better than the NAA and significantly worse than all other action alternatives indicating the reformulation requested by Division has helped identify superior courses of action.
    e. Removal of the cross-dike bridge is the common element for alternatives that have high HQSs for this metric. The HQS approaches or reaches 100% for the ditch exit (Alts 4A, 4B) and cross dike (Alts 5A-7) which indicates conditions are significantly improved for fish. However, the reduction in time below threshold for Alt 4B at the cross dike (worsened conditions) suggests this measure should not be implemented without inclusion of additional breaches or levee lowering.
    f. The June two-week average daily low tide at the confluence with Steamboat Slough (4.6 ft NAVD 88) is representative of conditions when peak ebb tide velocities occur. This stage would be well within the banks of natural tidal channels but due to subsidence at Spencer Island results in inundation outside of the extents of the existing ditch network. At the daily low-low tide, slack water conditions are approached, and velocities are infrequently above the impact threshold. Inundation maps associated with this condition used in the quantity scoring are shown in Figure 9 through Figure 18.

2. **Metric 2: Marsh Connectivity Habitat Quality**
    a. One of the primary objectives of Puget Sound restoration is to increase the availability of tidal marsh habitat which is critical for survival and recovery of threatened and endangered salmonids.
    b. Research by Dr. Greg Hood (Ref. 5) documented the “allometry”, or recurring geomorphic patterns of existing Puget Sound river delta tidal marsh islands with the

specific purpose if identifying natural trends and variabilities on island blind tidal channel frequency and size to aid in design of ecosystem restoration projects such as Spencer Island. The regression analysis relates marsh island area to the number of connections, the largest connecting channel size, the total length of the channel network, and many other variables.

c. The frequency (or number) of blind tidal channel connections between a marsh island and adjacent distributary channel network is an important output variable from the regression analysis as it directly correlates to the opportunities for fish to access a marsh island during the outmigration to the estuary.
d. Using Lidar data and air photos, we estimated that there are at least 31 connections between Spencer Island and Union and Steamboat Sloughs at present. Note that many of these occur along levees and the connected channels are truncated significantly reducing tidal flux and size. The highest frequency (and quality) of channels occurs at the north and south ends of the island where levees are absent or purposely breached.
e. Using the Hood regression equations, the median estimate for the total number of blind channel connections is 51, which indicates a potential restoration goal should be to add as much as 20 new connections to adjacent sloughs. Given the infrequency of connections along existing levees the PDT elected to focus on those areas.
f. Table 3 summarizes the number of existing and new breach channels by alternative that are connected to distributaries. Internal channels are not counted in this analysis.
g. The NAA alternative has the lowest HQS (0.61), which is negligibly increased by Alt 2 (PSNERP approved plan).
h. The Metric 2 HQS is simply the ratio of the total number of existing and new breach channel connections to the regression prediction.
i. Arguably this metric HQS could go above 1 if more channels were added to increase the likelihood of fully connecting the site.
j. Quantity scores for this metric were based in the average tidal elevation during the June 2022 simulation period. This stage (5.5 feet) corresponds to an elevation that is about equal to the zone of perennial vegetation and represents areas where fish would be able to access marsh vegetation for foraging or shelter.
k. Inundation maps associated with this condition used in the quantity scoring are shown in Figure 9 through Figure 18.

3. **Metric 3: Floodplain Connectivity**:
    a. Removal of stressors such as roads, dikes, levees, and revetments that are degrading estuarine habitat is a primary goal of the PSNERP project and Puget Sound recovery efforts.
    b. Spencer Island has a total shoreline length of 24,455 feet (4.6 miles). The island has been a focus of dike construction since the late 1800s. As shown in Table 4 The total length of actively maintained and remnant dikes (levees) higher in elevation than the maximum June tide (elevation 11 feet) is 19,510 feet (3.7 miles) for existing conditions, which represents a total dike to shoreline length ratio of 80%. In a sense 80% of the island has dikes that interrupt the fluvial and coastal processes associated with flooding.

c. Presumably removal of all dikes and levees from the island that disrupt natural processes associated with flooding would represent the largest potential restoration benefit when ranking alternatives.
d. Alternatives developed for this 10% analysis lowered levees consistent with the locations of the PSNERP conceptual report, but to increase connectivity to Union Slough and adjacent restoration sites, alternatives were developed by the PDT that remove portions of the Union Slough levee and south cross dike.
e. Target lowering elevations for all levees are 10.6 feet NAVD 88. This elevation corresponds to an elevation that corresponds to the average shoreline elevation along the undisturbed Otter Island, located just downstream of Spencer Island.
f. The peak June tide (modeled) exceeded 11 feet NAVD 88. This is an astronomic spring tide, not a flood, but is about 2 feet above the MHHW elevation of 9 feet and is exceeded a few times a year (not accounting for river flooding). Inundation maps associated with this condition used in the quantity scoring are shown in Figure 9 through Figure 18.
g. GIS was used to delete the portion of existing levee polylines that became inundated for the maximum June tide in the model to determine the total length of levee remaining on site that would likely continue to impair natural processes.
h. From inspection of Table 4 Alts 2 and 3 and 4B would more than double the NAA HQS, indicating they are highly beneficial from the standpoint of this metric. Alternative 5B has about 3 times higher HQS than the NAA. The alternatives that remove the levees without providing bridge access (4A, 5A, 6A, 7) have 3.5 to 4 times the HQS of the NAA.
i. Note that for the 35% - 100% designs, the actual shoreline length restored through levee removal will likely be less than that indicated in this analysis. This is because significant standing riparian trees will be preserved wherever possible.

NEXT STEPS

1. Once the selected plan is identified the existing and with project detailed models need to be incorporated into the full Snohomish model to evaluate conditions during the full range of floods, for existing and future (with and without project) conditions.
2. The existing conditions model will need to be calibrated to stage recorder data near Spencer Island. This will likely require considerable effort to accomplish given the long model run times.
3. New ditch survey data should be incorporated into the pending 35% model prior to calibration.

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TABLES

FIGURES

Table 1. Ebb tide velocity data for June tide series for three primary velocity barrier locations

Location	Statistic		Ex Cond	Alt 2	Alt 3	Alt 4A	Alt 4B	Alt 5A	Alt 5B	Alt 6A	Alt 6B	Alt 7
Main breach	Avg		1.06	1.02	0.79	0.73	0.73	0.79	0.74	0.73	0.75	0.69
	Min		0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00
	Max		3.17	3.26	2.52	2.56	2.49	2.54	2.35	2.41	2.51	2.49
	% Change from existing conditions	Avg		-4%	-25%	-31%	-31%	-25%	-30%	-31%	-29%	-35%
		Max		3%	-20%	-19%	-21%	-20%	-26%	-24%	-21%	-21%
Ditch Exit	Avg		1.07	1.03	0.95	0.53	0.50	0.74	0.72	0.88	0.71	0.47
	Min		0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00
	Max		3.38	3.20	3.13	1.56	1.43	2.19	2.22	2.64	2.01	1.41
	% Change from existing conditions	Avg		-4%	-11%	-50%	-54%	-31%	-33%	-18%	-34%	-56%
		Max		-5%	-7%	-54%	-58%	-35%	-34%	-22%	-41%	-58%
Cross Dike	Avg		1.43	1.36	1.08	1.45	1.48	0.32	0.32	0.28	0.28	0.31
	Min		0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Max		4.38	4.34	3.88	4.72	4.58	1.32	1.32	0.96	0.98	0.99
	% Change from existing conditions	Avg		-4%	-24%	2%	4%	-77%	-78%	-80%	-80%	-78%
		Max		-1%	-11%	8%	5%	-70%	-70%	-78%	-78%	-77%

Table 2. Metric 1 (Channel Connectivity) quality and quantity results

	Metric 1 Habitat Quality Score @ Barrier Locations (% time ebb tide below 1.5 ft/s)				Metric 1 Quantity
Alternative	Main Breach	Main Ditch Outlet	Cross Dike Bridge	Average	Acres Inundated at "Mean June Low Tide" (A1)
No Action	70%	69%	64%	68%	88.0
Alt 2	72%	69%	66%	69%	89.1
Alt 3	81%	78%	73%	77%	90.6
Alt 4A	83%	99%	64%	82%	89.6

Alt 4B	84%	100%	62%	82%	89.6
Alt 5A	81%	83%	100%	88%	91.7
Alt 5B	84%	85%	100%	89%	91.7
Alt 6A	83%	82%	100%	88%	92.0
Alt 6B	82%	87%	100%	90%	92.0
Alt 7	85%	87%	100%	91%	92.5

Table 3. Metric 2 (Marsh Connectivity) quality and quantity results

	Blind tidal channel connections between Marsh Island and Distributary Network			Metric 2 Habitat Quality Score	Metric 2 Quantity
Alternative	**Existing (#)**	**New (#)**	**Hood (2015) Restoration Target (#)**	**(Existing + New)/Target**	**Acres Inundated at "Mean June Tide" (A2)**
No Action	31	0	51	0.61	138
Alt 2	31	1	51	0.63	138
Alt 3	31	10	51	0.80	140
Alt 4A	31	12	51	0.84	139
Alt 4B	31	12	51	0.84	139
Alt 5A	31	18	51	0.96	141
Alt 5B	31	18	51	0.96	141
Alt 6A	31	20	51	1.00	142
Alt 6B	31	20	51	1.00	142
Alt 7	31	20	51	1.00	142

Note 1: # New connections excludes interior connections at North Cross Dike and South Cross Dike. Removal of existing south cross dike bridge at Steamboat Slough including bank resloping counted as a breach

Table 4. Metric 3 (Floodplain Connectivity) quality and quantity results

Alternative	Shoreline length data (see note 1)		Metric 3 HQS	Metric 3 Quantity
	Total Length of Levee (TLL)	Total Island Shoreline Length (TSL)	HQS 3 = (TSL-TLL)/TSL	Acres Inundated at "Max June Tide" (A3)
No Action	19510	24455	0.20	392
Alt 2	12782	24455	0.48	403
Alt 3	12782	24455	0.48	403
Alt 4A	7953	24455	0.67	411
Alt 4B	12598	24455	0.48	403
Alt 5A	7131	24455	0.71	412
Alt 5B	9993	24455	0.59	407
Alt 6A	5667	24455	0.77	413
Alt 6B	8449	24455	0.65	408
Alt 7	5667	24455	0.77	413

Note 1: Length of levee is length of all levee segments on island that are not inundated during max tide condition (i.e. are still impacting connectivity)

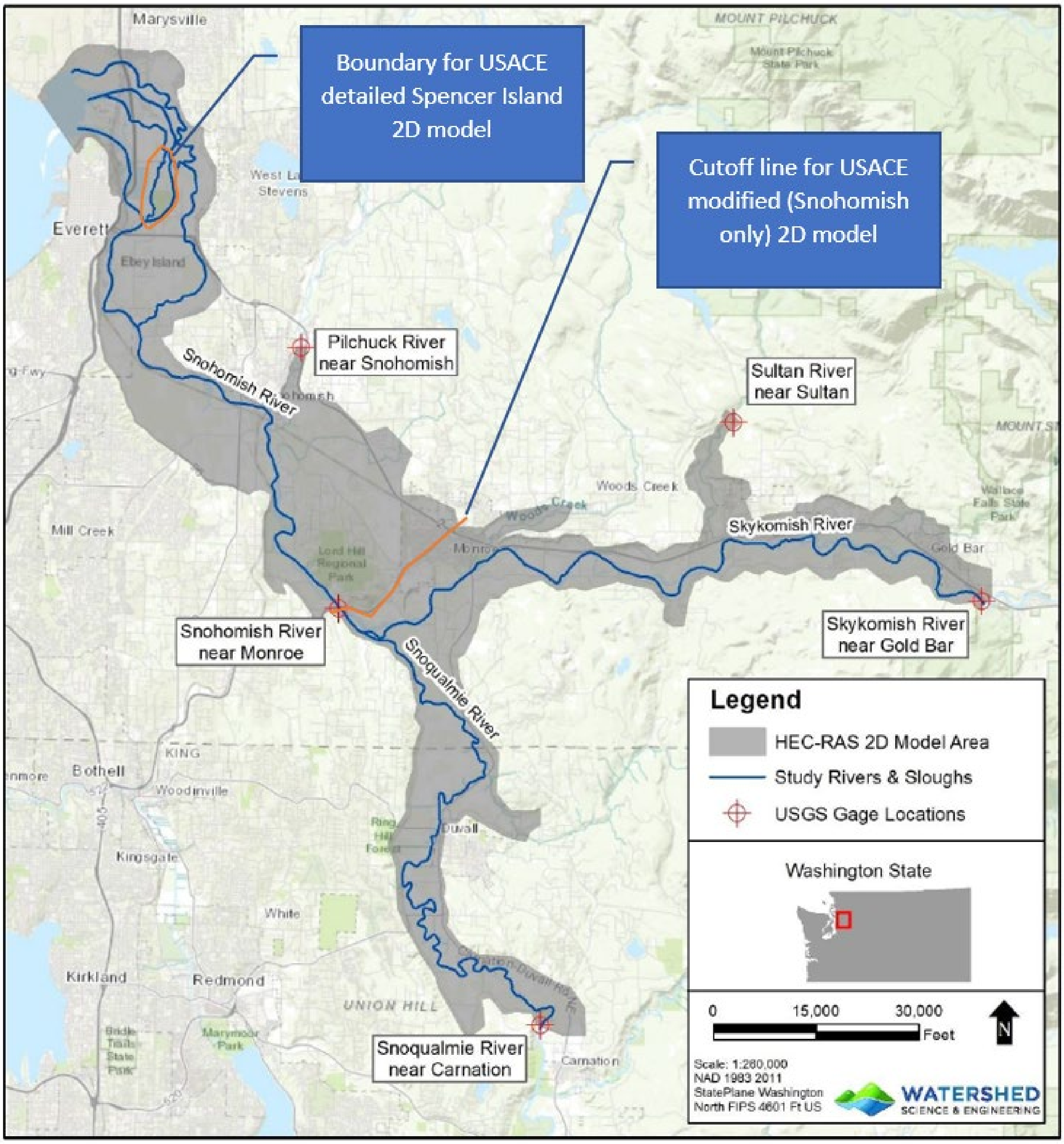


Figure 1. Modified and detailed model extents and boundary conditions

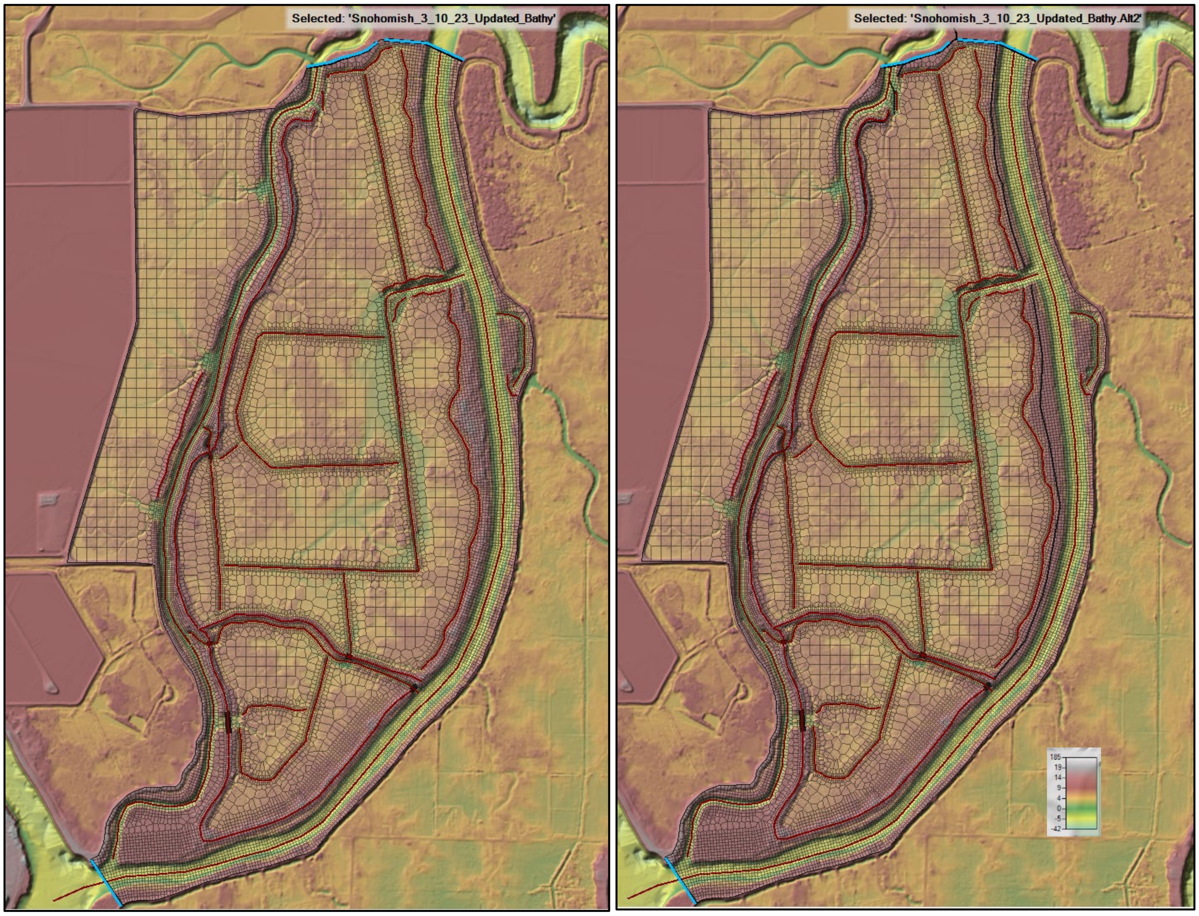
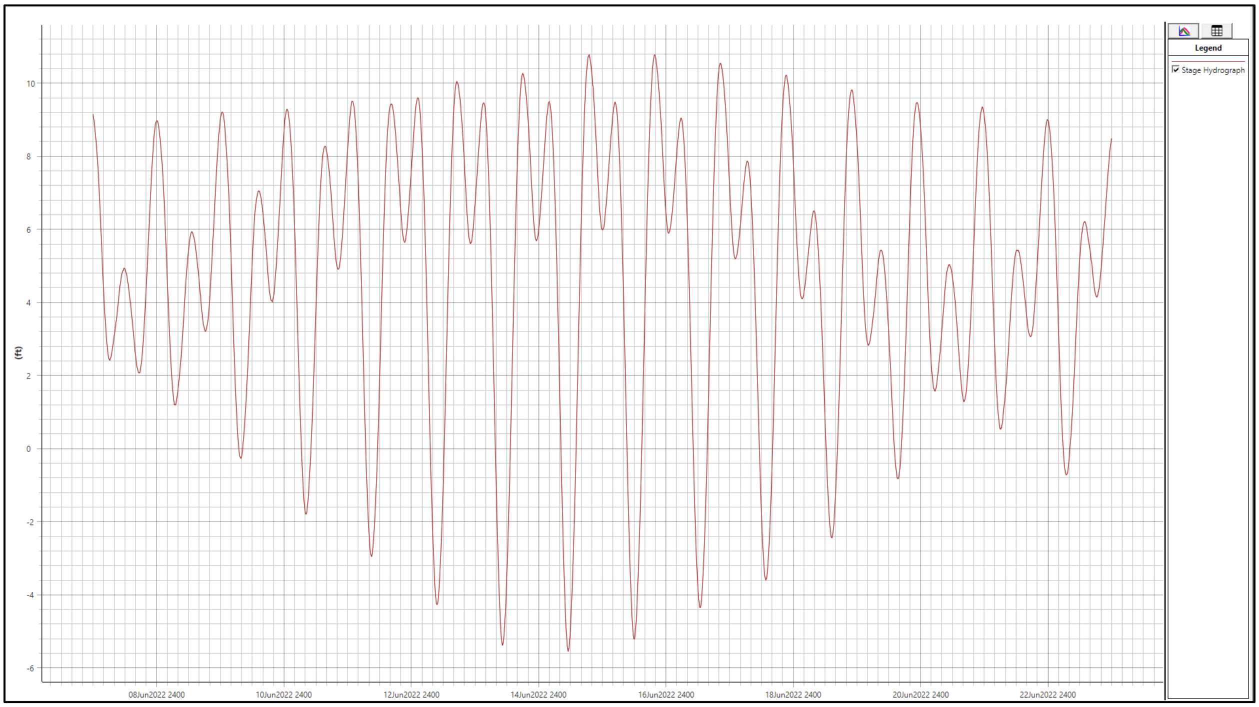


