Climate Impacts to Groundwater in the Lower Snohomish and Stillaguamish River Basins

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Acronyms

°C	degrees Celsius
CFA	comprehensive flow analysis
cfs	cubic feet per second
CIG	Climate Impacts Group
CTD	Conductivity, Temperature, and Depth
DD	Diking District
EC	electrical conductivity
eRAMS	Environmental Resource Assessment & Management System
FCD	Flood Control District
FDC	flow duration curves
GPS	global positioning system
I-5	Interstate 5
LiDAR	light detection and ranging
MHHW	Mean Higher High Water
mS/cm	microsiemens/centimeter
MTL	Mean Tide Level
NOAA	National Oceanic and Atmospheric Administration
PPT	parts per thousand
PSU	practical salinity units
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
RM	river mile
RSLR	relative sea-level rise
SC	specific conductivity
SCD	Snohomish Conservation District
SLR	sea-level rise
USGS	US Geological Survey
UW	University of Washington
VLM	vertical land movement
WCRP	Washington Coastal Resilience Project
WDFW	Washington Department of Fish and Wildlife
WSEL	water surface elevation

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1 Introduction and Background

Cardno has contracted with the Snohomish Conservation District (SCD) to assess sea-level rise impacts to groundwater in the lower Stillaguamish and Snohomish River basins. Figures 1-1 and 1-2 show the focused study areas. To provide a basis for comparison with alternative conditions of future sea-level rise (SLR), a first-order analysis of existing conditions (i.e., making use of available gage data but no hydrogeologic modeling) for 2018 groundwater levels and salinities was conducted. A primary focus was to characterize the current timing and inundation of groundwater surface saturation and ponding that may prevent farmers from accessing and planting their fields. A secondary consideration was to determine whether the onset of wet-season inundation of fields was likely to change as a result of rising sea levels. Additionally, SLR impacts on salinity intrusion into shallow groundwater was assessed.

This analysis was first compared to historical riverine hydrologic conditions to estimate how representative of average spring season groundwater ponding conditions was the present year. Then, spring 2018 conditions were extrapolated to predict conditions of 2050, 2080, and 2100 SLR under low and high greenhouse gas scenarios. Cardno timed delivery of our work to coincide with the release of the University of Washington (UW) Climate Impacts Group (CIG) study entitled *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al. 2018). That report adjusted global SLR projections to account for localized vertical land movement (VLM) to create local relative sea level rise (RSLR) projections applicable to community-level planning projects such as this one. Cardno and SCD worked with Guillaume Mauger of UW CIG to ensure applicability of the study's results to the lower Snohomish and Stillaguamish River systems. Dr. Mauger provided detailed descriptions of project output such that Cardno could determine applicable groundwater assessment methodologies. Cardno's Dan Elefant, PE and Sky Miller, PE provided input to UW CIG on the accuracy of their underlying hydraulic inundation models. Groundwater projections were completed using the 50% probability of exceedance RSLR for two scenarios that bracket the range of likely future conditions: a low RSLR with low greenhouse gas scenario (RCP 4.5) and high RSLR projections for a corresponding high greenhouse gas scenario (RCP 8.5) (Miller et al. 2018).

Timing and extent of groundwater saturation and inundation are major variables affecting agricultural operations in the lower Snohomish and Stillaguamish River basins. In the spring, farmers cannot access fields for preparation and planting until spring groundwater levels decrease. In the fall, rain and the associated rise in the groundwater table effectively end the cultivation season. A rise in RSLR is expected to raise groundwater levels and extend the period of inundation in the spring, which will prolong the time required for levels to recede such that agricultural operations may commence. RSLR may also shorten the agricultural season in the fall, as rains descend upon a groundwater table that may be higher in the future due to higher sea level.

This report seeks to address the following questions:

1. How well do measurements of the groundwater table for spring and fall 2018 represent average conditions of past years?
2. What is the current extent of tidal influence on river and groundwater levels?
3. What is the current timing of spring groundwater inundation that prevents access for crop cultivation, and how will RSLR delay those operations into the future?
4. Will RSLR also change the timing of late-summer and early-autumn inundation?
5. Will RSLR cause salinity intrusion into groundwater and to what extents?

In April 2018, Cardno installed and surveyed a series of shallow groundwater wells with Conductivity, Temperature, and Depth (CTD) data loggers (four in the lower Snohomish and two in the lower Stillaguamish River basins) in advance of the final spring river runoff peaks. Cardno also surveyed two Stillaguamish Tribe groundwater wells such that four water level datasets per river basin could inform the spring and fall 2018 analysis. This report presents the data collected, the analyses of results, and a discussion of how these data can guide climate change adaptation and Snohomish County agricultural resiliency planning efforts. The data also provide a baseline from which to compare future change.

This report is accompanied by the following high-resolution appendices, which cannot be interpreted or distributed without the full consideration of this analysis and limitations discussed herein:

- Appendix A Maps – SLR Delay to Spring Crop Cultivation
- Appendix B Maps – Ebey Island Future Groundwater Ponding
- Appendix C Maps – Florence Island Summer Salinity Intrusion to Groundwater
- Appendix D Data – Smith Island Partner Well Data
- Appendix E Data – Cardno Well Logs

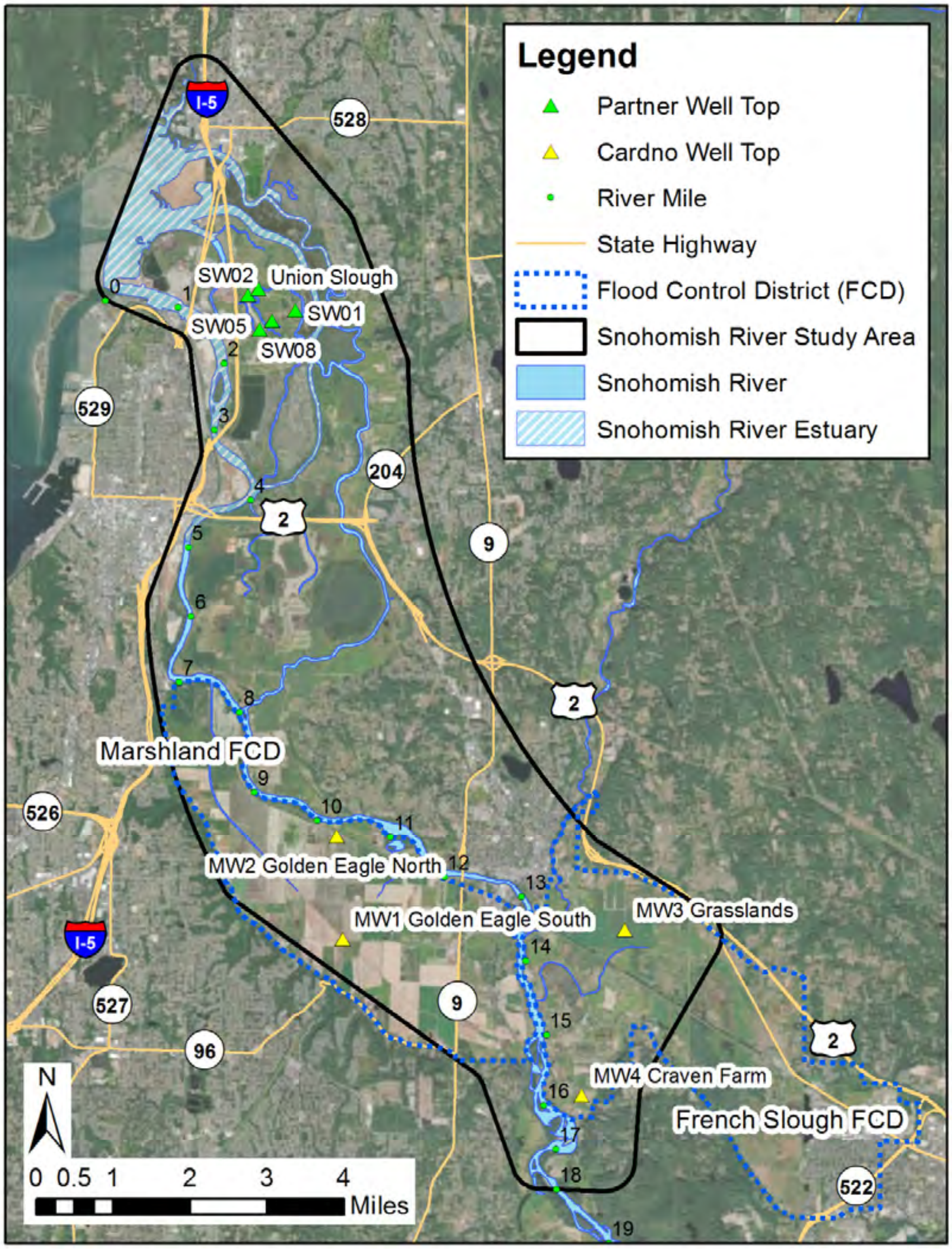

Figure 1-1 **Map of the preliminary study area (black outline) for the lower Snohomish River floodplain. Cardno installed four shallow groundwater wells (yellow) and analyzed data from five additional shallow wells on Smith Island (green).**