Figure 2. Example of detailed 2D meshes used for HEC-RAS analysis of existing conditions (No Action Alternative) and Alternative 2



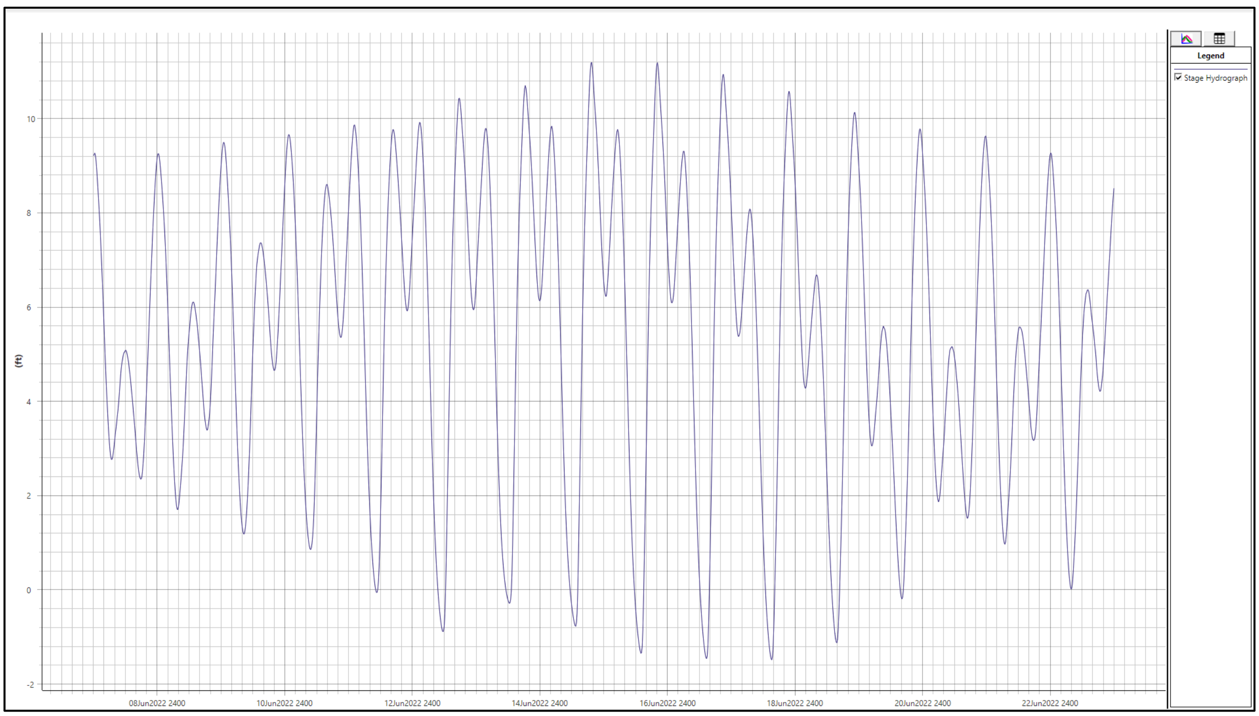


Figure 3. June tide series used as Modified model downstream boundary condition (above) and boundary conditions computed from Modified model used in detailed model at Steamboat Slough downstream boundary (below)

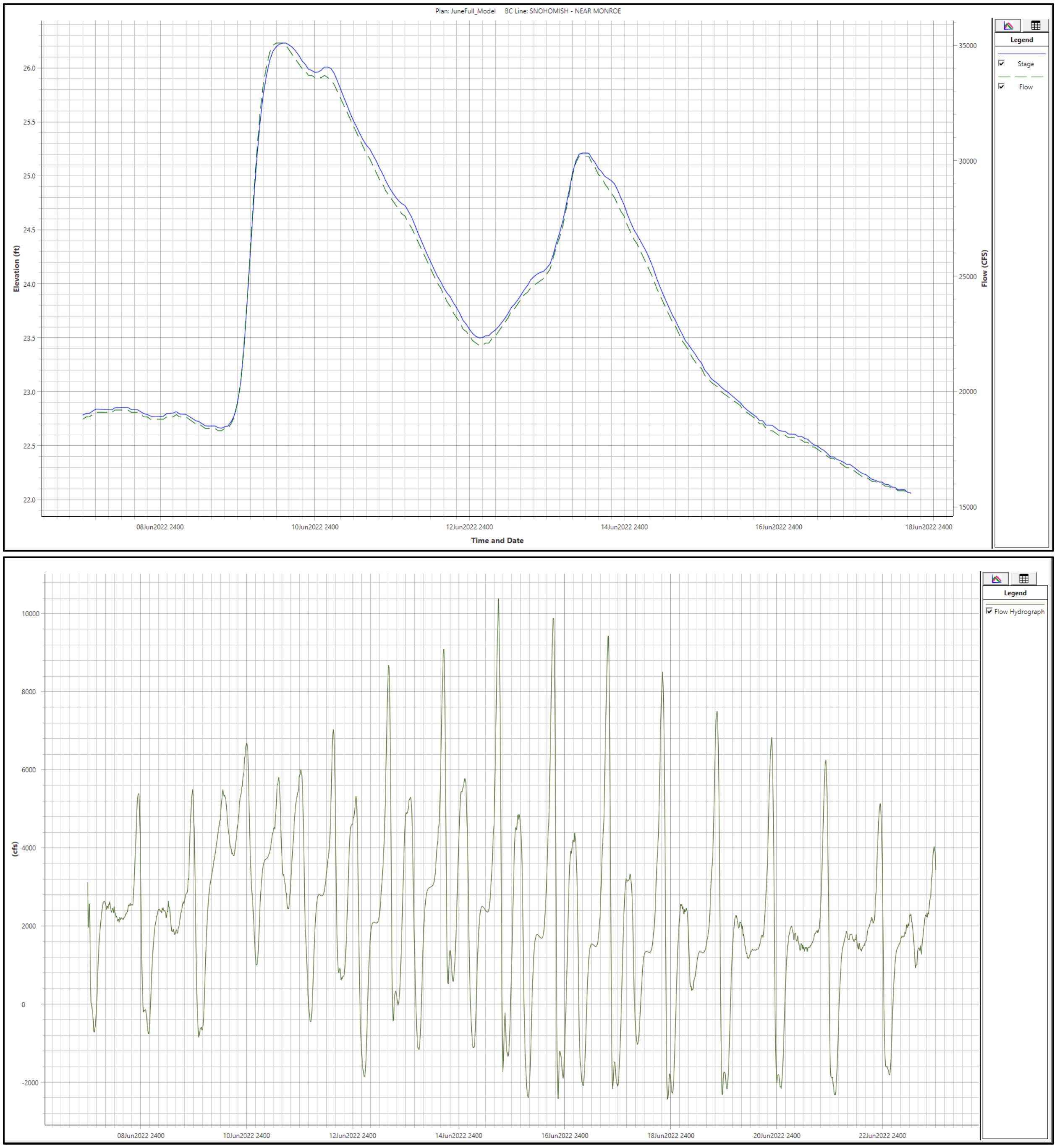


Figure 4. June flows at the Monroe USGS gage used as Modified model upstream boundary condition (above) and computed flows used for detailed model upstream boundary condition (below)

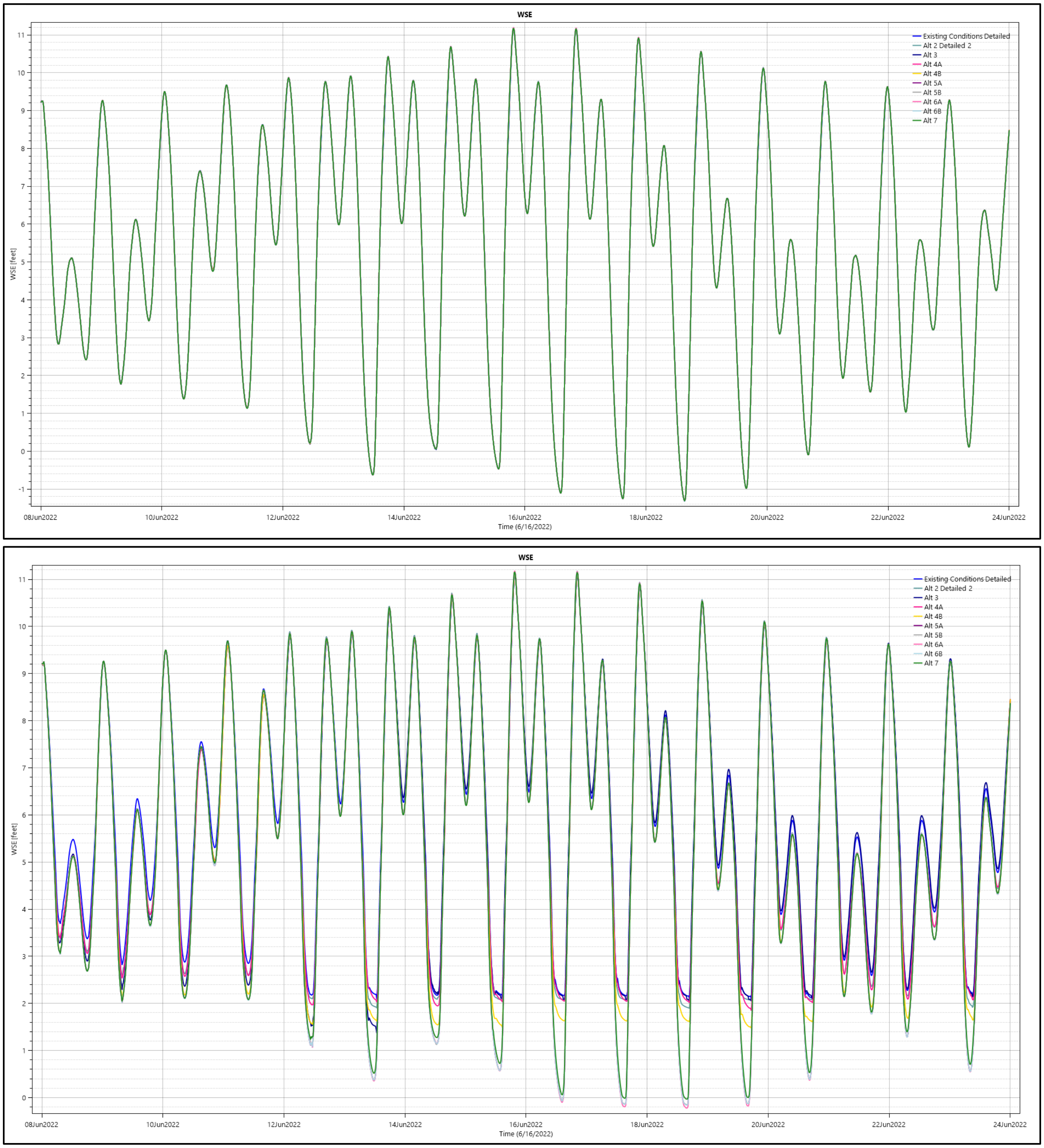


Figure 5. Simulated stages at main breach (above) and cross dike bridge (below) for all alternatives

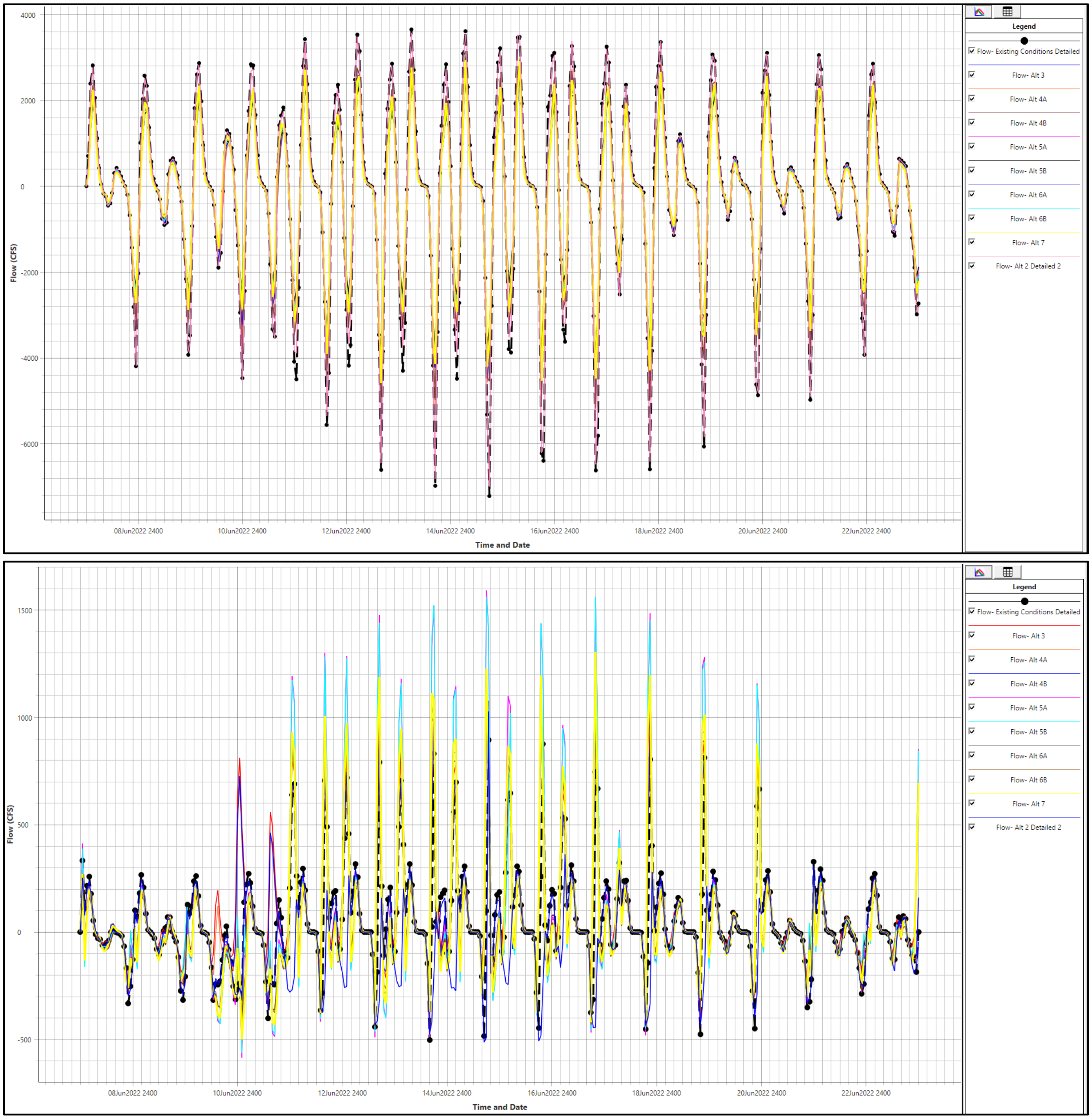


Figure 6. Simulated flows at main breach (above) and south cross dike bridge (below) for all alternatives

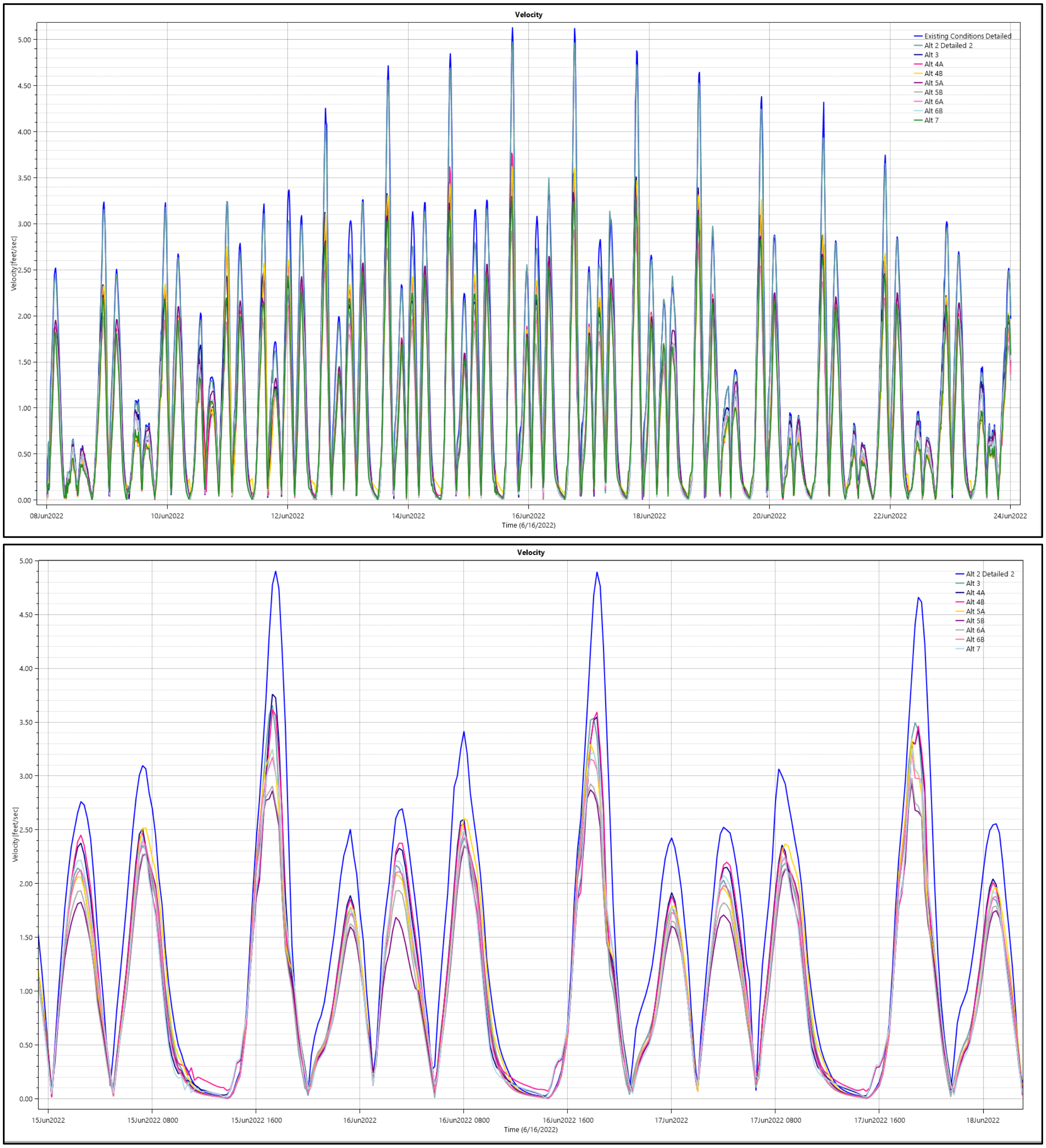


Figure 7. Simulated velocities at main breach for all alternatives (entire simulation period, above, peak velocity period, below)

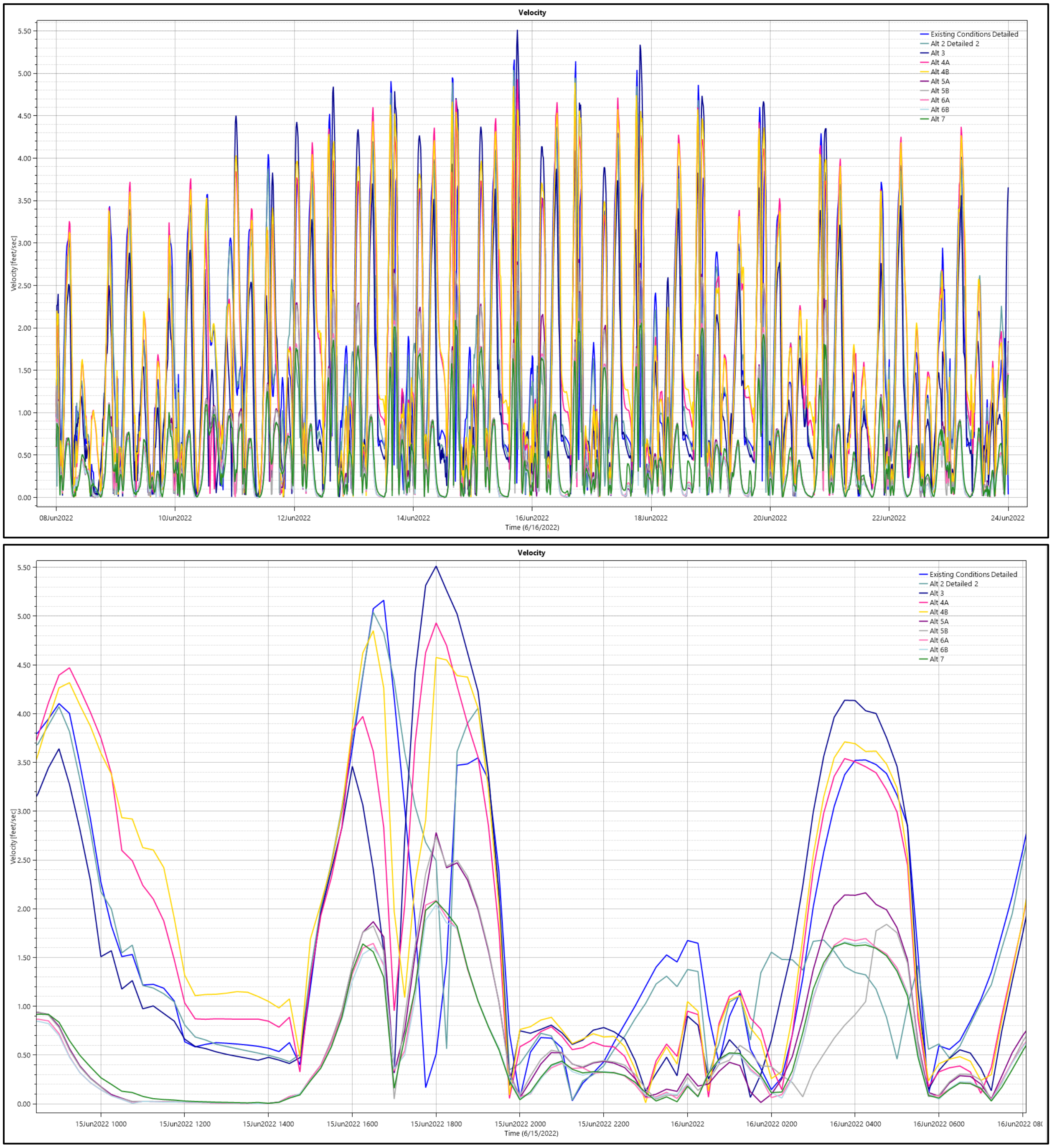


Figure 8. Simulated velocities at main breach and cross dike bridge for all alternatives