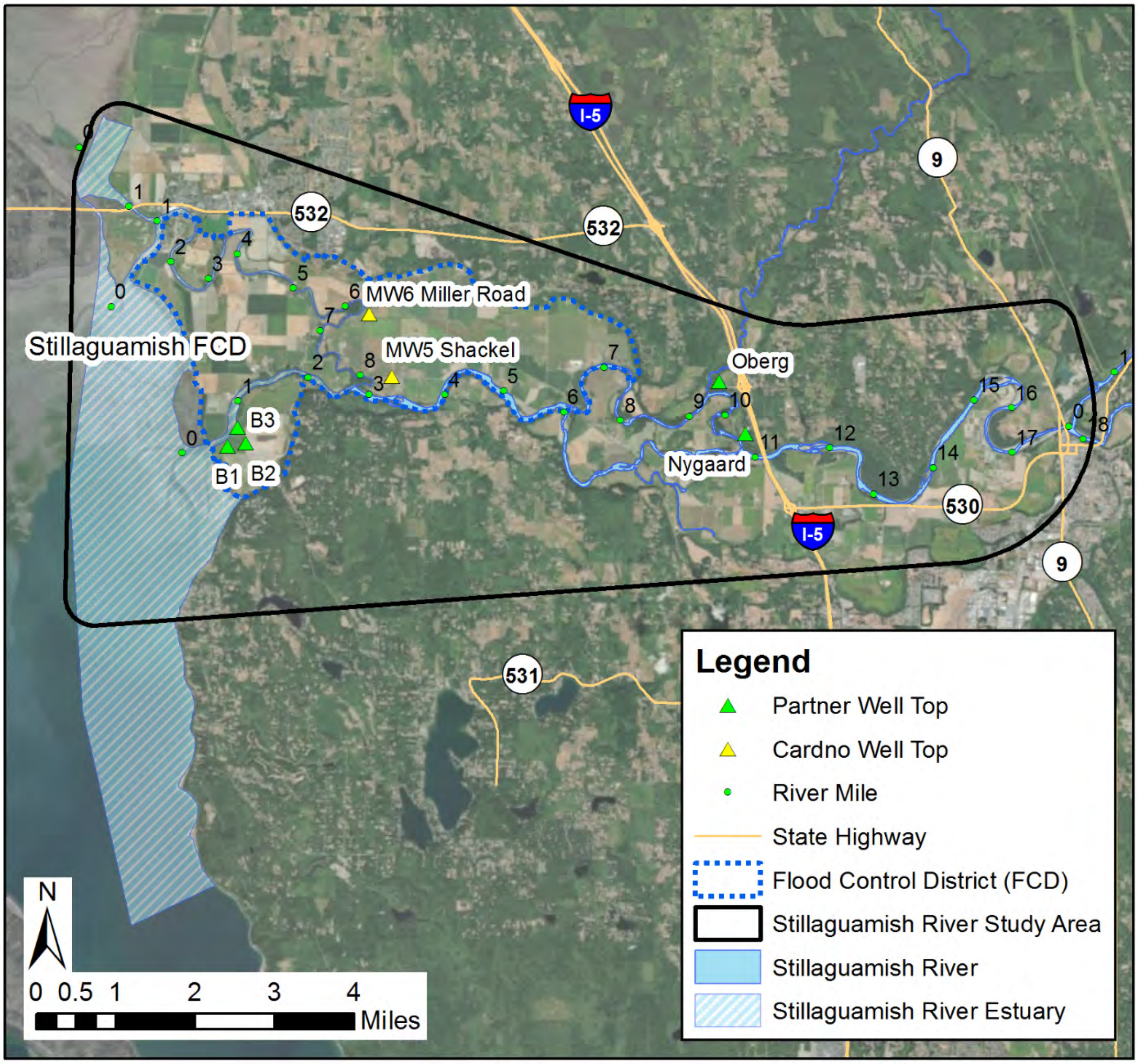

Figure 1-2 Map of the preliminary study area (black outline) for the lower Stillaguamish River floodplain. Cardno installed two shallow wells (yellow). This study includes analysis for five additional partner wells: B1, B2, and B3 (Snohomish County shallow wells installed for the Hatt Slough Estuary Restoration Project) and Stillaguamish Tribe wells (Oberg and Nygaard).

2 Setting

The upper surfaces of both the Snohomish and Stillaguamish River aquifers coincide with the land surface throughout the two study areas. These aquifers are “unconfined,” meaning that the water table (the top water-surface elevation of groundwater) can freely fluctuate in elevation and is hydraulically connected to the water-surface elevation in adjacent river channels and ponds. The general direction of groundwater flow follows that of the rivers, from upstream to downstream.

The two study areas are defined by the extent of tidal influence for each river system, under the assumption that long-term changes in sea level are unlikely to be expressed much beyond the (far greater) fluctuations presently expressed by the tides. Subsequent sections present a detailed analysis of the extent of tidal influence on both river systems. For the Snohomish River, the study area extends from the mouth of Possession Sound at Everett, Washington, to river mile (RM) 16.1, where minimal tidal influence is observed upstream of Bob Heirman Wildlife Park at Thomas’ Eddy. The Stillaguamish River study area reaches from the current mouth at Hatt Slough, across Florence Island, to the Old Main Channel and upstream to the Pioneer Highway Bridge at RM 7.4.

The general configuration of the groundwater table in an unconfined alluvial aquifer typically presents a subdued reflection of the ground surface—“mounds” in the groundwater table underlie high points in the surface topography, and the low points in the topography, occupied by waterbodies, reflect the surface expression of the water table (Figure 2-1).

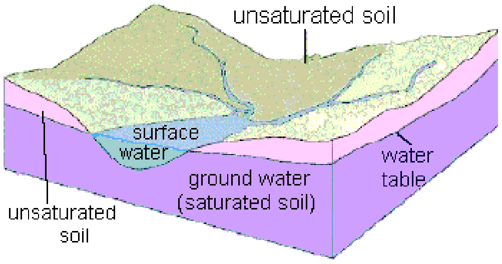

Figure 2-1 Typical configuration of the water table of an unconfined aquifer, the overlying ground topography, and surface-water bodies (Source: US Geological Survey 2018).

Local factors can complicate this picture. In the Snohomish and Stillaguamish River valleys, a rising water table can reflect not only broad, regional increases in groundwater but also more limited and brief inputs of water from rainfall across the alluvial valleys or flood discharges into the lower river. Either of these phenomena can produce a local rise in the water table that may persist for days or even weeks. Conversely, a lowered water table can result from either enhanced drainage or water-well pumping, which can distort the “typical” geometry displayed in Figure 2-1 for as long as the withdrawals are occurring. All of these complicating factors are present in the Snohomish and Stillaguamish River valleys, and their competing effects can only be unraveled with hydrogeologic modeling that is outside the scope of this study. Nevertheless, existing data on tidal fluctuations, river stage, and groundwater levels allow development of a generalized picture of the groundwater regime in these valleys that yields useful answers to the questions that motivated this study.

2.1 Methods

The objectives of the CTD sensor installation and associated subsurface exploration were to collect data to:

1. Confirm expected geological substrates within 10 feet of the surface; and
2. Document groundwater tables and estimate gradients and flow directions over time.

The data loggers collected simultaneous CTD data from April 2018 through December 2018. During that period, the study areas experienced typical spring and early summer seasonal conditions, including one period of high late-spring flows and a subsequent decline in the water table toward summer conditions. All elevations were corrected to the NAVD88 vertical datum.

2.1.1 Well Installation and Site Selection

Cardno installed six wells with six Schlumberger Diver CTD loggers and one Barometric Diver logger. Cardno and SCD determined that Marshland Flood Control District (FCD) and the French Slough FCD along the lower Snohomish River would receive two wells each for this study. The two remaining wells were targeted for installation along the lower Stillaguamish River. Cardno reviewed data from partner wells prior to selection and installation of the shallow groundwater wells and CTD loggers. The following partner wells contributed data for analysis in this study:

Snohomish River:

- Snohomish County – wells were installed as part of the Smith Island Restoration Project; Cardno assessed well data and used summer 2017 data from SW-01, SW-02, and SW-08 to inform the magnitude of tidal attenuation for this project.

Stillaguamish River:

- Stillaguamish Tribe – Oberg and Nygaard wells are located near the river at Interstate 5 (I-5); data were collected at 15-minute intervals from October 2017 to summer 2018. Cardno used engineering-grade global positioning system (GPS) survey to allow conversion of water depths to water surface elevations (WSEL) on NAVD88 vertical datum.
- Snohomish County – three shallow wells are located south of the mouth of the river; data were collected at 15-minute intervals from February to May 2017. Cardno was the prime contractor for the Hatt Slough Estuary Restoration Project and helped with engineering survey of these wells, which informed analysis of tidal attenuation.
- Washington Department of Fish and Wildlife (WDFW) – nine wells are associated with the Leque Island Restoration Project; data were collected at 30-minute intervals from March 2015 to the present. Data were assessed but not used for this study because each well was located within the influence of multiple tidal boundaries, and because extensive ditch networks and tide gates likely imposed significant by locally varying effects on WSELs and salinities.