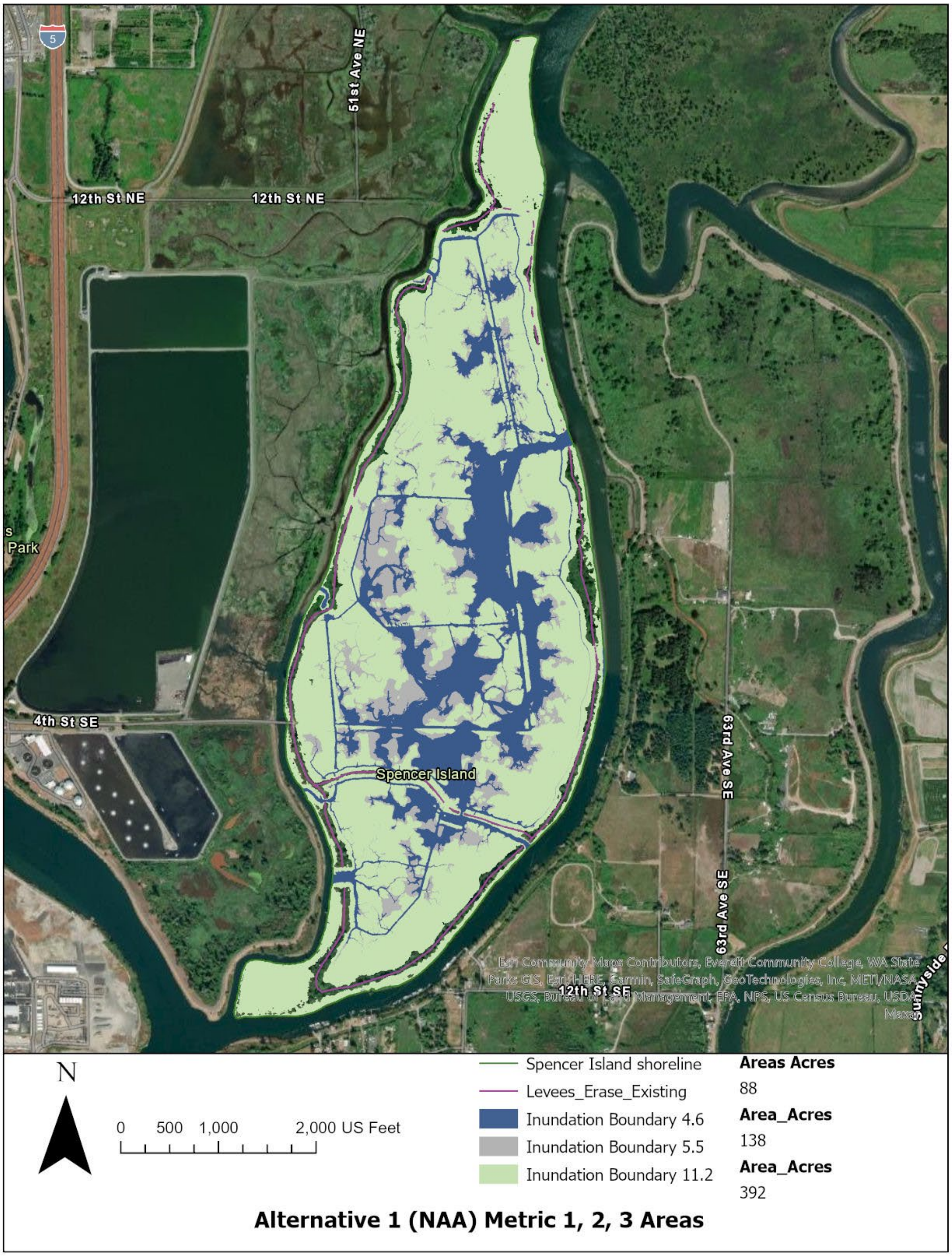


Figure 9. Alternative 1 (No Action) inundation limits for Metrics 1, 2, 3

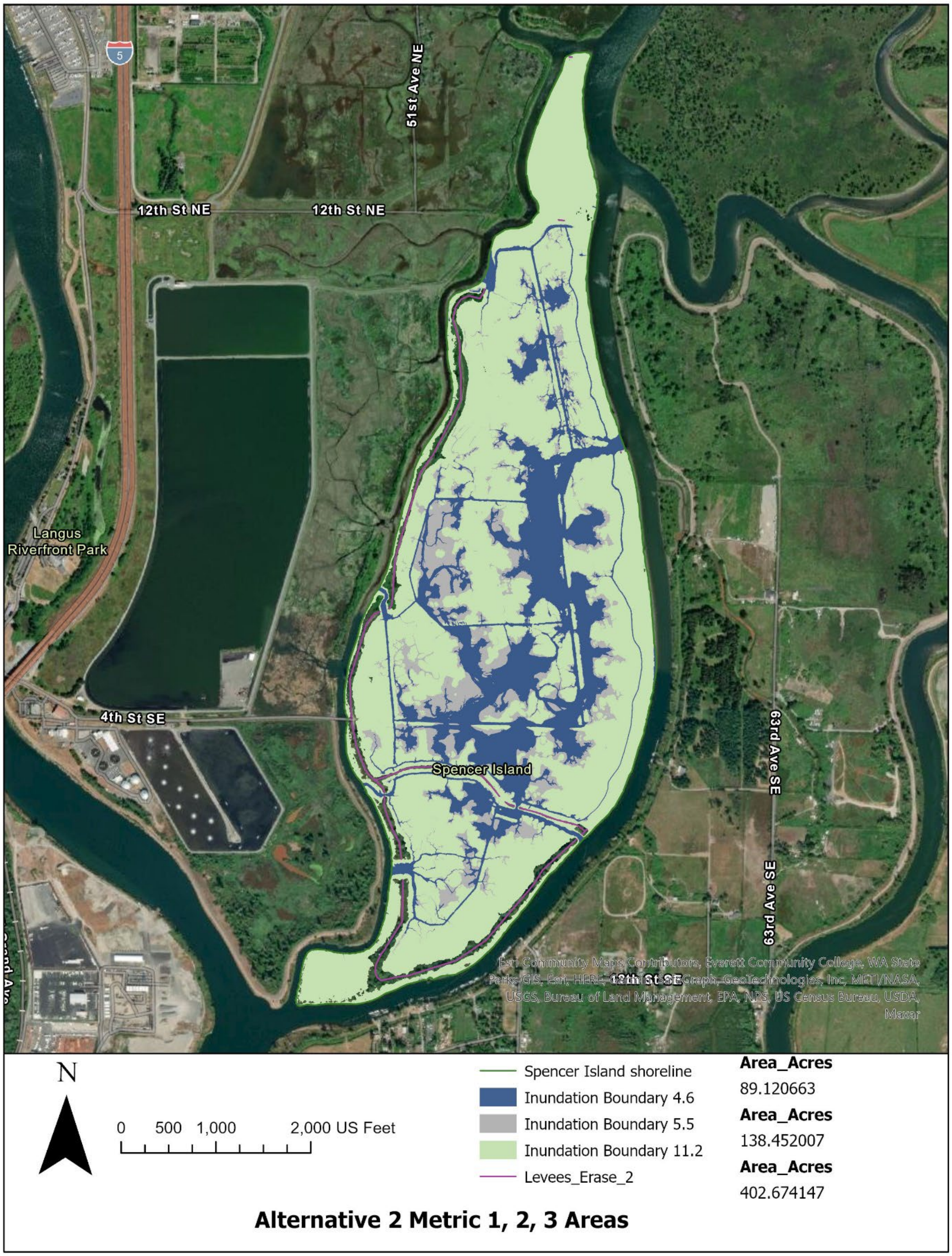


Figure 10. Alternative 2 inundation limits for Metrics 1, 2, 3

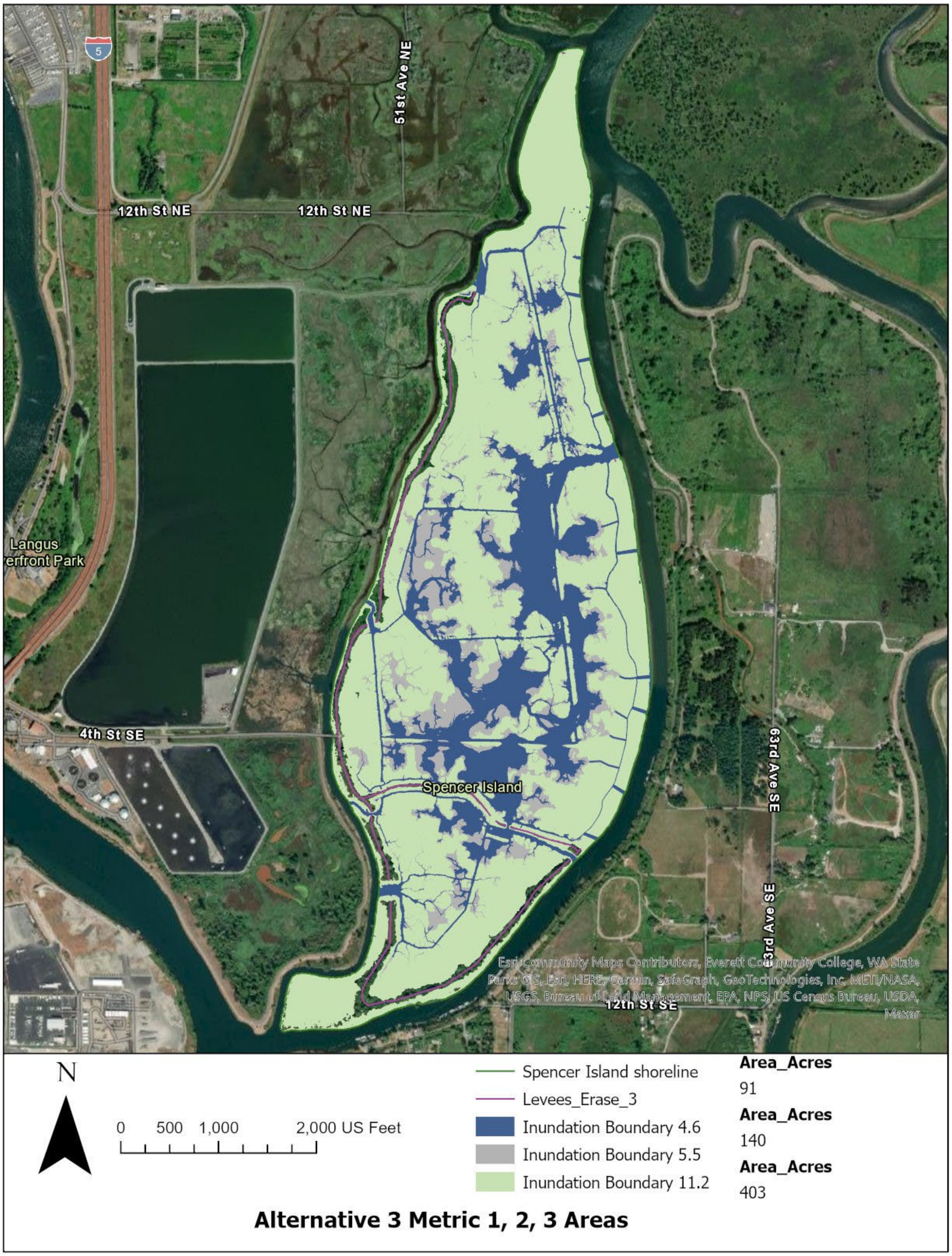


Figure 11. Alternative 3 inundation limits for Metrics 1, 2, 3

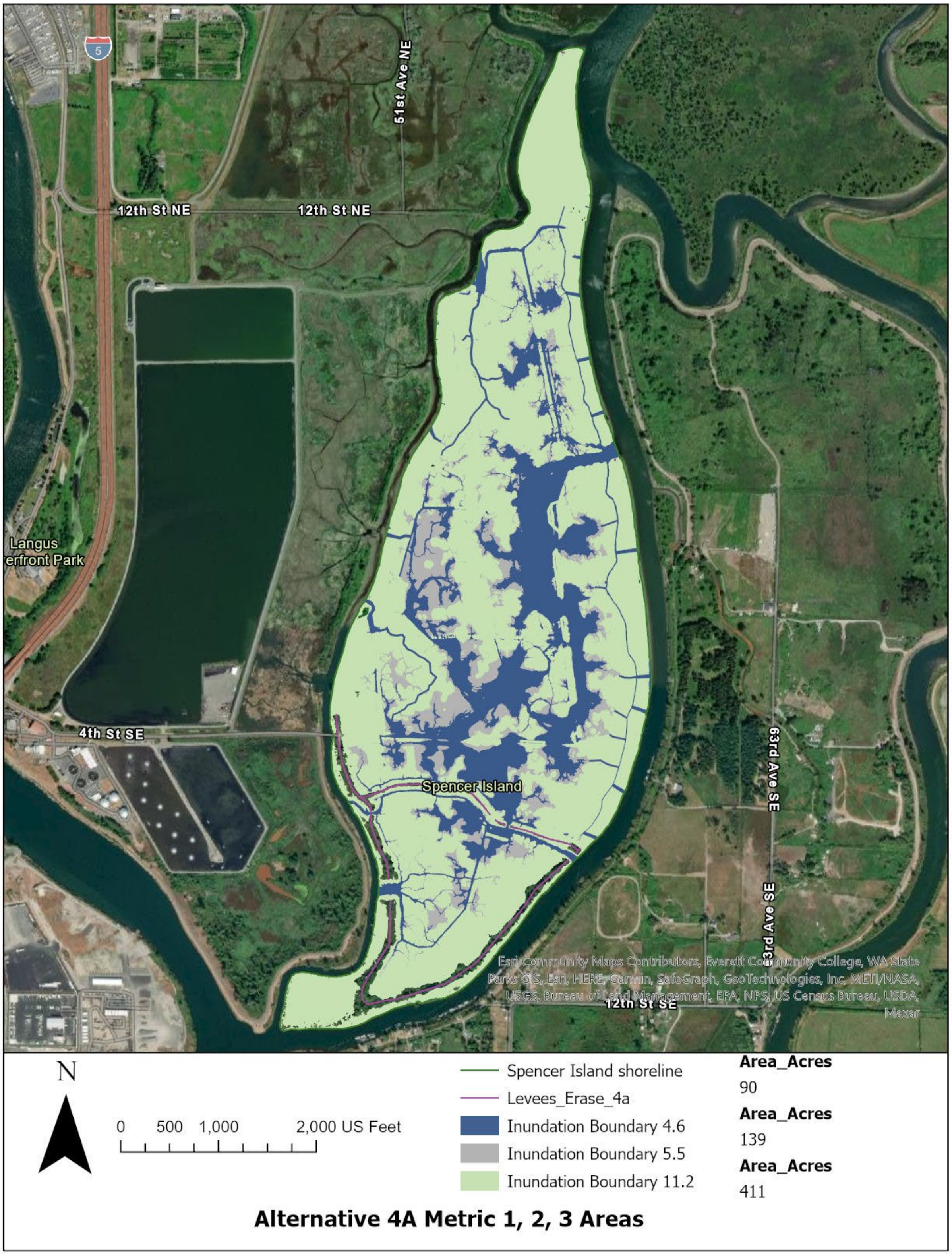


Figure 12. Alternative 4A inundation limits for Metrics 1, 2, 3

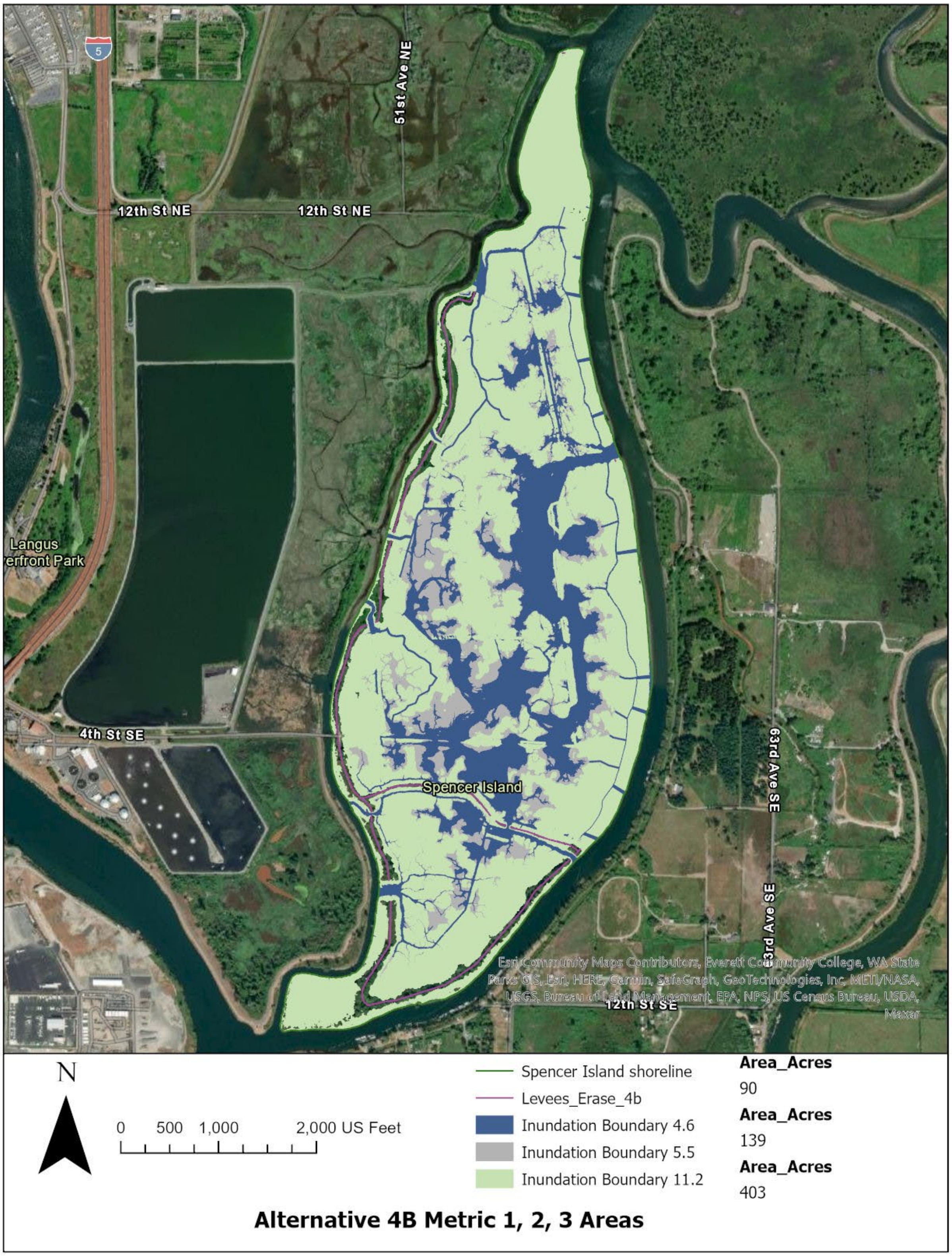


Figure 13. Alternative 4B inundation limits for Metrics 1, 2, 3

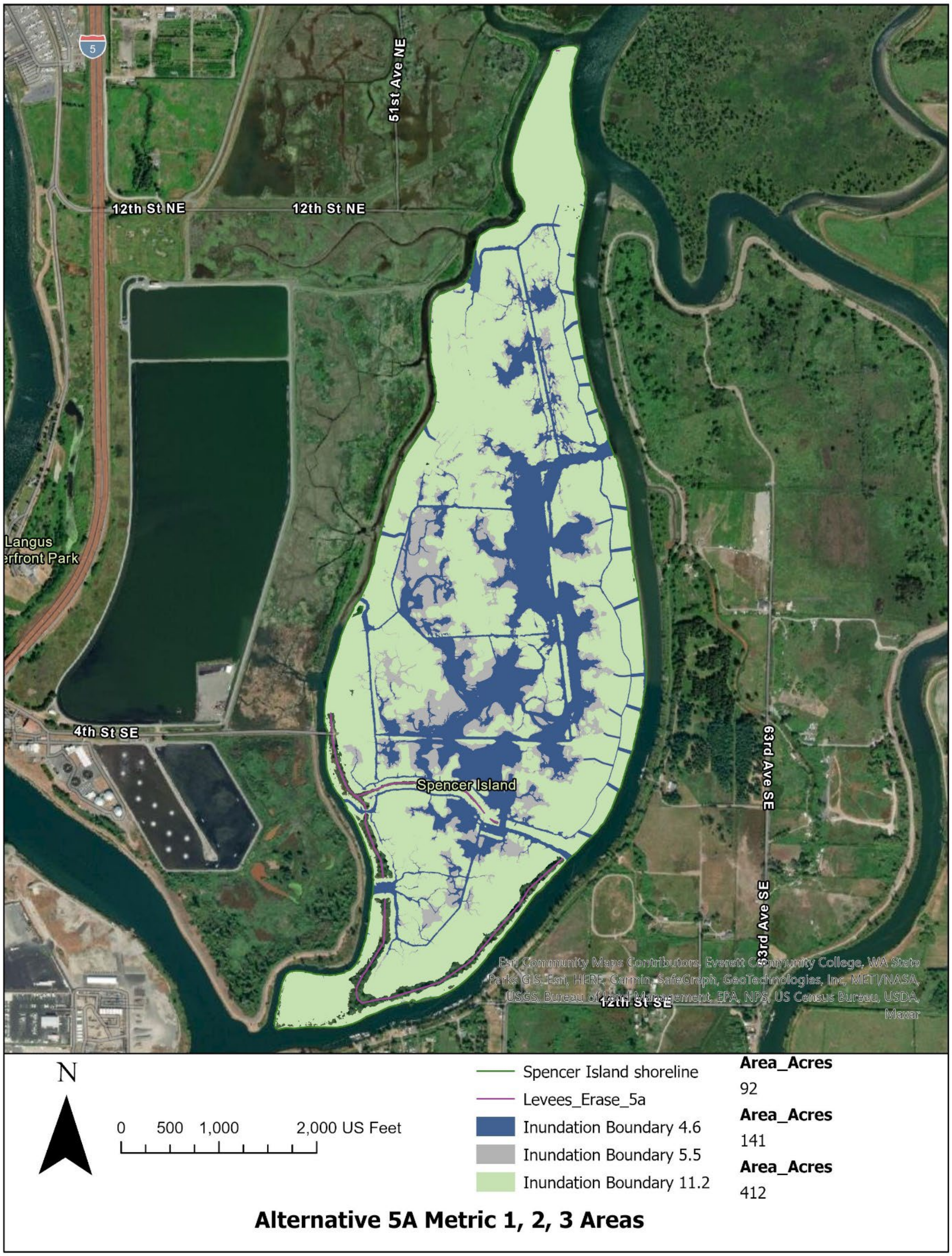


Figure 14. Alternative 5A inundation limits for Metrics 1, 2, 3

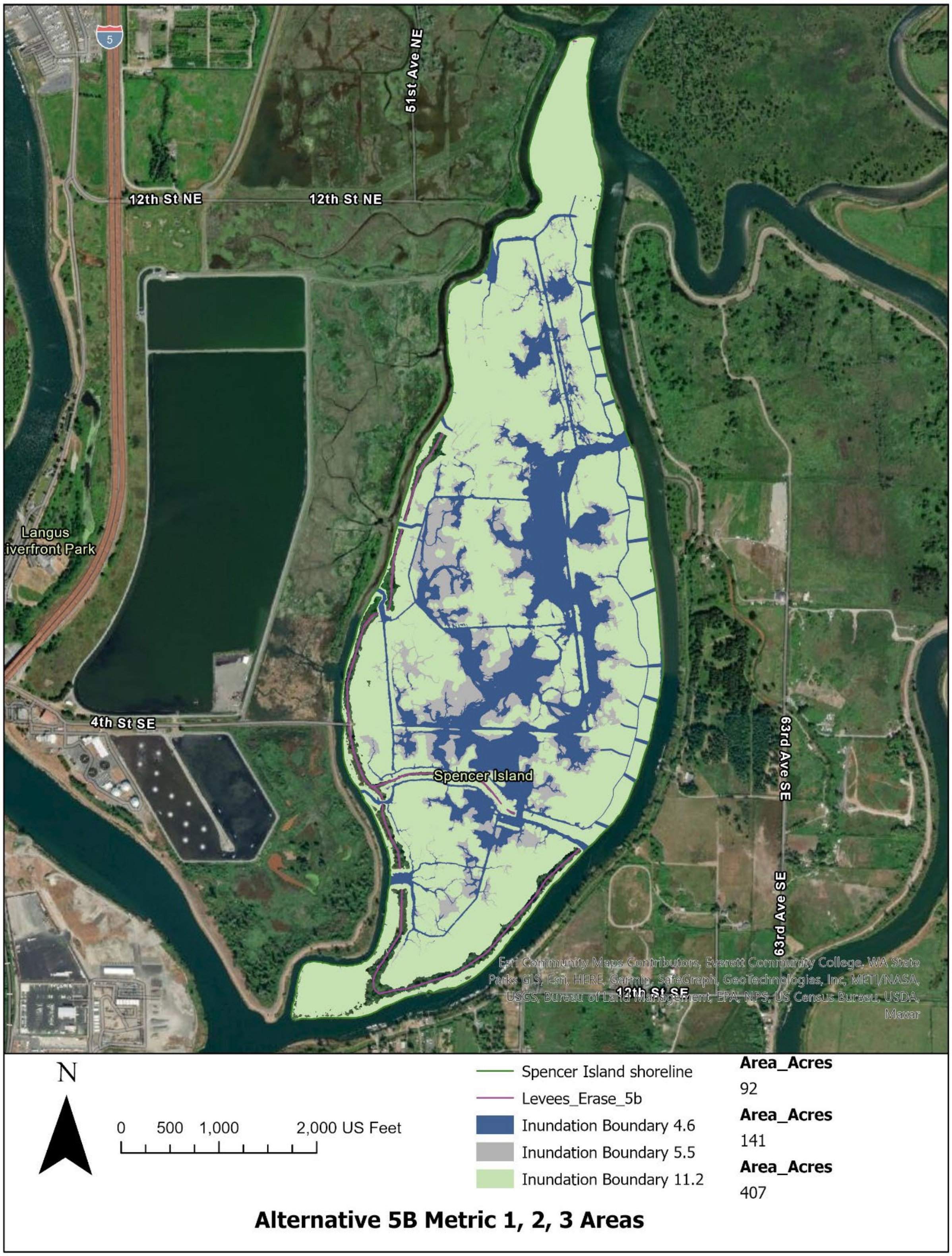


Figure 15. Alternative 5B inundation limits for Metrics 1, 2, 3

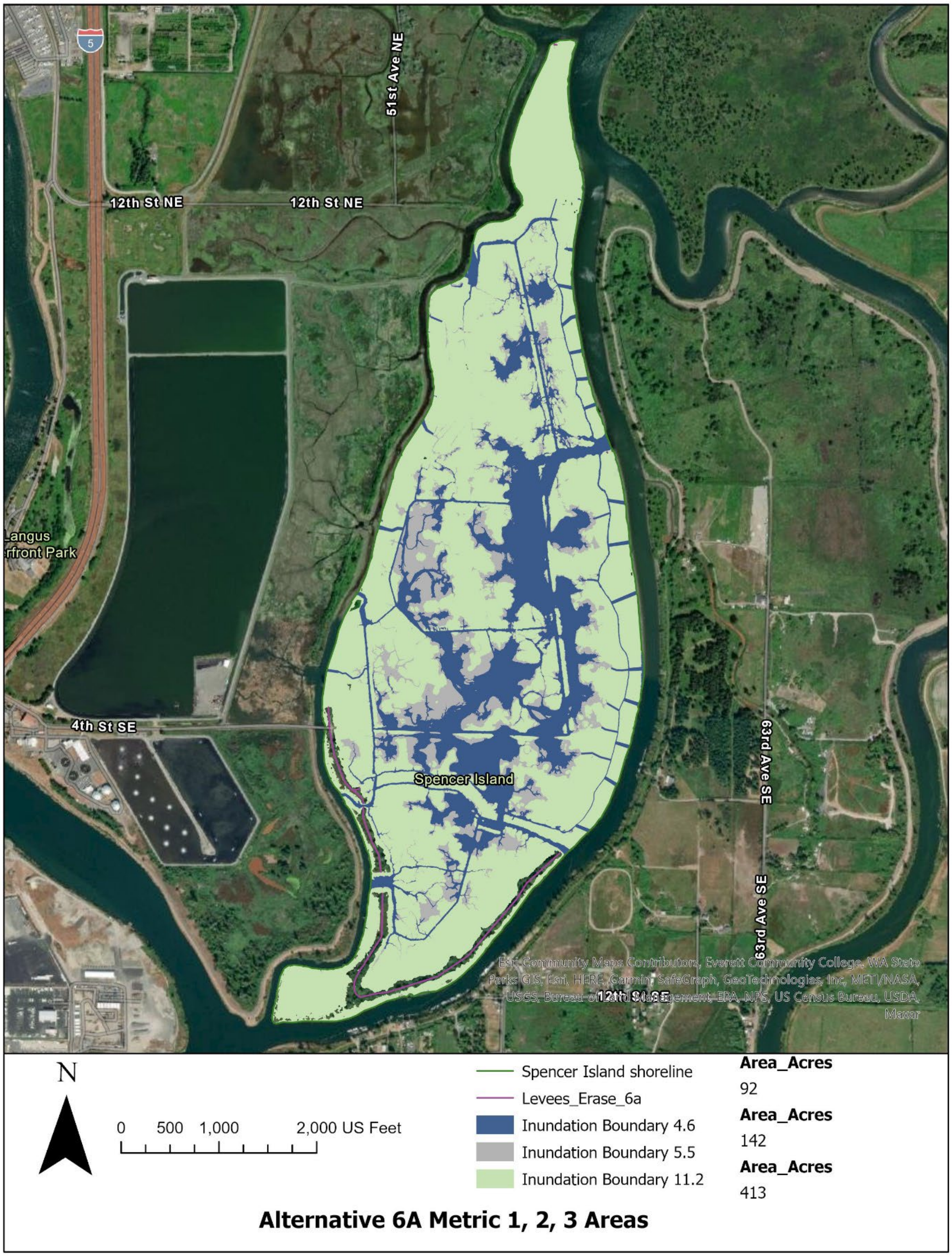


Figure 16. Alternative 6A inundation limits for Metrics 1, 2, 3

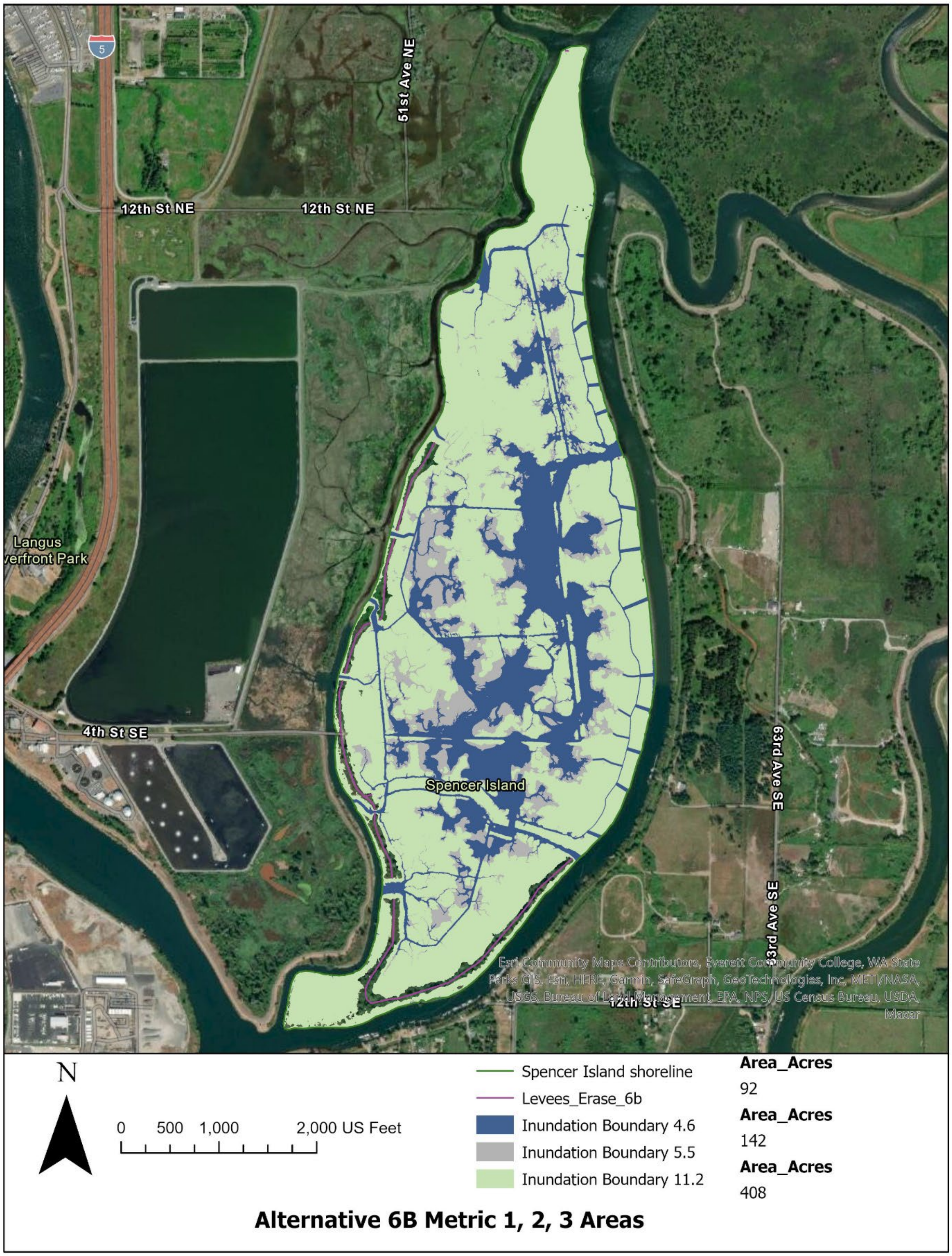


Figure 17. Alternative 6B inundation limits for Metrics 1, 2, 3

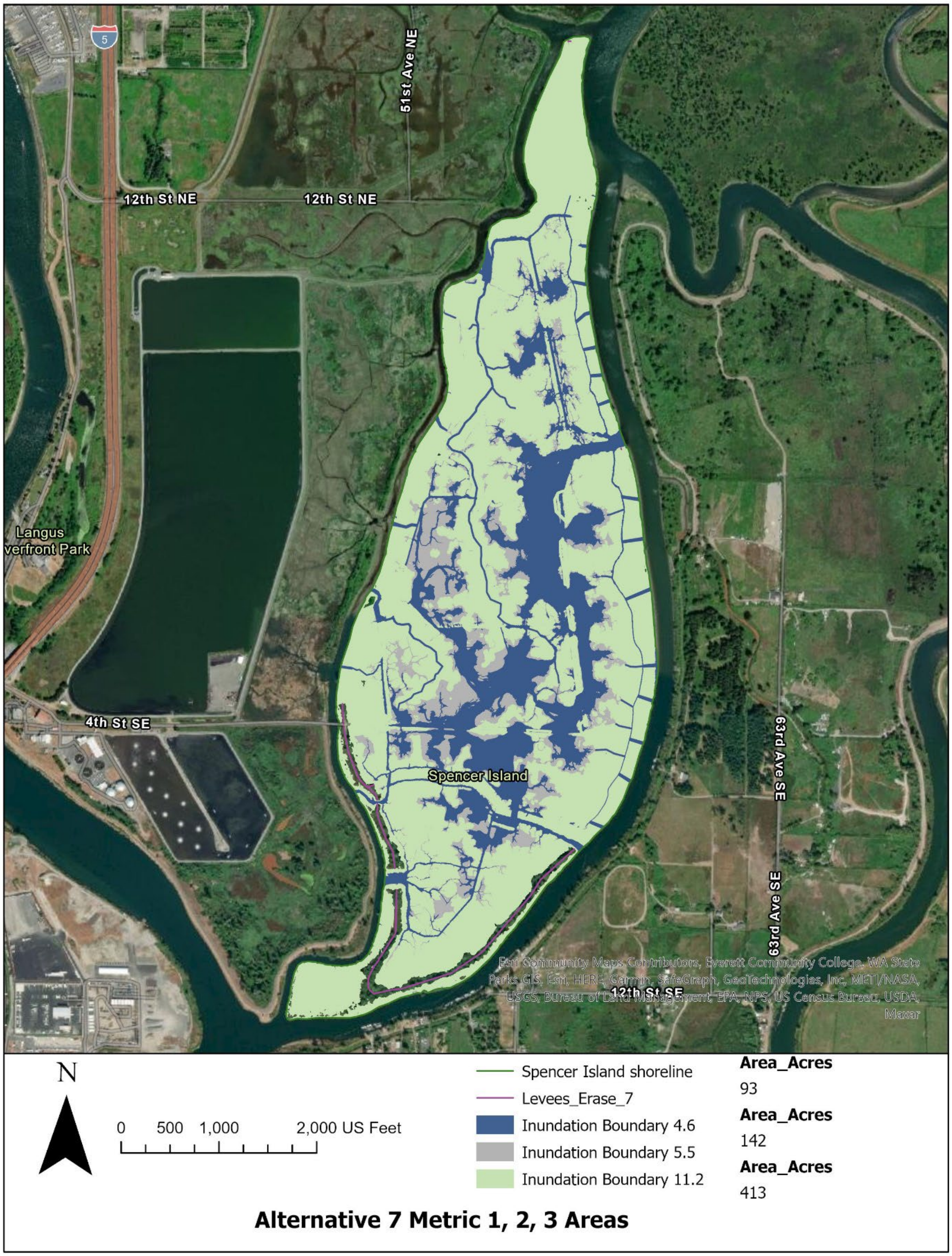


Figure 18. Alternative 7 inundation limits for Metrics 1, 2, 3

PUGET SOUND & ADJACENT WATERS

SPENCER ISLAND ECOSYSTEM RESTORATION

35% DESIGN DOCUMENTATION REPORT

ENGINEERING APPPENDIX

ANNEX D5: FUTURE CONDITIONS ANALYSIS

Contents

Tables

Figures

CLIMATE CHANGE ASSESMENT

Relative Sea Level Rise Impact Assessment

See Annex D1 for RSLC forecasts and Annex D3 for potential impacts to marsh habitat.

Sea Level Rise Considerations for Nearshore Restoration Projects in Puget Sound Checklist

The information in the checklist below is derived from the relative sea level rise (RSLR) forecasts for the Snohomish River delta (See Annex D1) and inland hydrology impact assessments by the Corps and UW Climate Impacts Group (presented below). The checklist was developed for Washington Coastal Resilience Project (WCRP) for use in Puget Sound restoration projects to highlight their resiliency and potential risk drivers. Refer to WCRP 2018 for more information.

Table 1. Sea Level Rise Considerations Checklist

Sea Level Rise Considerations for Restoration	Considered? (Yes/No)	Basis
VEGETATION		
Consider how vegetation species will be impacted by climate change-induced inundation, greater wave stress, erosion, and exposure to saltwater.	Yes	Levees will be degraded to adjacent ground elevations and decompacted and covered with conserved organic material and topsoil to accelerate native vegetation reestablishment. The restored areas will respond to climate change stressors at similar rates as native undisturbed marsh. The restored areas will not impose impediments to vegetative community migration.
Consider the extent to which additional land may be necessary to support landward migration of habitats or increased shoreline erosion due to SLR	Yes	Construction of disposal areas (mounds) and degraded levees at or just above the OHW will increase opportunities for tidal marsh to migrate up-elevation. Delta sedimentation combined with vertical land movement may keep up with sea level rise for some period of time delaying the inevitable. Tidal flat area will increase within the site and valley as salt marshes are drowned out. Freshwater tidal marsh will convert to salt tolerant marsh. Effects could be extensive. See Annex D3 for potential marsh migration maps.
Consider the extent to which future conditions of	Yes	CIG forecasts indicate fall, winter and spring river runoff are expected to increase, however

freshwater input will support development of marsh vegetation		summertime freshwater flows could significantly decrease. The inclusion of more breaches will disperse freshwater across the entire island. This, combined with levee removal will likely increase opportunities for marsh establishment, but it is unclear if the expected decrease in summertime freshwater availability and increase high tide elevations will exceed salinity stress thresholds. It is unclear what plant communities will be best adapted to this condition and how this change in the freshwater availability will impact marsh vegetation. (Check with Caren?).
H&H		
Can the project objectives for habitat creation/restoration be achieved with projections for additional climate change related inundation, erosion, and landward migration of habitat types?	Yes	The project design restores natural processes at Spencer Island not specific vegetation communities or habitat types. Levee removal makes most of the island available to accommodate additional inundation, erosion and upland (mound) migration of habitat types. Constructed breaches, channels, and mounds are not restrained from changing over time.
Consider the extent to which greater coastal flooding will contribute to erosion of restored habitats. Are higher rates of erosion expected due to SLR (see row above) and is there upland space to accommodate the erosion?	Yes	Site is sheltered from wind by headlands, limiting erosion, and will continue to be so. However, SLR will increase exposure of riparian areas to inundation and wind wave erosion. Most of these lands would be subject to inundation during riverine floods and are floodprone. Salinities will increase over time which could initiate freshwater tolerant plants to be replaced with salt tolerant plants.
Consider what effects increased climate change induced stormwater runoff will have on restored habitat given proximity to impervious surfaces.	No	No impermeable surface present at Spencer Island. Not possible to distinguish between these effects at the site vs. climate altered hydrology.
Consider how tidal and riverine forcing will combine to affect the position of tidal exchange over time and resultant habitat shift.	Yes	The head of the salt wedge extends upstream from Spencer Island by several miles. Tidal backwater extends to Snohomish and will extend further upstream over time. In base flow periods the upvalley extents of this mixing zone should increase. Channel marginal tidal wetlands may emerge along the banks and migrate upvalley. Tide flats will move upvalley as marshes erode. Subsided farmlands behind levees will become increasingly vulnerable to flooding and higher

		salinities. This could result in abandonment of large areas and conversion to tidal marsh, significantly increasing tidal prism.
Consider the extent to which sediment deposition and current rates of marsh accretion are expected to keep pace with SLR.	Yes	Median RSLR rates in the next 50 year are likely to be greater than historical delta sedimentation rate, which could result in upvalley shifts in, but no significant decrease in delta area in the 50-year project life. Levee overtopping will likely result in abandonment of historical marshlands, increasing the availability of delta habitat, however due to deep subsidence these will likely tend toward mudflats rather than marsh. Note that we do not have detailed sedimentation rates for the Snohomish River delta however we know the mainstem is dredged annually and that sediment appears to have aggraded the sloughs near Spencer Island since the last comprehensive surveys. At present relative SLR is estimated to be 0.3 to 2.4 feet (by 2070) for high emission scenarios, with a median estimate of 1.1 feet (equating to a rate of 6.7 mm/yr).
Consider the extent to which past subsidence on the site will interact with future inundation levels to affect the expected trajectory of habitat development.	NA	This site has subsidence several feet due to historical land use activities. Rates of natural vertical land movement near the Snohomish are estimated to be +0.0 mm/yr (+/-0.5mm/yr) based on data presented in Newton et al, 2021 https://doi.org/10.3390/w13030281 and 0.0 +/- 0.2 feet per century by the CIG. It is unclear if sedimentation induced by vegetation will keep up with sea level rise or not. Refer to Annex D3 for potential changes in marsh habitat and area resulting from different relative sea level rise rates. Most scenarios show preservation of significant areas of marsh vegetation within Spencer Island for the planning period.
Consider the extent to which increases in storm surge and wave-driven erosion will affect restored habitat.	NA	Storm surge will increase the frequency of inundation of Spencer Island. Project area is sheltered by headlands and wind driven waves are not a significant factor.
Consider the extent to which future rates of riverine sediment transport and deposition could alter rates of marsh accretion.	Yes	Likely a slight to beneficial impact. Climate change impacts to the watershed could offset some impacts of SLR on marsh accretion if the expected increase in storm total precipitation results in increases in hillslope erosion and riverine sediment loading. At present there are

		no basin wide sediment yield models or forecasts.
INFRASTRUCTURE		
Consider the extent to which project infrastructure will continue to function as expected given greater inundation, coastal flooding, and changes in groundwater hydrology.	Yes	Existing infrastructure such as trails and bridges will experience more frequent and severe flood damage over time. For this reason existing bridges most at risk will be removed from the project. Trails will be maintained.
Consider the extent to which increased inundation and coastal flooding will affect the intended function of the setback dike or other project infrastructure	Yes	Other than recreational trails and the Jackknife bridge there is no permanent infrastructure present within the Spencer Island ecosystem restoration project footprint. Trails will need increased maintenance over time (resurfacing, potentially repairs of eroded dikes).
Consider the extent to which project infrastructure could be physically stressed by greater wave energy.	NA	Project area is sheltered by headlands
ADJACENCY		
Consider the extent to which the expected level of adjacent property protection from erosion for existing or planned infrastructure will be achievable with increasing coastal flooding and wave run-up.	NA	Mainstem Snohomish, Union, Steamboat Sloughs extensively armored historically, and very stable. Not expected to change in future. City of Everett WWTP dikes designed for overtopping.
Consider the extent to which the combination of infrastructure removal, inundation, and higher extreme water levels, and/or greater wave energy could affect flood hazard to adjacent properties.	Yes	Not considered in design, but included in hydraulic models.
Consider the extent to which increased exposure to saltwater affects adjacent land uses	No	Saltwater intrusion affects adjacent properties regardless of restoration activities to same amount and is not part of project considerations.
Consider the combined effects of structure removal and SLR on the	Yes	Captured in 2D hydraulic modeling, flooding is reduced upstream of 101 where development is concentrated, new hardscapes are designed to

implications of flooding, drainage, and saltwater intrusion on adjacent properties and land uses.		mitigate for increased runoff with new stormwater facilities. Refer to FVCOM 3D model for forecasted salinity changes and effects.

Inland Hydrology Impact Assessment

The USACE Climate Hydrology Assessment Tool (CHAT) was used to summarize expected changes in climate, precipitation and streamflow means between the current climate epoch (1976-2005) to the mid-century epoch (2035-2064) and end-century epoch (2070-2099) for consistency with USACE policy ECB 2018-14 (19 August 2022). The CHAT tool automatically populates changes in temperature, precipitation and streamflow normal based on basin location.

The CHAT uses downscaled results from several global climate models to provide insights on temperature, precipitation and streamflow trends and future changes at the watershed scale. The following data and information were generated by the CHAT tool and summarize potential outcomes based on a moderate and high emission scenario, accounting for variability between the models used to create the forecasts. Because of the proximity to the coast sea level change must be considered. Refer to the Coastal Engineering Annex and DDR for more information on potential changes to coastal flood risk posed by sea level change.

The following information presented demonstrate that the Snohomish River has a historical trend of increasing temperatures, precipitation, with steady to declining annual runoff. Both the medium and high emission scenario forecasts show significant increases in basin average temperature throughout the year, increases in precipitation (during floodprone months), and weak to no trend in average annual streamflow but a significant increase in maximum flows and monthly average flows. Fall and winter months experience warmer temperatures and higher runoff. Spring and summer are also warmer but due to reduced snowpack should expect significant reductions in streamflow, which will likely affect salinities and marsh vegetation.

The CHAT forecasted change in annual mean streamflow at midcentury and late century under the RCP 4.5 scenario is - 3% by midcentury, and - 4% by late century. High emission median predictions range from -5 % by midcentury and a - 7% by late century. The maximum increase predicted (upper confidence limit) is +17% by the end of midcentury epoch for the high emission scenarios.

UW Climate Impacts Group (CIG 2015) confirm the CHAT results but provide significantly higher ranges for increases in flood runoff, potentially exceeding 100% under a high emission scenario late century. The mixed snow rain flooding transitions to rain dominated by late century. This results in loss of the annual snow melt pulse in the spring and higher flood magnitudes in fall and winter.

Increased precipitation and streamflow in flood producing months and decreases in summertime streamflow strongly suggest conditions will worsen for aquatic species and habitat availability will decline due flood damage, and water quality (temperature) issues. The frequent flooding in in the lower Snohomish valley will only worsen over time. Buyouts of flood damaged properties will create opportunities to enhance the habitat along the river and estuary. The aquatic ecosystem restoration project will be impacted by expected changes in climate and hydrology (streamflow changes and sea level rise), however by increasing accommodation space for the river and estuary to respond to these stressors, the project should be resilient.

The USACE Time Series Toolbox non-stationarity detection tool was also used – the tool did not detect non-stationarities. There was no trend in the historical annual peak streamflow detected.

References

USACE CHAT tool: https://www.usace.army.mil/corpsclimate/Public-Tools-Developed-by-USACE/Climate-Impacted-Hydrology/

UW CIG 2015 report: State of Knowledge: Climate Change in Puget Sound (uw.edu)

WCRP 2018. Raymond, C., Conway-Cranos, L., Morgan, H., Faghin, N., Spilsbury Pucci, D., Krienitz, J., Miller,I., Grossman, E. and Mauger, G., 2018. Sea level rise considerations for nearshore restoration projects in Puget Sound. A report prepared for the Washington Coastal Resilience Project.