The six shallow wells (<10 feet deep) were encased in 2-inch-diameter polyvinyl chloride (PVC) with screens, installed by Holocene Drilling, Inc. Approximately 2 inches of annular space was filled with sand around the outside of the PVC. CTD sensors recorded data at 6-minute intervals from April 12, 2018, to June 7, 2018. A barometric pressure logger was installed such that all level data were compensated for barometric pressure fluctuations. Level data compensated for barometric pressure were converted to groundwater surface elevations on the NAVD88 datum using well survey data (Janisch 2006). Cardno CTD loggers were reset for 15-minute intervals beginning June 7, 2018, and remained *in situ*, logging through December 2018.

Four wells and CTD loggers were installed in the Snohomish River basin to ensure spatial coverage of the Marshland and French Slough FCDs (Figure 1-1). The four wells were installed as pairs, with one close to the main channel and the other farther from the main channel.

Monitoring of the Stillaguamish Tribe wells is current and ongoing, with continuous level loggers located at the upper extent of the study area. Given sufficient current data coverage upriver, two Cardno CTDs were installed in the lower Stillaguamish River basin: one at the Schakel property near the southwest corner of the Sildahl Farms dairy process facility and the other on the Ellingsen Farm property adjacent to Miller Road (Figure 1-2).

A topographic field survey of the elevations of all groundwater wellheads—the six Cardno wells and the two Stillaguamish Tribe wells (Oberg and Nygaard)—was completed on April 12, 2018.

2.1.2 Well Geology

The boring logs (Appendix E) confirmed the presence of alluvial soils, which ranged from silty sands to silty clays with little to no gravel. Sandy soil lenses were interspersed through most of the borings.

2.1.3 Well Calibration – Water Levels and Conductivity

Cardno partnered with SCD to accomplish calibration for groundwater levels. Calibration followed protocols outlined in the Quality Assurance Project Plan (QAPP). SCD intern Allison Bachner manually recorded water levels at all six well sites to allow quality control checks. All well sensors accurately recorded water levels up to June 7, 2018, and no calibration of the sensors was required. Quality control for fall water levels occurred via manual water level recorded by SCD. Temperature was not recorded or calibrated for purposes of this study.

On June 7, 2018, Cardno checked all CTD sensors for accuracy in recording conductivity. All sensors recorded 15 minutes of accurate conductivities within ± 0.2 milliSiemens/centimeter (mS/cm) of a HACH Company Conductivity Calibration Standard of 1.4 mS/cm. No CTD sensors recorded values less than 1.4 mS/cm.

2.1.4 River Gages

Stages from the US Geological Survey (USGS) and Snohomish County gages on both the Snohomish River and the Stillaguamish River were established to the vertical datum of NAVD88 with input from Zach Brown, PE (Snohomish County Surface Water Management division).

2.1.5 Tidal Extents

Tidal extents were assessed for both rivers' main channels by considering continuous time series of stage for available gages (see Section 5). The extent of tidal effects on the groundwater table (also called tidal attenuation) was assessed lateral to the main river channels (see Section 6.2).

2.1.6 Sea Level Rise

All RSLR projections used in this study reference the recently released *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al. 2018). This is the best available and most current report for RSLR planning at the local community scale within Washington state. The RSLR projections include absolute SLR, which "concern[s] the long-term change in sea level, affecting the height of the water surface at all tidal elevations as well as during storm events," and modeled estimates of VLM. The RSLR projections "are not tied to any particular datum. This is because we [they] assess the change in absolute and relative sea level over time, which could be applied to any water surface elevation." The projections assume that "tidal ranges remain the same in the future." Miller et al. (2018) created a set of probabilistic projections for the percentage likelihood of exceedance of a particular RSLR value, to better align with coastal risk management:

> "By providing likelihoods, users can select probabilities to align with a particular decision context or risk management approach. For example, planners might want to consider high-impact low-probability projections for decisions regarding critical infrastructure (e.g., a hospital), whereas the low-end or middle projections might be the best approach for situations where management can easily be adapted in the future (e.g., vegetation management)." (Miller et al. 2018)

The RSLR values at 50% likelihood for exceedance were selected for use in this study. These values represent the best current estimate for RSLR. Two greenhouse gas scenarios were considered for this study: one for higher rising sea levels and higher greenhouse gas emissions (RCP 8.5) and the other for lower rising sea levels and lower greenhouse gas emissions. Table 2-1 presents the RSLR values selected for application to this study.

Table 2-1 **RSLR Projections with a 50% Likelihood for Exceedance for the Snohomish River and Stillaguamish Rivers under Greenhouse Gas Scenarios RCP 4.5 (low) and RCP 8.5 (high)**

	Year 2050	Year 2080	Year 2100
Snohomish River Mouth:			
RSLR 50% for RCP 8.5 (feet)	0.8	1.5	2.2
RSLR 50% for RCP 4.5 (feet)	0.7	1.3	1.7
Stillaguamish River Mouth:			
RSLR 50% for RCP 8.5 (feet)	0.7	1.5	2.2
RSLR 50% for RCP 4.5 (feet)	0.7	1.3	1.7

Source: Washington Coastal Resilience Project (WCRP) 2018

SLR was assumed to propagate up the main river channels proportional to the current main channel tidal propagation and extent. Well data were used to obtain rates of water table decline. The delay imposed on initial cultivation of fields was calculated by assessing the time it would take to drain the elevated groundwater table, due to RSLR, to match existing conditions. Spatial maps of time delay due to RSLR for years 2050, 2080, and 2100 were then created and cropped to the expected extent of tidal influence to groundwater.

3 Historical Hydrology – Spring and Fall

The historical hydrology of the Snohomish and Stillaguamish Rivers was evaluated to understand the relationship between the spring and fall 2018 groundwater monitoring datasets, which relate to the historical hydrologic conditions of each river system.

Whereas the Snohomish River has often conveyed large peak winter flows that exceed 60,000 cubic feet per second (cfs), average peak spring (April 1–June 30) and fall (September 1–November 30) flows typically fall between 20,000 and 50,000 cfs, with occasional spikes during the fall period (Figure 3-1). Since the installation of CTD loggers on April 12, 2018, major peak events were recorded from the Monroe gage at 32,500 cfs on April 18, 2018, for spring and 39,900 cfs on November 2, 2018, for fall. The 2018 peak spring and fall flows indicate a 2.0% chance of exceedance relative to the historical spring and fall flows from 1997 to 2018 (Figure 4-1 and Figure 4-2, respectively). Tables 3-1 and 3-2 provide comparable spring and fall statistics for the recorded 55 years of stream flow gage data (1963–2018). The 2018 peak spring flow was identified to be above average, but within one standard deviation of the historical dataset, while the 2018 peak fall flow fell below the average of 41,187 cfs. Hence, 2018 groundwater levels are expected to represent slightly wetter than average historical conditions during spring and lower than average historical groundwater levels for the fall season.

A similar analysis was completed for the Stillaguamish River based on data from the North Fork gage. No gage with published discharge values for the mainstem exists below the confluence of the North and South Forks but above tidal influence. Behavior of flows for the North Fork (which is gaged) was therefore assumed to represent the character of flow inputs to the groundwater system downstream. These data also indicate a somewhat wetter-than-normal early spring, but with May and June peak flows falling in the lower quartile of the historical record. Given the current onset of sufficiently dry conditions in late March or early April, spring 2018 groundwater levels are also expected to represent slightly wetter-than-average historical conditions in the Stillaguamish River valley.

Table 3-1 **Peak Spring 2018 Measured Discharge Relative to Historical Spring Peaks (Snohomish River)**

Year	Spring Runoff Peak Discharge (cfs)
April 18, 2018	32,500
Minimum	11,700
Average	26,418
Maximum	55,600
Standard deviation	8,667
Average + standard deviation	35,085

Table 3-2 **Peak Fall 2018 Measured Discharge Relative to Historical Fall Peaks (Snohomish River)**

Year	Fall Runoff Peak Discharge (cfs)
November 2, 2018	39,900
Minimum	7,230
Average	41,187
Maximum	132,000
Standard deviation	24,167
Average + standard deviation	65,354