Basin and location

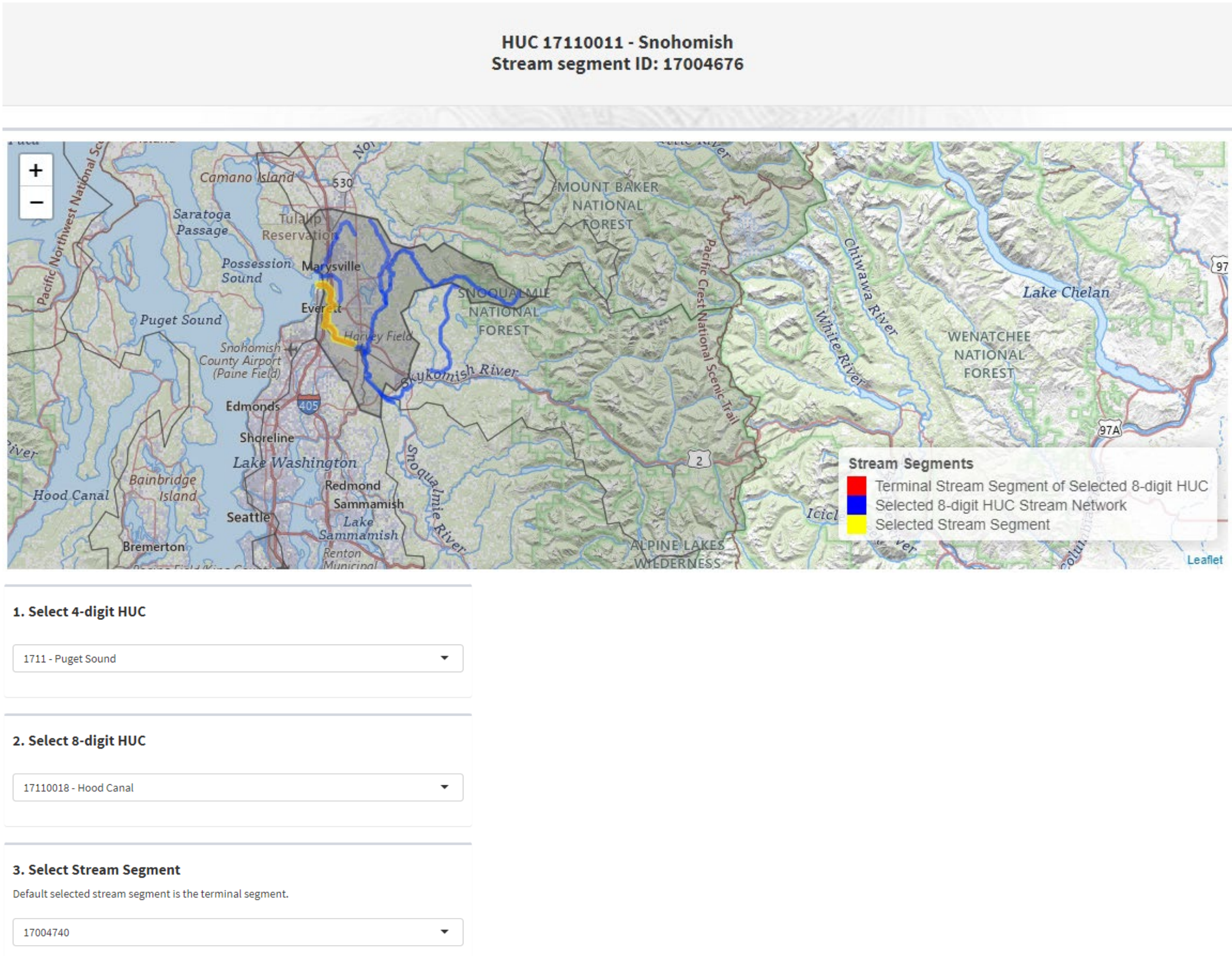


Figure 1. Basin and location map

Time series explorer results

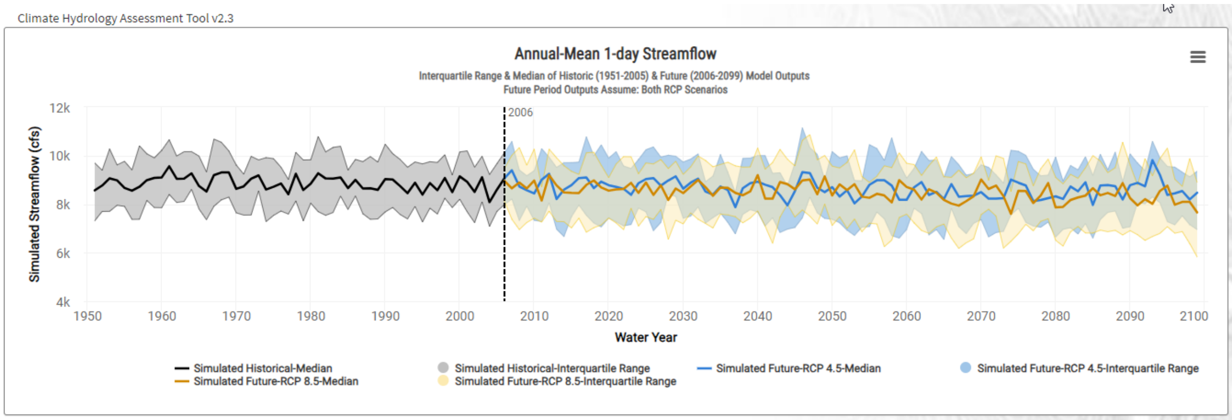


Figure 2. Annual Mean 1-day streamflow – historical and forecasted. Median forecast of average daily flows are not expected to significantly change (could increase or decrease). Future variability is likely to exceed historical. The decrease at the end of the forecast period is attributable to loss of basin snowpack due to increasing freezing levels.

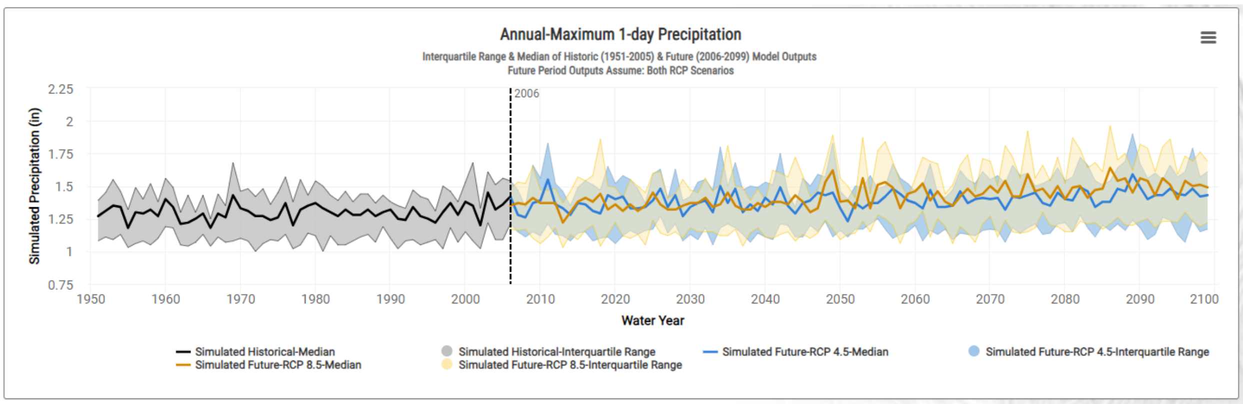


Figure 3. Annual Maximum 1-day precipitation – historical and forecasted. Median forecast of annual maximum 1-day precipitation are expected to increase slowly, similar to historical trend. Future variability is likely to exceed historical (some rainstorms could have 2 more inches than the largest storms in the historical period) suggesting flooding is likely to worsen.

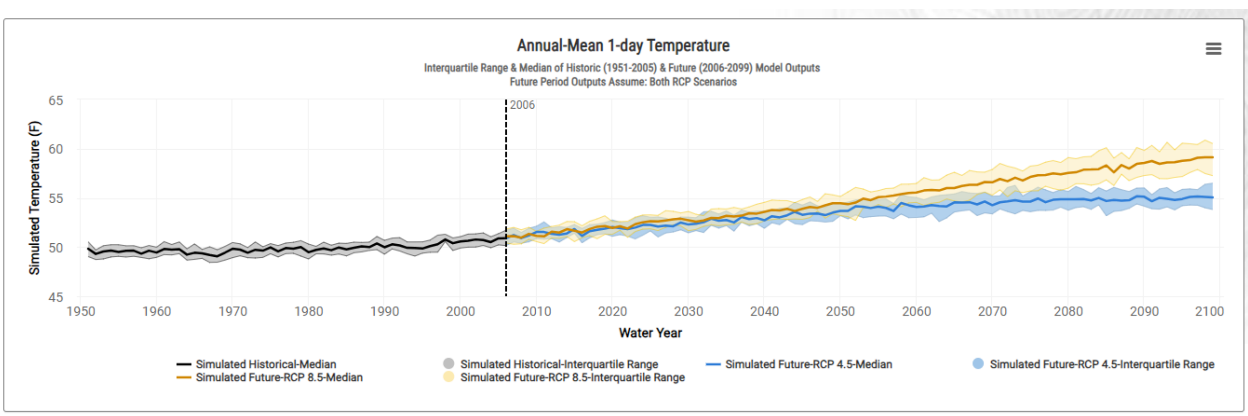
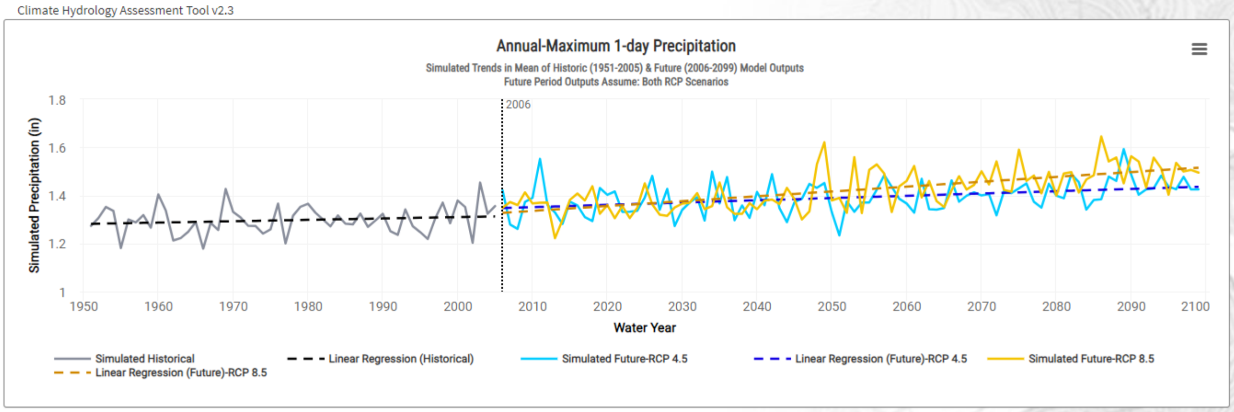


Figure 4, Annual mean 1-day temperature – historical and forecasted. Median annual 1-day temperatures are expected to increase by as much as 10 degrees F at end of the future period. Forecasted mean temperatures could vary significantly suggesting future conditions could be highly uncertain.

Time Series Trend Analysis Results



Simulated Trend Lines

Simulated Historical (1951 to 2005)	Simulated Future (2006 to 2099)	
6e-04 Traditional Slope	**0.001** Traditional Slope-RCP 4.5	**0.002** Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.253
Mann-Kendall	0.4
Spearman Rank-Order	0.34

Statistical Significance Tests (Future)

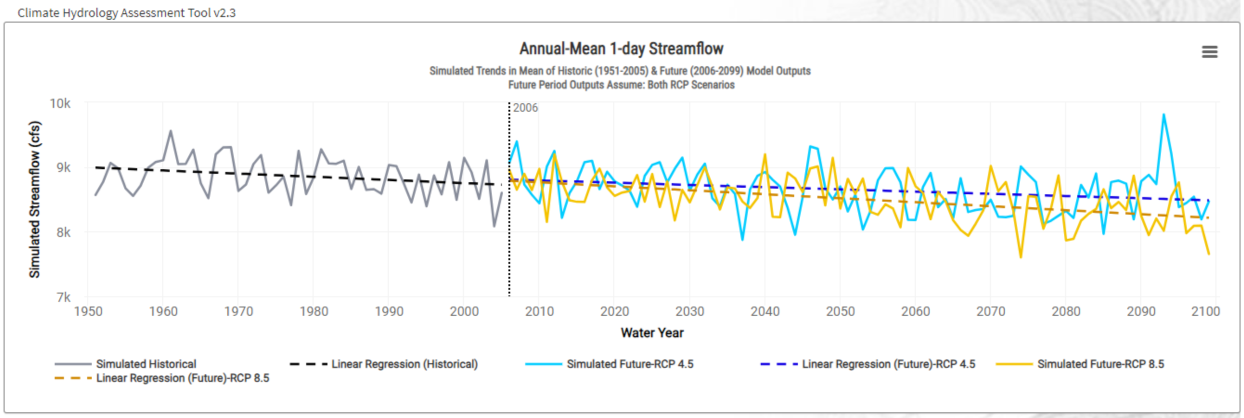
Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	<0.001**	<0.001**
Mann-Kendall	<0.001**	<0.001**
Spearman Rank-Order	<0.001**	<0.001**

p-value Guidance

The p-values displayed below are reflective of the linear regression fit drawn above. A smaller p-value indicates greater statistical significance. The typically adopted threshold for statistical significance prescribed by the majority of statistical references is 0.05 is associated with a 5% risk of a Type I error or false positive. This is the threshold of significance applied by the CHAT. ** **Indicates a statistically significant simulated trend (at the alpha = .05 level) was detected.**

Figure 5. Annual mean daily flow trends and forecasts. Forecasts for mean daily streamflow suggest a continued declining trend, likely due to loss of high elevation snowpack and increase in peak flows

Figure 6. Annual max 1-day precip trends and forecasts both show statistically significant increases in precip over time



Simulated Trend Lines

Simulated Historical (1951 to 2005)	Simulated Future (2006 to 2099)	
-4.8928 Traditional Slope	**-3.4387** Traditional Slope-RCP 4.5	**-6.1619** Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.0498**
Mann-Kendall	0.0979
Spearman Rank-Order	0.0886

Statistical Significance Tests (Future)

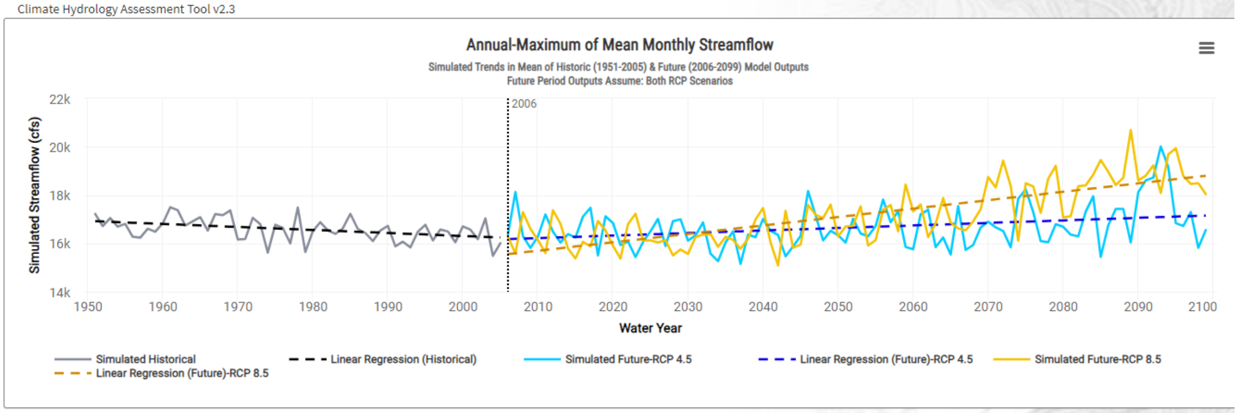
Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	0.0107**	<0.001**
Mann-Kendall	0.00289**	<0.001**
Spearman Rank-Order	0.0033**	<0.001**

p-value Guidance

The p-values displayed below are reflective of the linear regression fit drawn above. A smaller p-value indicates greater statistical significance. The typically adopted threshold for statistical significance prescribed by the majority of statistical references is 0.05 is associated with a 5% risk of a Type I error or false positive. This is the threshold of significance applied by the CHAT. **** Indicates a statistically significant simulated trend (at the alpha = .05 level) was detected.**

Figure 7. Annual mean daily flow trends and forecasts. Forecasts for mean daily streamflow suggest a continued declining trend, likely due to loss of high elevation snowpack and increase in peak flows

Climate Hydrology Assessment Tool v2.3



Simulated Trend Lines

Simulated Historical (1951 to 2005)

-12.469
Traditional Slope

Simulated Future (2006 to 2099)

10.476
Traditional Slope-RCP 4.5

34.841
Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.00154**
Mann-Kendall	0.00163**
Spearman Rank-Order	<0.001**

Statistical Significance Tests (Future)

Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	0.0013**	<0.001**
Mann-Kendall	0.00897**	<0.001**
Spearman Rank-Order	0.009**	<0.001**

p-value Guidance

The p-values displayed below are reflective of the linear regression fit drawn above. A smaller p-value indicates greater statistical significance. The typically adopted threshold for statistical significance prescribed by the majority of statistical references is 0.05 is associated with a 5% risk of a Type I error or false positive. This is the threshold of significance applied by the CHAT. ** **Indicates a statistically significant simulated trend (at the alpha = .05 level) was detected.**

Figure 8. Monthly streamflow maximums are steadily declining historically. This trend is forecasted to reverse in the future. This is attributed to ongoing high altitude snowpack loss and future increases in rain storm intensity

Monthly Epoch Changes

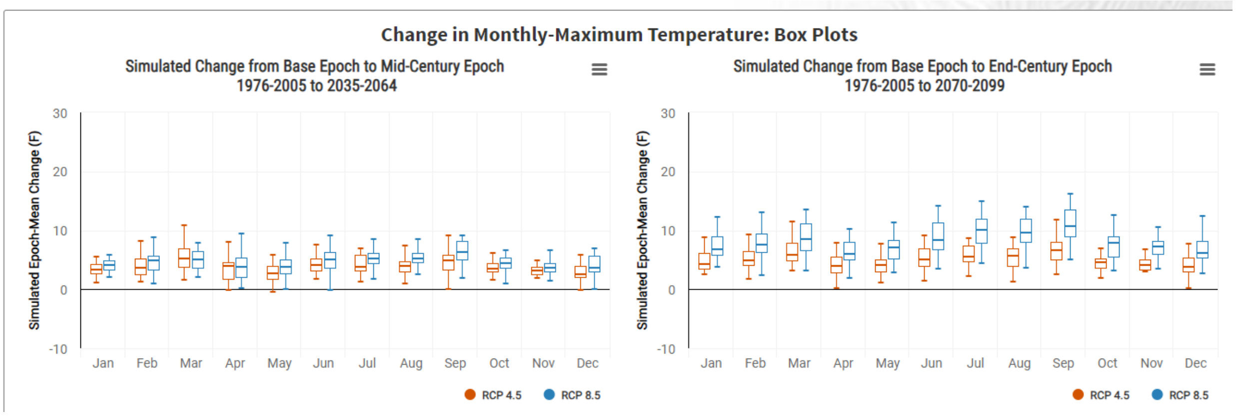


Figure 9. Change in monthly mean air temperatures at midcentury and late century. Temps increase in all months potentially exceeding 10 degrees (F) by the late century. Winter streamflows should increase, and spring and summer streamflows should decrease and water temperature increases could be problematic for aquatic species.

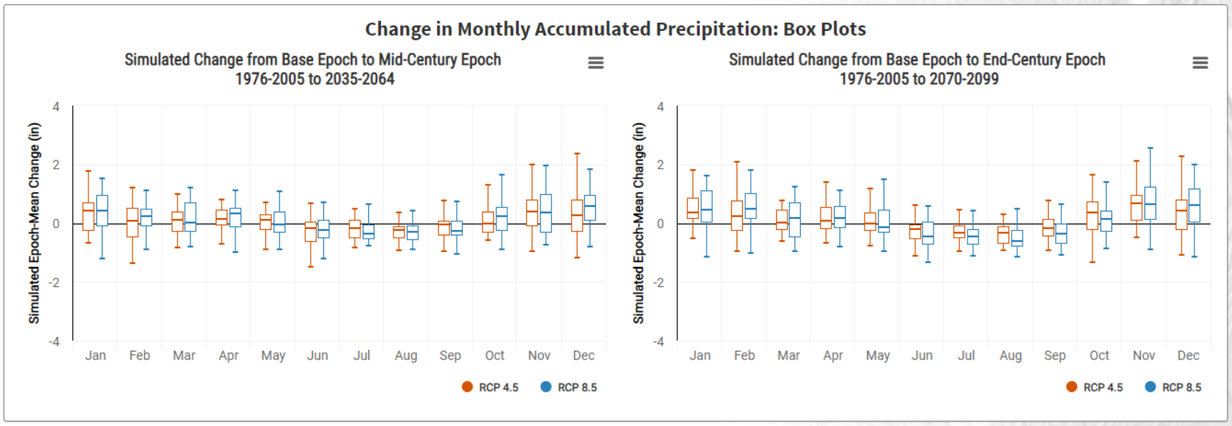


Figure 10. Change in monthly accumulated precipitation at midcentury and late century. The model mean estimates show a general increase in precip in Oct through April with small decreases in the summer. Variability in the estimates is notably high however the mean estimates are consistent between emission scenarios.

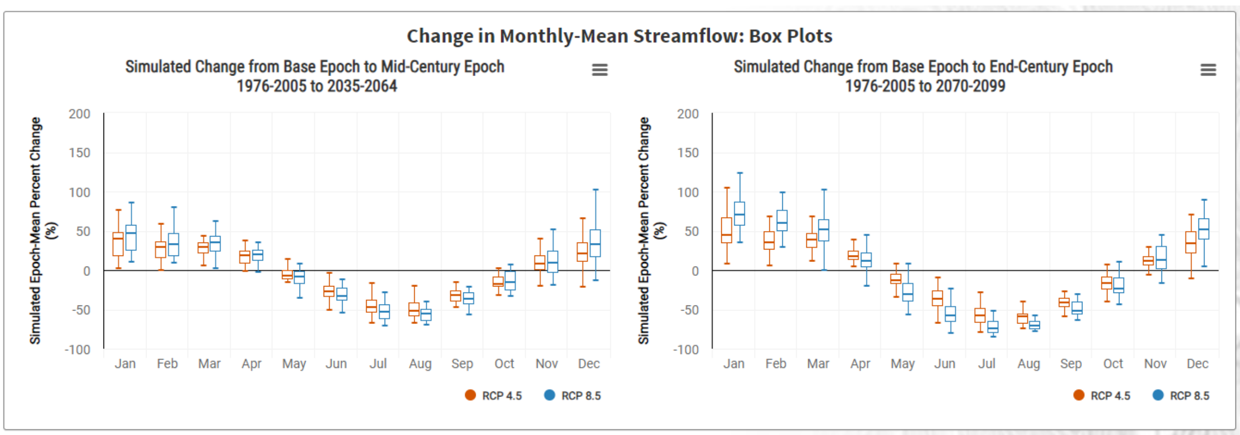


Figure 11. Change in monthly mean streamflow at midcentury and late century. Fall and winter streamflow increase but are offset by large summer and early fall declines. Late century increases in monthly avg streamflows during flood producing months approach or exceed 50 %, strongly suggesting worsening flooding in the basin should be expected. Summertime streamflow decreases and water temperature increases could be problematic for some runs of salmon. The reduction in freshwater flows will increase salinities at Spencer Island and could shift the marsh vegetation from fresh to salt tolerant species.

Annual Epoch Changes

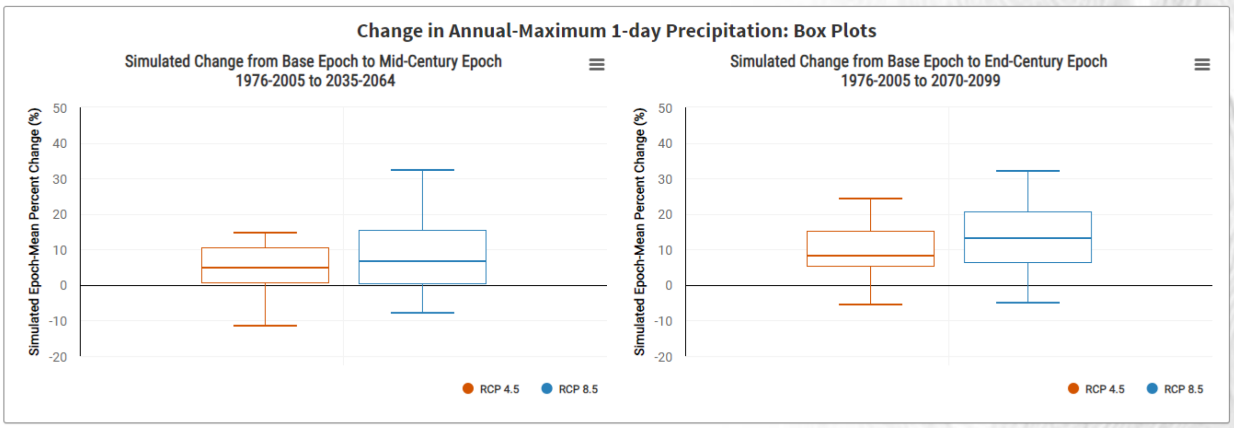


Figure 12. Change in annual maximum 1-day precipitation at midcentury and late century. The RCP 4.5 runs predict an average increase of 5% by mid century, and 8% by late century. High emission runs predict an average increase of 7 % by mid century and an increase of 10% by late century.

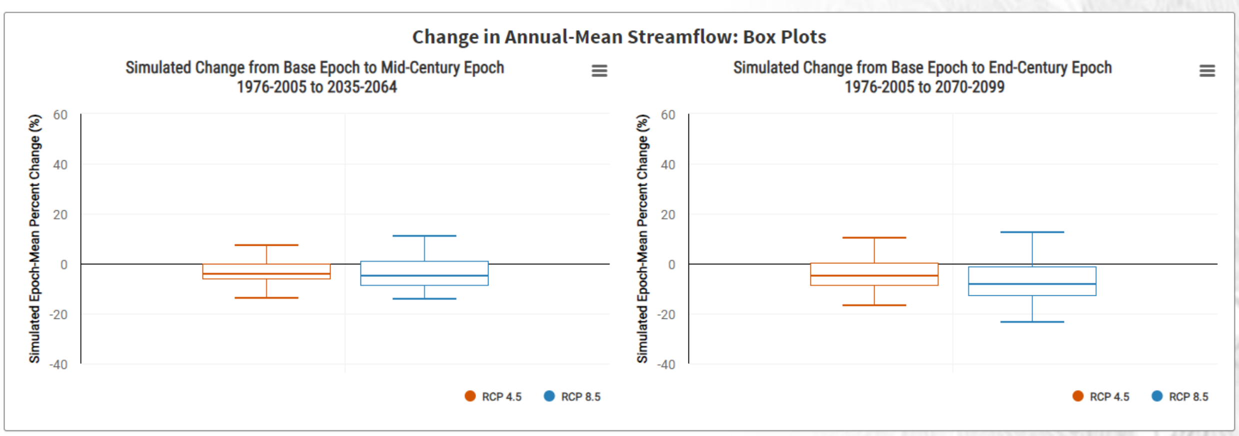
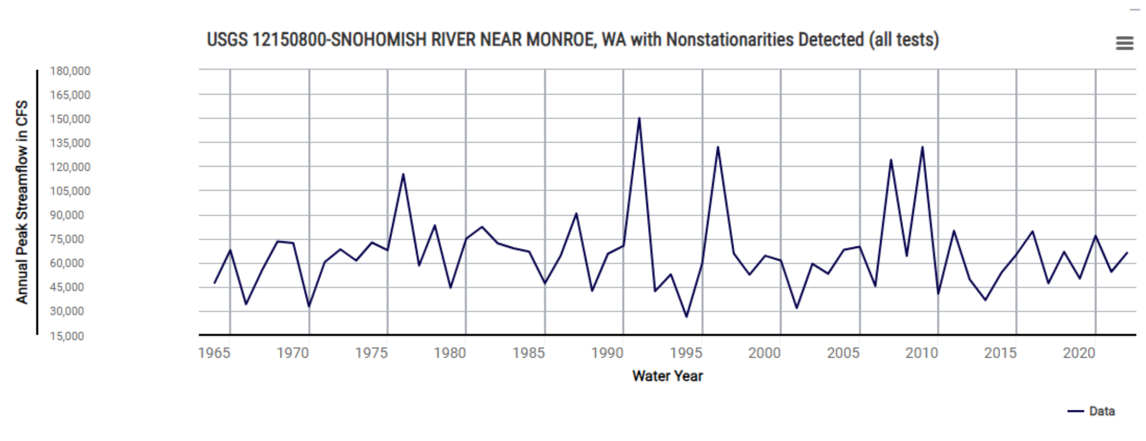
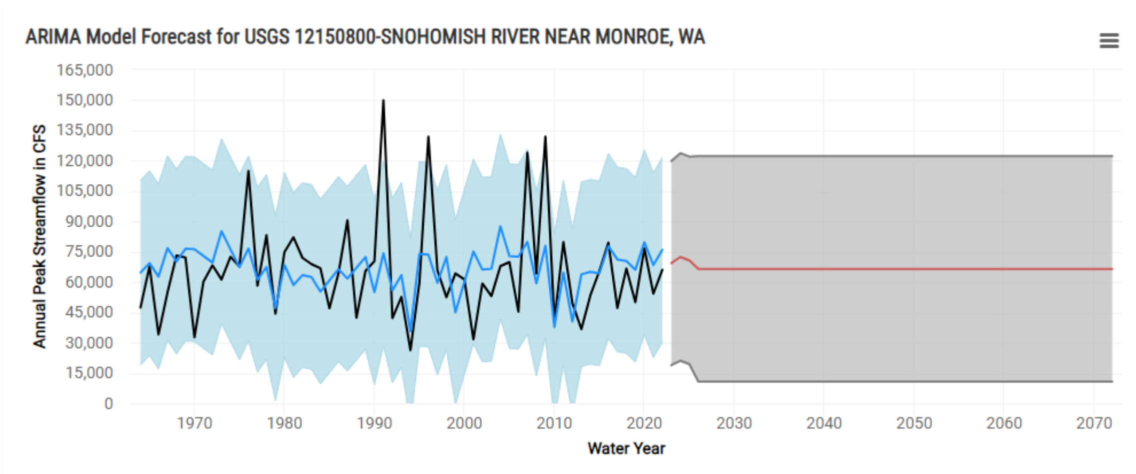


Figure 13. Change in annual mean streamflow at midcentury and late century. The RCP 4.5 runs predict an average decrease of 3% by mid century, and 4% by late century. High emission runs predict an average decrease of 5 % by mid century and a decrease of 7% by late century.

Time Series Toolbox non-stationarity detection analysis



No nonstationarities detected!



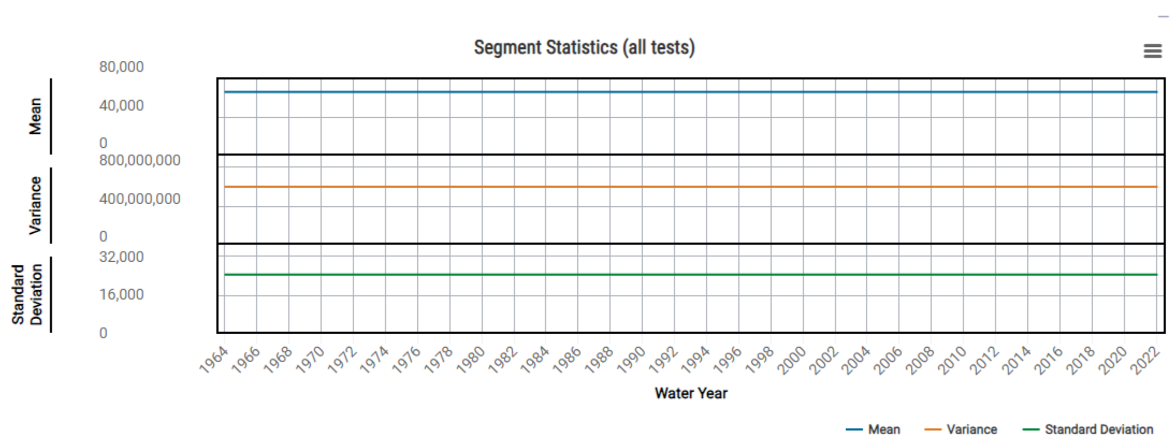


Figure 14. Results of Time Series Toolbox analysis of historical peak streamflow stationarity. The mainstem Snohomish River does not have any detectable non-stationarities in the period of record.

UW CIG 2013 State of Knowledge: Climate Change in Puget Sound Synthesis Report excerpts

Box ES-1. Projected changes in several key physical drivers.

- **Average annual temperature:** By the 2050s (2040-2069), the average year in the Puget Sound region is projected to be +4.2°F (range: +2.9 to +5.4°F) warmer under a low greenhouse gas scenario and +5.5°F (range: +4.3 to +7.1°F) warmer under a high greenhouse gas scenario (RCP 4.5 and 8.5, respectively),[A] relative to 1970-1999.[B,4]

- **Heavy Rainfall:** By the 2080s (2070-2099), the wettest days (99th percentile or 24-hour precipitation totals) in the Pacific Northwest are projected to increase by +22% (range: +5% to +34%) for a high greenhouse gas scenario (RCP 8.5), relative to 1970-1999.[C,5]

- **Declining Spring Snowpack:** By the 2040s (2030-2059), the average year in the Puget Sound region is projected to have −23% (range: −34 to −6%) less April 1st snowpack under a low greenhouse gas scenario (B1), and −29% (range: −47 to −4%) under a moderate greenhouse gas scenario (A1B), relative to 1970-1999.[C,3]

- **Sea Level Rise:** By 2050, relative sea level in Seattle is projected to rise by +6.5 inches (range: -1 to +19 inches) for a moderate, low, and high greenhouse gas scenario (A1B, B1 ,and A1FI, respectively), compared to 2000.[6] Sea level rise at other locations may differ by up to 8 inches by 2050, due to different rates of uplift or subsidence.

- **Higher Storm Surge Reach.** Although storm surge is not projected to increase, sea level rise will cause the same events to have a greater impact. In Olympia, a +6 inch rise in sea level (the middle projection for 2050 is +9 inches) would cause the 100-year surge event to become a 1-in-18 year event.[7]

[A] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for details.

Variable	Projected Long-term Change
Snow	
Snowpack	Declines • Declines projected for all greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted.[A] • Projected change in April 1st snowpack,[D] on average for Puget Sound:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): −45% (range: −53 to −32%) high emissions (RCP 8.5): −53% (range: −66 to −37%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): −56% (range: −65 to −50%) high emissions (RCP 8.5): −74% (range: −85 to −59%)
Streamflow	
Annual	Small changes projected. Some models project increases while other project decreases. • Change in annual runoff, on average for Puget Sound:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): 0% (range: −5 to +12%) high emissions (RCP 8.5): −1% (range: −10 to +12%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): +1% (range: −8 to +8%) high emissions (RCP 8.5): −2% (range: −12 to +2%)
Winter	All scenarios project an increase in winter streamflow. • Change in Winter (Oct-Mar) runoff, on average for the Puget Sound region:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): +26% (range: +17 to +38%) high emissions (RCP 8.5): +34% (range: +20 to +55%)

[D] These numbers indicate changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Northwest. Changes are only calculated for locations that regularly accumulate snow (historical April 1st SWE of at least 10 mm, or about 0.4 inch, on average).