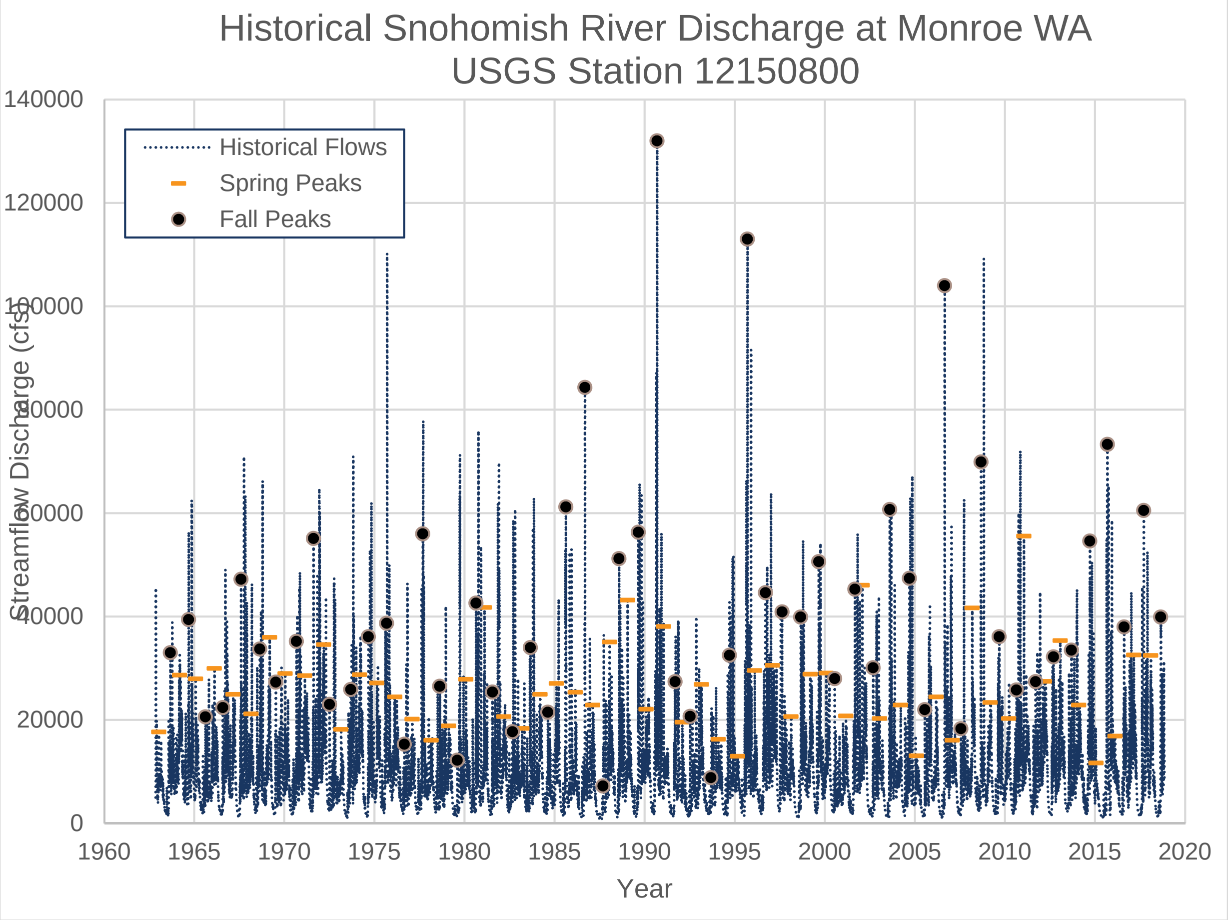

Figure 3-1 **Historical flows (blue) of the Snohomish River (USGS Gage 12150800) near Monroe, Washington, from 1963 to the present, with spring peak flows hatched in orange and fall peak flows represented as black dots.**

4 Flow Duration Analysis for Seasonal Spring and Fall

Analyses of the 2018 seasonal spring and fall flow durations relative to flow durations from previous years were performed for both the Snohomish and Stillaguamish Rivers. Nested flow duration curves (FDCs) were created for one gage site in each river system. Comparison of the average FDC to all nested water years of record allows observation of variability. Inspection of FDC points created for the 2018 spring and fall seasons allows interpretation of that year’s wetness conditions from high to mid-range to low flows compared to all other years of record.

The comprehensive flow analysis (CFA) tool from the Environmental Resource Assessment & Management System (eRAMS) allow users to access a variety of flow data such that multiple FDCs can be examined simultaneously for a specified time step. FDCs show the probability (percentage of time) that flow in a stream is likely to equal or exceed a particular value of interest. The CFA tool organizes and plots flow data from the USGS stream gages on a scale of percent exceedance, providing a quick visualization of current and historical records with an overall average FDC curve.

4.1 Lower Snohomish River – Spring (April 1–June 30)

The Snohomish River had slightly higher spring 2018 flows than the average FDC for high flows and mid-range flows, although these flows were within the historical variation of nested FDCs back to the year 1963 (Figure 4-1). No difference was observed in the early set of 20 years of FDCs versus the most recent 20 years of nested FDCs. Thus, the spring 2018 groundwater measurements and analysis are expected to reflect slightly wetter groundwater conditions; however, groundwater levels are expected to fall within the upper standard deviation of expected conditions.

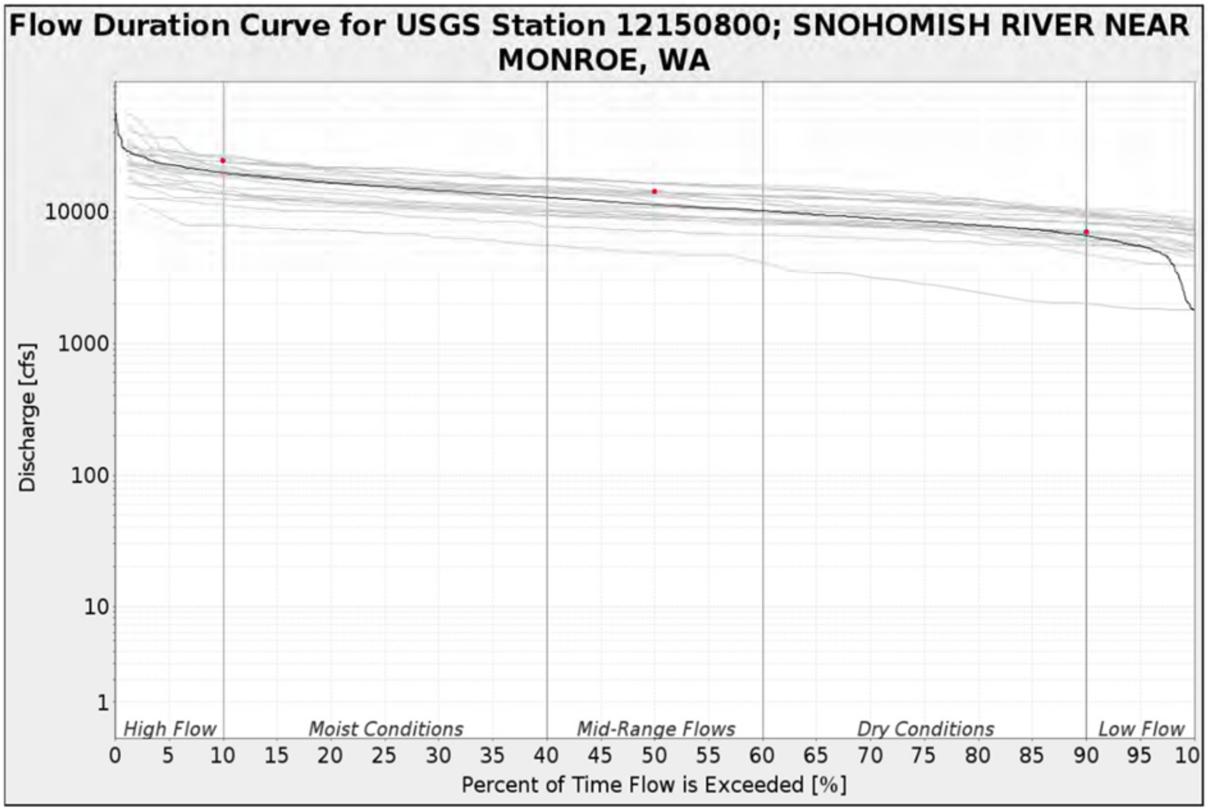

Figure 4-1 **Seasonal spring FDCs for 1997 to 2017 during the April 1 to June 30 time period. The three red dots represent three data points from the 2018 spring FDC: 10th, 50th, and 90th percentiles of flow exceedance.**

4.2 Lower Snohomish River – Fall (September 1–November 30)

The Snohomish River experienced lower fall 2018 flows than the average FDC for mid-ranged flows (Figure 4-2), though these flows are within the historical variation of nested FDCs that date back to 1963. Comparison between the earlier (1963–1983) and more recent (1998–2018) 20 years of nested FDCs revealed minimal hydrologic variability with minor increases from the earlier 20 years' nested FDC (Figure 4-2, red line) during mid-range to low flow conditions. However, the more recent 20 years (1997–2017) show decreases of high flow events as compared to the 20-year period from 1963 to 1983. The fall 2018 groundwater measurements and analysis are expected to reflect lower groundwater conditions and drop below the standard deviation of expected conditions.

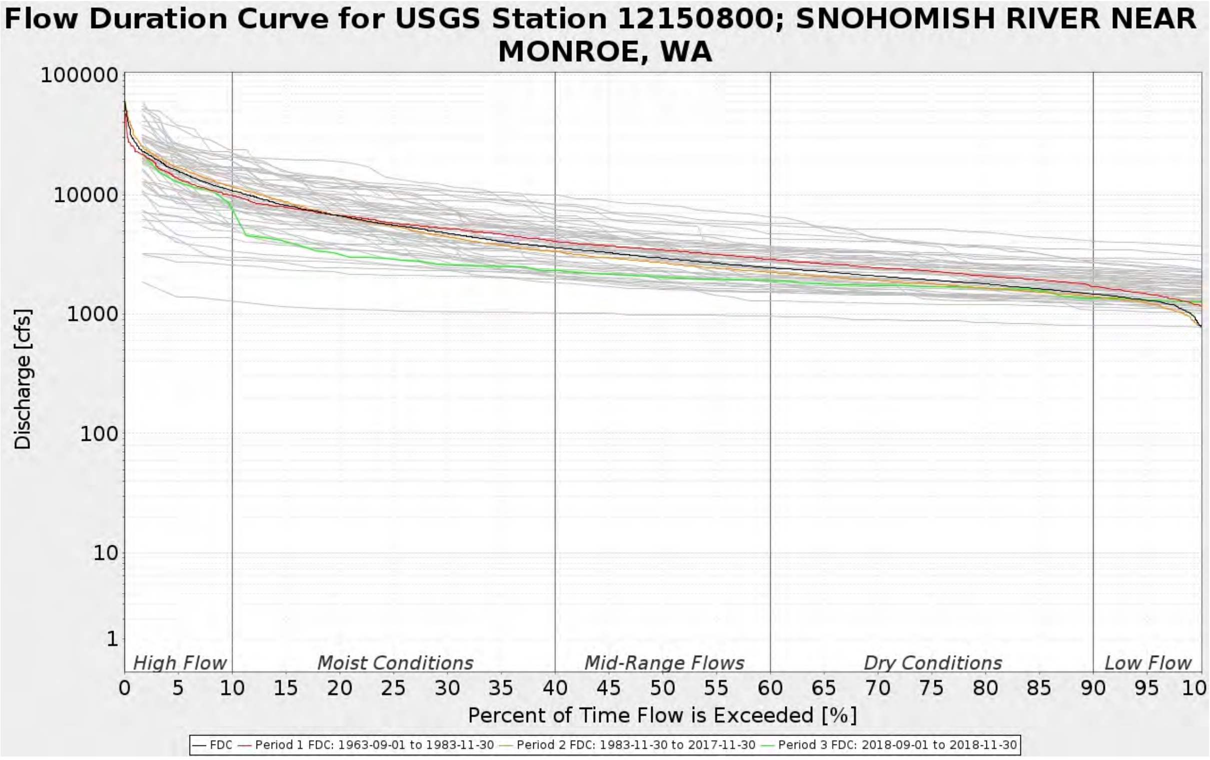

Figure 4-2 **Seasonal fall FDCs for 1963 to 1983 (red line) and 1997 to 2017 (yellow line) during the September 1 to November 30 time period. The green line represent the 2018 fall flow duration curve. The black line is the average FDC for all years.**

4.3 Lower Stillaguamish River – Spring (April 1–June 30)

Utilizing the CFA tool, flow records for the North Fork Stillaguamish River near Arlington, Washington, were compared for the spring season (April 1–June 30) for the years 1928 to 1948, 1998 to 2017, and 2018 (spring 2018). Based on spring 2018 flow durations compared to the previous years, the 3% (highest discharges) and 97% (lowest discharges) exceedance flows were above the average FDCs, while all others (10%, 50%, and 90% exceedance) fell below (Figure 4-3). These indicate that extreme flows in spring 2018 were greater than the average, but mid-range flows were lower than usual. Absent time-dependent modeling there is no simple method to deduce the overall effects on groundwater levels, but we expect that the spring 2018 groundwater measurements for the Stillaguamish River will reflect broadly similar groundwater conditions as compared to the past.

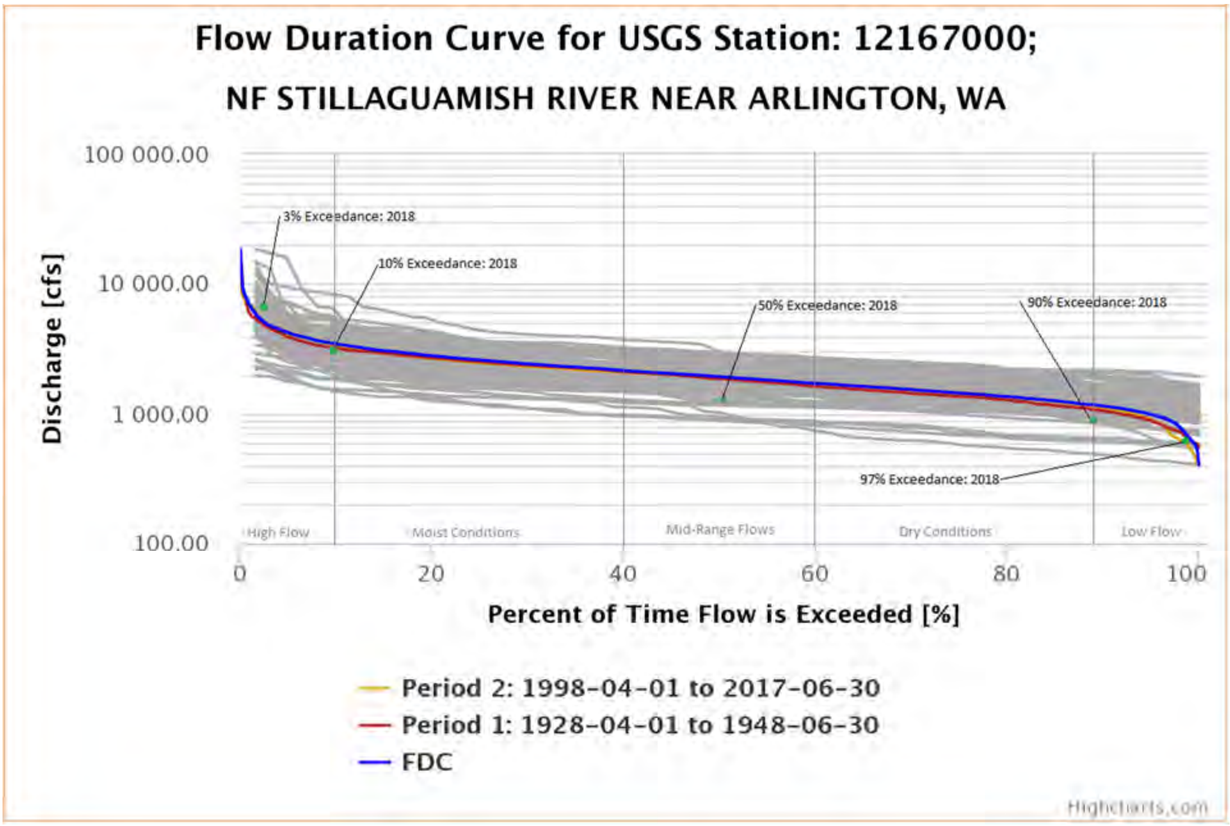

Figure 4-3 North Fork Stillaguamish River spring FDCs with 2018 in red. There is no apparent difference in average spring FDC for spring 1928 to 1948 versus spring 1998 to 2017. Spring 2018 (green points) shows higher peak flows and lower mid-range flows compared to average FDCs.

4.4 Lower Stillaguamish River – Fall (September 1–November 30)

Similar to the results for the lower Stillaguamish River spring data, comparable FDCs from seasonal fall years 1928 to 1948, 1998 to 2017, and 2018 show close resemblance to the overall average FDC (Figure 4-4, black line). During high flow events (3%–10% exceedance), the fall 2018 flow duration exceeded the average FDC, while mid-range flows (50% exceedance) were slightly lower. Following a similar trend to the North Fork Stillaguamish River FDC (Figure 4-4), it is anticipated that the fall 2018 groundwater wells experienced increased water levels during high flow events and slightly lower levels during mid-range flow events when compared to previous years.

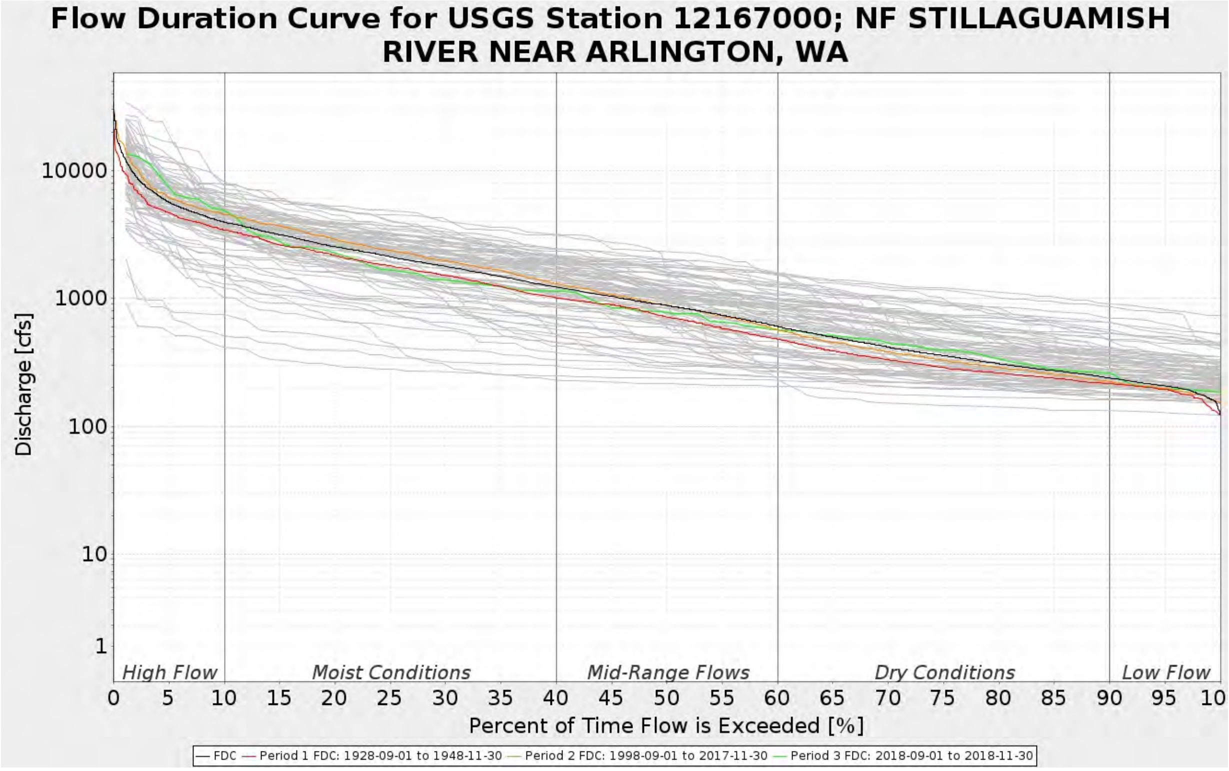

Figure 4-4 **North Fork Stillaguamish River fall FDCs with 2018 in green. Average FDC for fall 1928 to 1948 (red) is slightly lower than the overall average FDC (black). The fall 1998 to 2017 (orange) average FDC follows a similar trend to the overall average FDC, with slight increases and decreases, respectively, during high and mid-range flow events. 2018 shows higher peak flows and lower mid-range flows compared to average FDCs.**