Variable	Projected Long-term Change
	2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): +40% (range: +20 to +56%) high emissions (RCP 8.5): +60% (range: +43 to +77%)
Summer	All scenarios project a decrease in summer streamflow. • Change in Summer (Apr-Sep) runoff, on average for the Puget Sound region:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): −15% (range: −20 to −7%) high emissions (RCP 8.5): −18% (range: −26 to −8%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): −19% (range: −25 to −9%) high emissions (RCP 8.5): −29% (range: −41 to −20%)
Streamflow timing	Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers in the Puget Sound region. • Change in the timing of peak streamflow for 12 Puget Sound watersheds for the 2080s (2070-2099, relative to 1970-1999).[E,F] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: −21 days (RCP 4.5), −28 days (RCP 8.5) Samish R.: −6 days (RCP 4.5), −7 days (RCP 8.5) Skagit R.: −21 days (RCP 4.5), −33 days (RCP 8.5) Stillaguamish R.: −19 days (RCP 4.5), −24 days (RCP 8.5) Snohomish R.: −23 days (RCP 4.5), −30 days (RCP 8.5) Cedar R.: −21 days (RCP 4.5), −24 days (RCP 8.5) Green R.: −18 days (RCP 4.5), −20 days (RCP 8.5) Nisqually R.: −17 days (RCP 4.5), −19 days (RCP 8.5) Puyallup R.: −19 days (RCP 4.5), −26 days (RCP 8.5) Skokomish R.: −11 days (RCP 4.5), −14 days (RCP 8.5) Dungeness R.: −25 days (RCP 4.5), −40 days (RCP 8.5) Elwha R.: −28 days (RCP 4.5), −37 days (RCP 8.5)
Flooding	Increases projected for most scenarios. • Projected change in streamflow volume associated with the 100-year

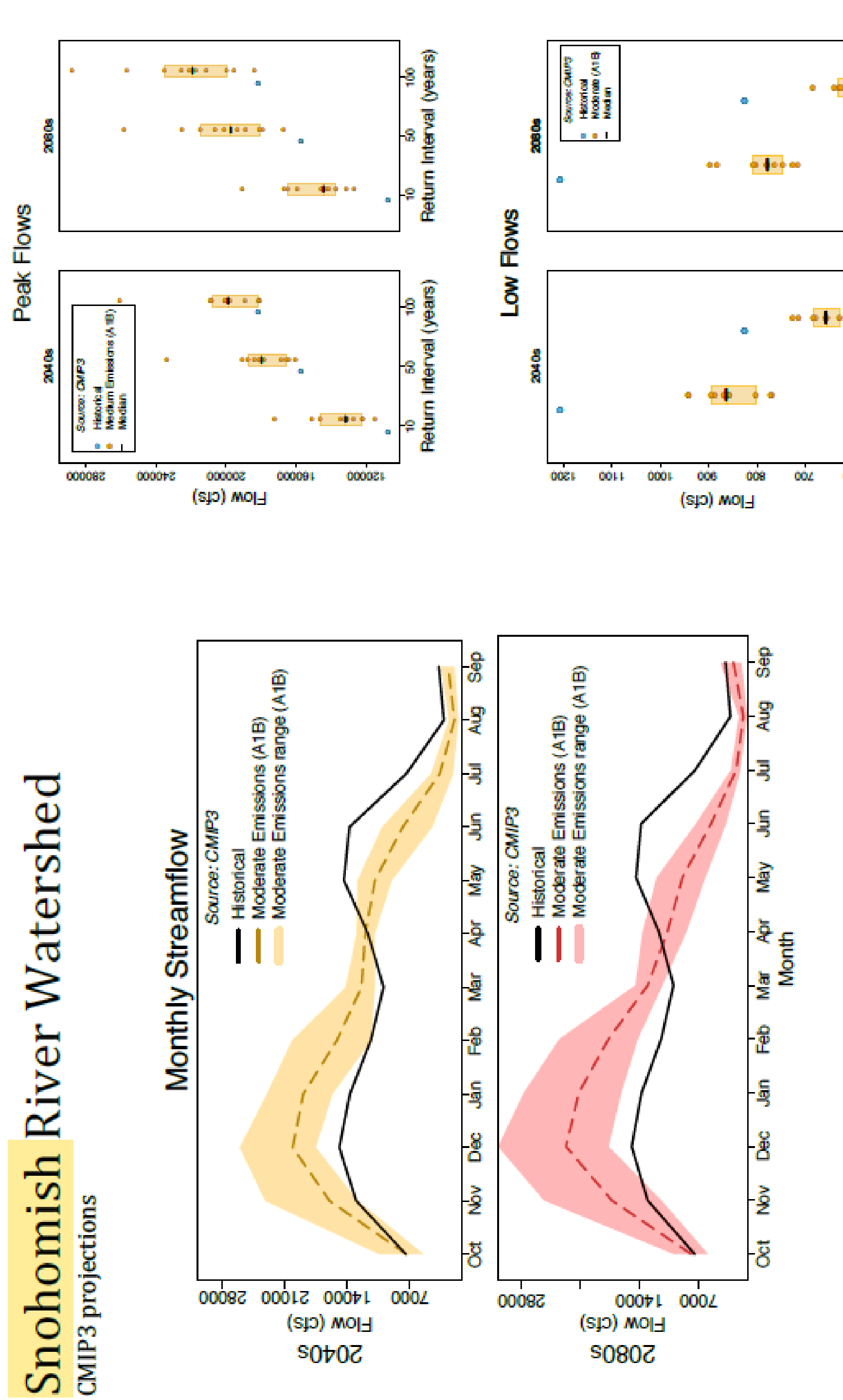
Note the CIG reports do not provide forecasts for the Duckabush river basin, however the basin shares headwaters with the Skokomish, Dungeness and Elwha basins. Changes in these basins likely provide a reasonable range for expected changes on the Duckabush.

Appendix A – DRAFT 10.26.2015

Variable	Projected Long-term Change
	(1% annual probability) flood event for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999):[E] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: +71% (RCP 4.5), +102% (RCP 8.5) Samish R.: +56% (RCP 4.5), +60% (RCP 8.5) Skagit R.: +111% (RCP 4.5), +147% (RCP 8.5) Stillaguamish R.: +55% (RCP 4.5), +99% (RCP 8.5) Snohomish R.: +72% (RCP 4.5), +104% (RCP 8.5) Cedar R.: +44% (RCP 4.5), +84% (RCP 8.5) Green R.: +43% (RCP 4.5), +71% (RCP 8.5) Nisqually R.: +37% (RCP 4.5), +57% (RCP 8.5) Puyallup R.: +49% (RCP 4.5), +80% (RCP 8.5) Skokomish R.: +5% (RCP 4.5), +38% (RCP 8.5) Dungeness R.: +99% (RCP 4.5), +119% (RCP 8.5) Elwha R.: +81% (RCP 4.5), +94% (RCP 8.5)
Minimum flows	Decreased flow in all Puget Sound watersheds • Projected changes in summer minimum streamflow (7Q10)[G] for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999).[E] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: −34% (RCP 4.5), −51% (RCP 8.5) Samish R.: −20% (RCP 4.5), −31% (RCP 8.5) Skagit R.: −46% (RCP 4.5), −71% (RCP 8.5) Stillaguamish R.: −40% (RCP 4.5), −53% (RCP 8.5) Snohomish R.: −39% (RCP 4.5), −53% (RCP 8.5) Cedar R.: −44% (RCP 4.5), −49% (RCP 8.5) Green R.: −42% (RCP 4.5), −48% (RCP 8.5) Nisqually R.: −38% (RCP 4.5), −47% (RCP 8.5) Puyallup R.: −32% (RCP 4.5), −47% (RCP 8.5) Skokomish R.: −42% (RCP 4.5), −61% (RCP 8.5) Dungeness R.: −52% (RCP 4.5), −74% (RCP 8.5) Elwha R.: −56% (RCP 4.5), −77% (RCP 8.5)

Note that the CIG report alerts the reader that the increase in peak flows presented may be unrealistic and refers the reader to a previous investigation (Hamlet 2012) which produced model results that forecast peak flow changes in the order of 80% less than these results

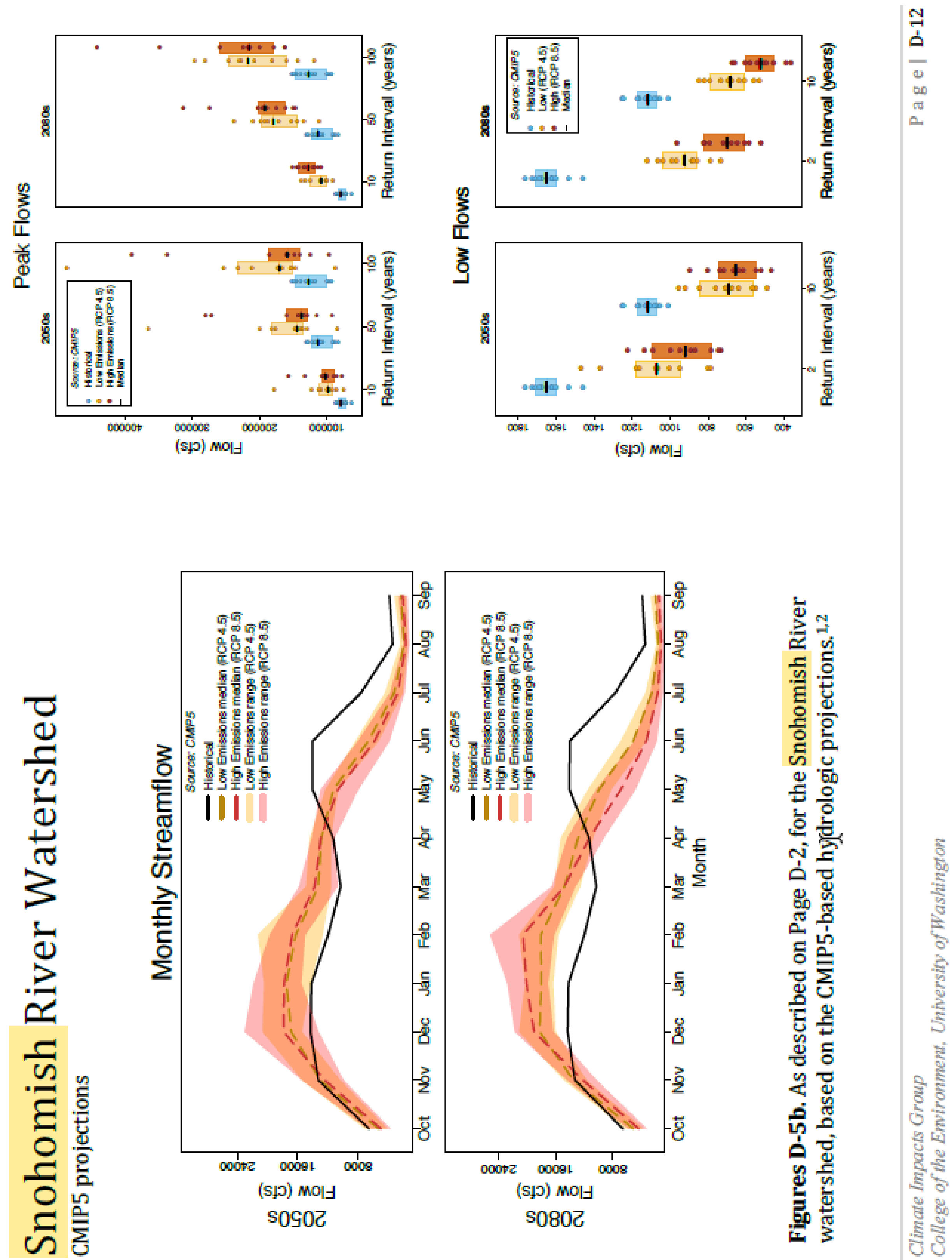
Appendix D



Figures D-5a. As described on Page D-2, for the Snohomish River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Climate Impacts Group
College of the Environment, University of Washington

Page | **D-11**



Figures D-5b. As described on Page D-2, for the Snohomish River watershed, based on the CMIP5-based hydrologic projections.[1,2]

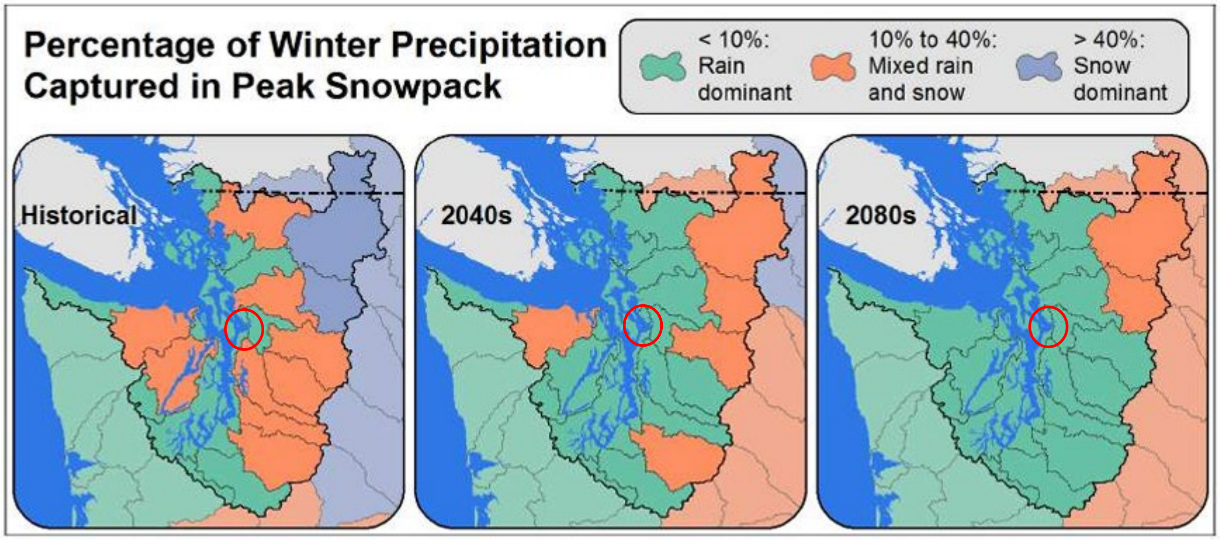


Figure 3-1. Models project a dramatic shift to more rain-dominant conditions in Puget Sound watersheds. Maps above indicate current and future watershed classifications, based on the proportion

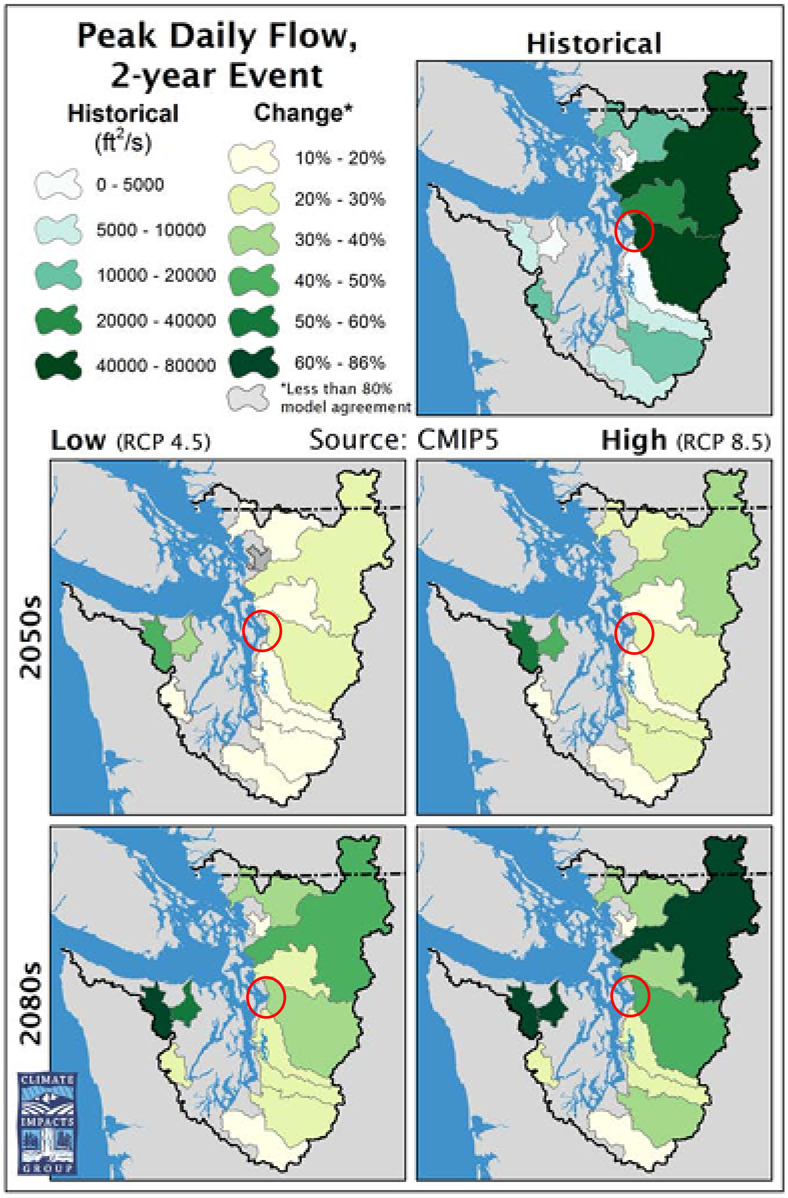


Figure 16b. Peak daily streamflow, 2-year event, newer projections. As in Figure 16a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013*[2] *report. Data source: Mote et al. 2015.*[1]

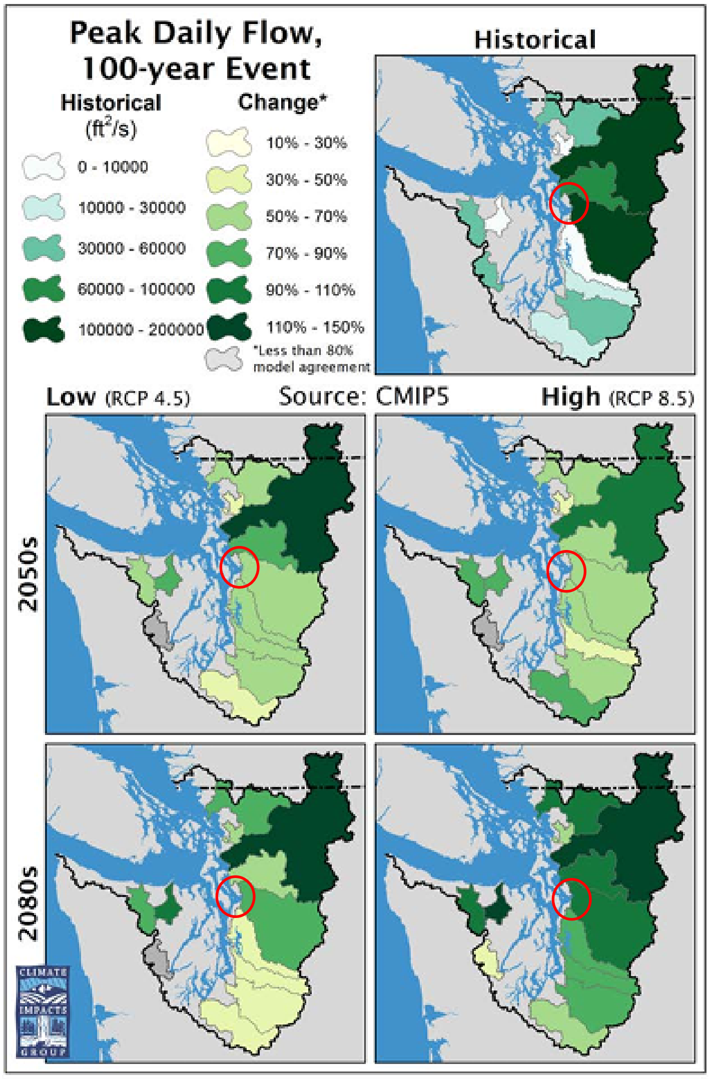


Figure 19b. Peak daily streamflow, 100-year event, newer projections. As in Figure 19a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*