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5 Main River Tidal Extents

Critical to the evaluation of RSLR effects on groundwater is an understanding of the extent of tidal influence on the two river systems—that is, how far does the tide extend upstream? Gage WSEL data on each river system were reviewed for tidal influence during spring 2018 conditions, using data from the following gages: National Oceanic and Atmospheric Administration's (NOAA's) Everett tide gage; Snohomish County's Ebey Island gage; the USGS gage at Snohomish, Washington; the USGS gage on the Pilchuck River; Snohomish County's Snohomish River gage at French Slough; and the USGS gage near Monroe. Figure 5-1 shows a plot of tidal influence on the Snohomish River. Under spring flows of 30,000 cfs, the tide extends to approximately RM 16 but at a muted range as compared to lower spring flows around 12,000 cfs. The Stillaguamish River exhibits similar behavior, where tides are muted by higher river discharges. However, tide extends up the current main channel of the Stillaguamish River (Hatt Slough) only as far as RM 7.4 for lower flows and RM 5 for higher flows (Figure 5-2). This analysis is corroborated by R2 Resource Consultants' independent evaluation of tidal extent, based on the intersection of Mean Tide Level (MTL) and river thalweg elevation presented in their geomorphic assessments of each lower river system (DeVries [2015] for the Snohomish River and DeVries [2013] for the Stillaguamish River). Furthermore, Cardno's observations during the design and installation of the Backwater Channel Reconnection Restoration Project on Mr. Moga's property in 2017 (Snohomish River at RM 16.1) confirmed that tidal amplitude was negligible this far upriver.

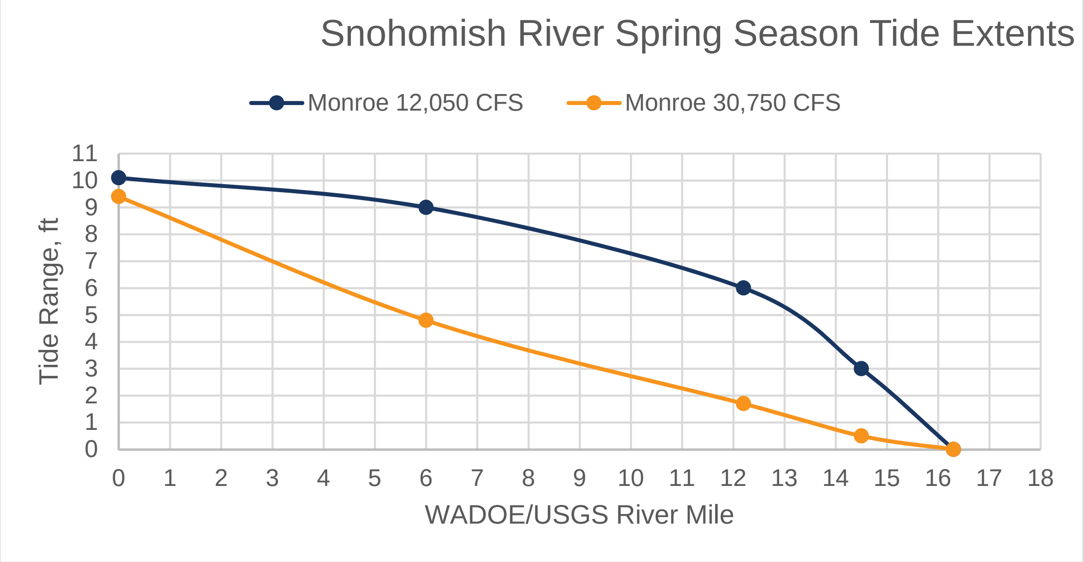


Figure 5-1 **Current 2018 tides extend at most to RM 16.1 under two generalized spring flow scenarios for the Snohomish River.**

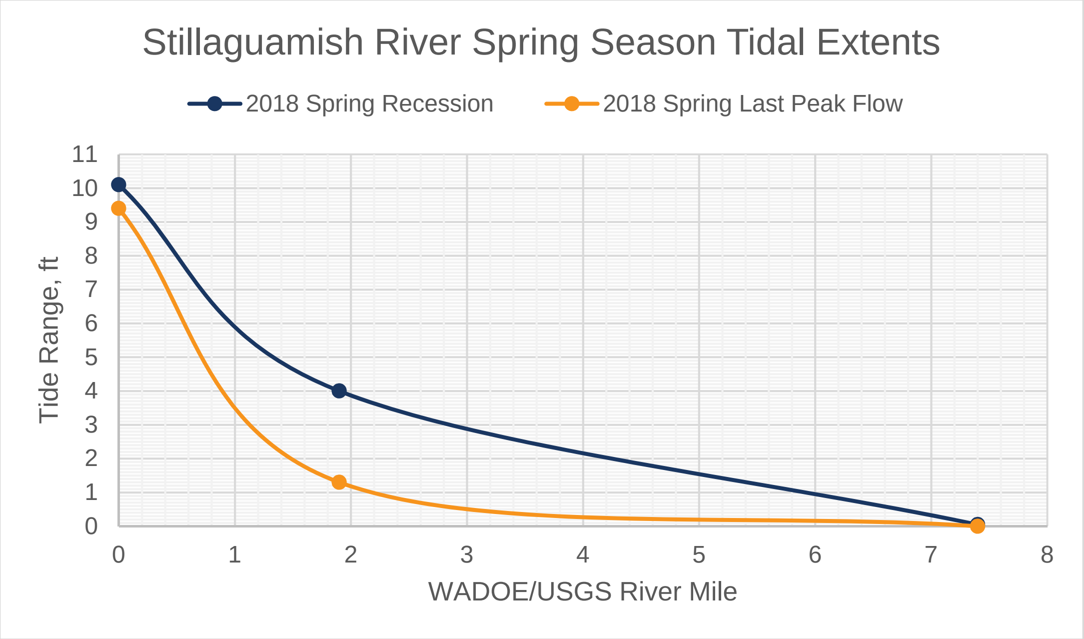


Figure 5-2 **Current 2018 tides extend at most to RM 7.4 near the Pioneer Highway Bridge under two generalized spring flow scenarios for the Stillaguamish River.**

6 Groundwater Level Analysis

6.1 Shallow Groundwater Level Analysis

6.1.1 Lower Snohomish River

The Snohomish River groundwater and river stage dataset is presented in Figure 6-1. All four Cardno wells—Eagle North, Eagle South, Craven Farm, and Grasslands Farm well sites—successfully logged CTD data. Three continuous river stage gage sites were also plotted to the same vertical datum: USGS Snohomish River gage near Monroe, Snohomish County gage for the Snohomish River at the French Slough outlet, and USGS Snohomish River gage at Snohomish, Washington. Water surfaces decline moving downvalley from Monroe to Snohomish. Both the French Slough and Snohomish, Washington, river gages demonstrated a semi-diurnal tidal signature, which generally shows two high and two low tides per day.

None of the well sites showed a discernable tidal signature, however, despite persistent tidal fluctuation in the adjacent main channel river. WSEL was highest at Craven Farm and lowest at Eagle South. All four wells showed a response to the 32,500 cfs peak flow, which had two pulses between April 15 and April 18, 2018. The relative head differential between all four wells remained constant after the mid-April recession, which suggests a relatively stable water table slope that trends downvalley toward Puget Sound.

Anomalous peaks in WSEL were recorded at the Eagle South well. The well was placed about 10 feet away from the main drainage channel of the Marshland FCD. Thus, the Eagle South well has WSELs that more likely reflect WSELs of the drainage canal than of the average surrounding groundwater table. Furthermore, the Eagle South well responds to precipitation pulses from multiple drainages on steep slopes to the south of the Marshland FCD. As a result, only the Craven Farm, Grasslands Farm, and Eagle North wells were used in representing the regional groundwater table.

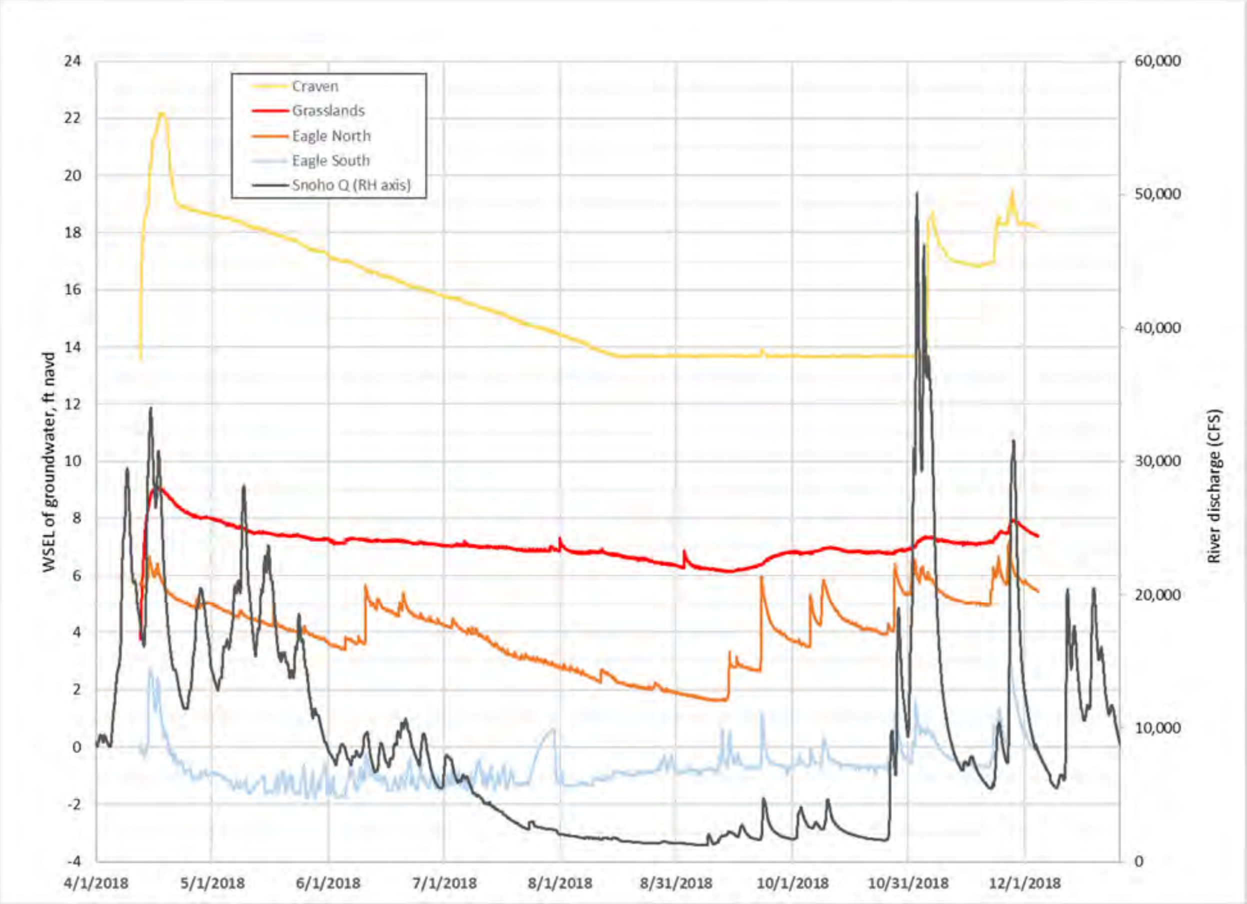


Figure 6-1 **Datasets used to analyze groundwater conditions through the 2018 monitoring period, using three of the four shallow wells installed by Cardno (Craven Farm, Grasslands Farm, and Eagle North). Eagle South data are shown but were not used in analysis.**

Choosing the first day for field access is a complex decision made by farmers and relates to complex interactions of rainfall, river runoff (spring snowmelt and precipitation higher in the basin), and elevated shallow groundwater levels. Wetter years will result in delayed access to fields since farmers avoid driving through standing water or tracking through groundwater-saturated soils. Drier years may allow earlier access depending on crop types. Farmers may decide to add more extensive ditch drainage networks in the fall when they expect wetter conditions for the subsequent year.

Although climactic conditions (precipitation and river levels) that delay access to fields will vary from year to year, the rate of recessional decay for the groundwater table to reach levels suitable for cultivation should remain relatively stable into the future. Higher water tables will take longer to reach a stable rate of decline. Thus, a higher water table due to RSLR will take longer to decrease, under the basic assumption that soil drainage conditions remain similar into the future.

Figure 6-2 presents the datasets selected for analysis of the rate of groundwater recession through spring 2018. The Craven Farm, Grasslands Farm, and Eagle North wells have similar rates of decline, dropping about 1 foot per month.

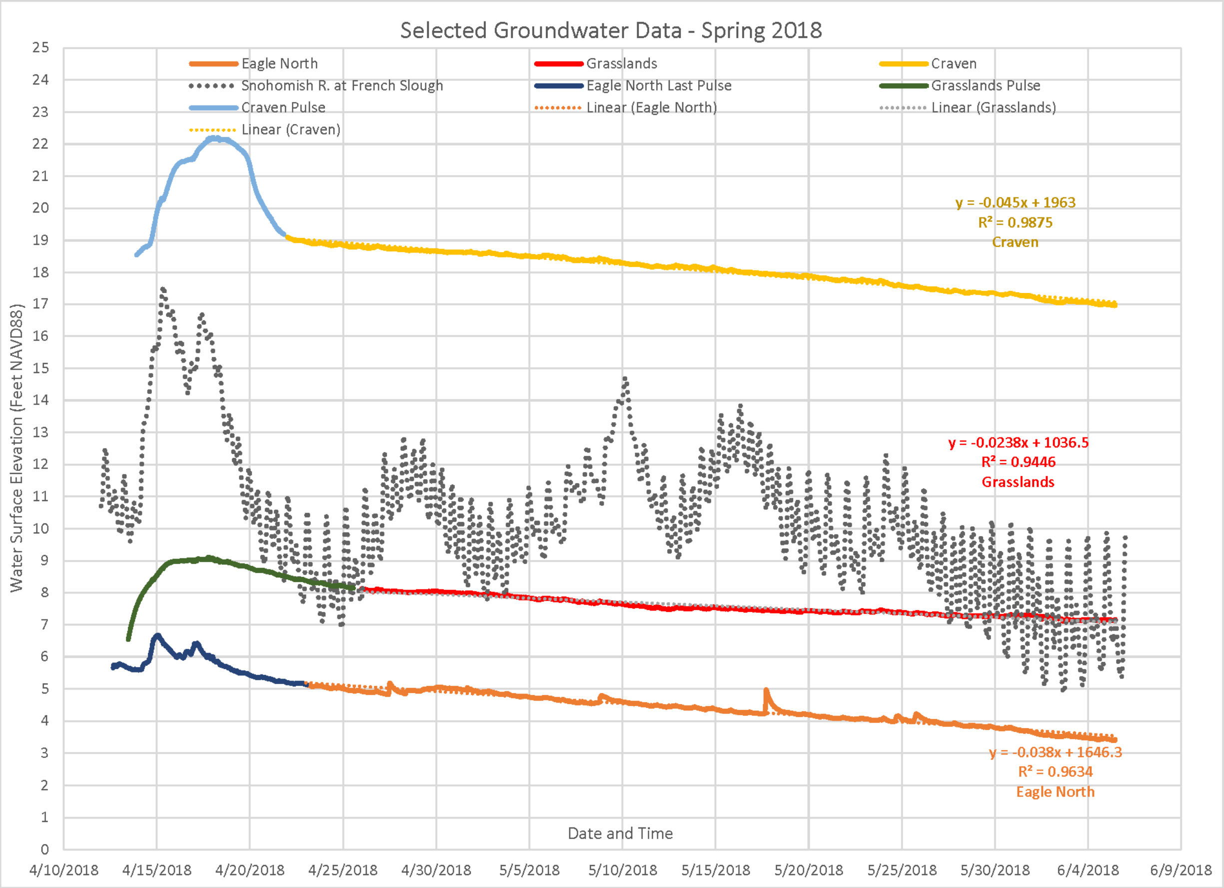


Figure 6-2 **Selected groundwater data relative to WSEL of the Snohomish River at French Slough (Eagle South well data omitted due to local influence of pumping). Linear trend lines were fit to the groundwater datasets after the last significant detectable response to pulses in river flow resulting from spring floods. Slope of the trend line is the groundwater table rate of decline. Generally, the three wells record water table lowering at an average rate of about 1 foot per month.**

Throughout the summer of 2018, shallow groundwater levels continued to fall. Grasslands Farm, which had expressed the slowest regression of the three wells in Figure 6-2 during the spring, maintained an even slower rate through the summer (less than 1 foot of additional decline over the following 3 months). Craven Farm and Eagle North maintained more rapid rates of decline that approximated those of the spring, but with two distinct patterns: Craven Farms declined over 3 feet in less than 3 months but then maintained a virtually static level until the first major river discharge in early November, whereas Eagle North declined at a steady rate of 1 foot per month, but punctuated with an abrupt 2-foot rise during a late spring rainstorm that began on June 9 (Figure 6-1). (As noted previously, shallow groundwater levels in Eagle South were dominated by the effects of local pumping and are not considered further.)

The late summer rise in groundwater levels exhibited two distinct patterns. Levels at Craven Farm clearly match the first significant rise in river levels, reflecting the first large storm of the 2018–2019 winter season that arrived at the beginning of November. River levels, and then the Craven Farm groundwater levels, responded within a day or two thereafter. In contrast, groundwater levels at Eagle North showed an abrupt 2-foot rise on June 10, during the only significant rainstorm of the entire summer. The reason for this behavior, distinct from the other wells in this valley, is unknown but is likely related to strictly local conditions. A second rise, presaging the autumn increases associated with November (and later) river discharges, occurred in mid-September during the first rainstorm greater than 0.1 inch since June.

The third well, Grasslands Farm, displayed no response to the early June rainstorm and only muted responses to both the September rain and the November high river flows. Its location, nearly 2 miles from the Snohomish River, likely explains its minimal response to changes in river discharge. Its minimal response to rainfall, similar (but not identical) to that of the Craven Farm well, suggests a limited, attenuated connection with surface conditions.

In every case, the return of groundwater levels to early-spring elevations was triggered by an “external” event: in the case of Craven Farm, high discharges in the river; for Eagle North and Grasslands Farm, early-season rainfall. Neither of these events are affected by SLR, and for the two sites close to the river (Craven Farm and Eagle North) the autumn groundwater rise was sufficiently rapid that even a systemic, SLR-induced delay in groundwater recession would not appear to change the date at which groundwater levels returned to problematically high levels.

The same degree of SLR insensitivity cannot be asserted with as much confidence for Grasslands Farm. From the well’s mid-spring maximum to its summer minimum the change was only 3 feet, and the early-autumn average rise was so slow (about 0.5 foot per month) that even a modest fractional SLR could change the date substantially for when any chosen groundwater elevation was reached. If the end of the growing season in and around Grasslands Farm is now determined by groundwater inundation, future SLR could shorten the period of summer–autumn dry ground. This same dependency does not appear to hold at the other sites monitored for this study.

6.1.2 Lower Stillaguamish River

The Stillaguamish River groundwater and river stage dataset is presented in Figure 6-3. The spring 2018 Schakel well dataset was lost due to error, but data were recovered beginning in early June. Cardno’s Miller Road well successfully logged CTD data. The Stillaguamish Tribe’s Nygaard and Oberg wells also successfully logged water level data. Three continuous river stage gage sites were also plotted to the same vertical datum: USGS Stillaguamish River near Stanwood (Marine Drive Bridge), Snohomish County gage for the river at the Pioneer Highway Bridge, and Snohomish County gage for the river at I-5.

Water surfaces declined downvalley from I-5 to the mouth at Hatt Slough. WSEL was highest at the Nygaard well and lowest at the Miller Road well. All three wells showed a response to river peak flows, which had two pulses between April 15 and April 17, 2018. The relative head differential between all three wells remained constant after the mid-April recession, which suggests a relatively stable water table slope that trends downvalley toward Puget Sound.

The USGS gage on the Marine Drive Bridge demonstrated a semi-diurnal tidal signature, which generally shows two high and two low tides per day. The Miller Road, Oberg, and Nygaard well sites did not show a discernable tidal signature despite persistent tidal fluctuation in the adjacent main channel river. The Schakel well showed tidal fluctuation of 2 to 3 feet.

The Nygaard well (370 feet northeast of the northern channel split) had WSELs about 2 feet higher than the Oberg well (965 feet northeast of the split) because of its closer proximity to the main river channel. The Oberg well receives groundwater from the Pilchuck Creek drainage, which may also elevate WSELs relative to the Nygaard well. Figure 6-4 presents the datasets selected for analysis of the rate of groundwater recession through spring 2018. The Miller Road, Oberg, and Nygaard wells showed that the lower Stillaguamish River basin has similar rates of water table decline (with average rates slightly greater than 1 foot per month) to those of the Snohomish River basin.

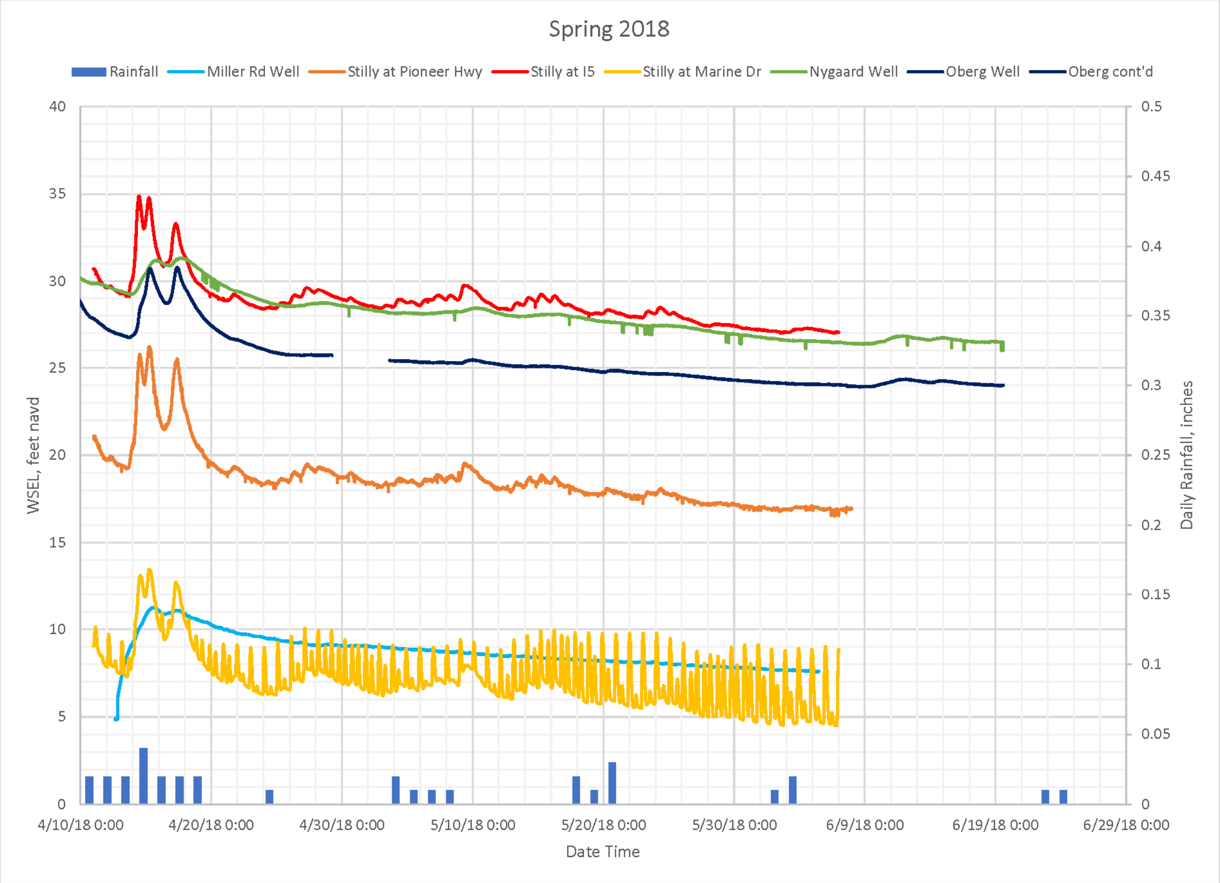


Figure 6-3 Datasets considered for analysis of spring 2018 groundwater table conditions including three shallow wells: one installed by Cardno (Miller Road) and two installed by the Stillaguamish Tribe (Oberg and Nygaard). April rainfall corresponded to a double peak in river flows. The well water tables declined linearly after April 25, 2018.

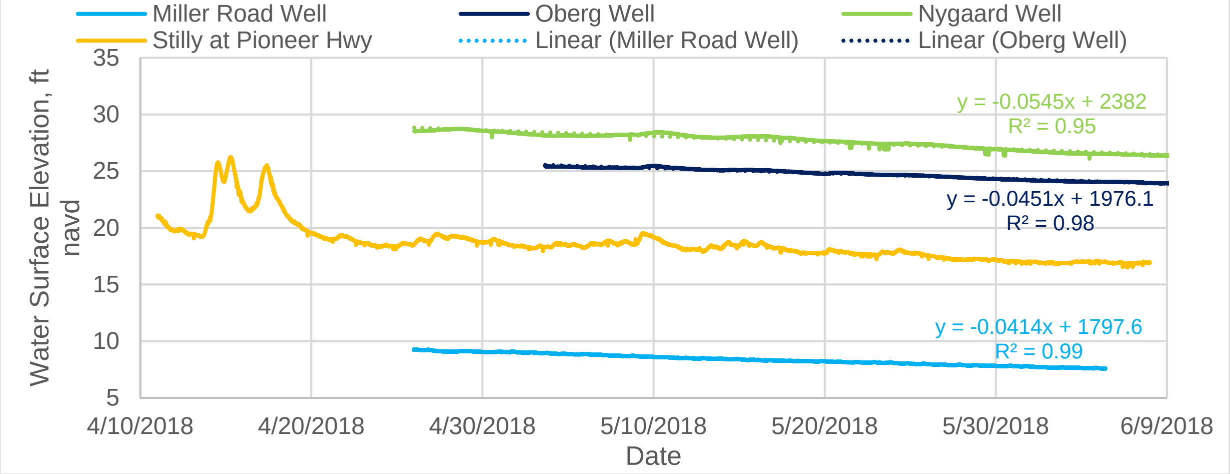


Figure 6-4 Selected groundwater data relative to WSEL of the Stillaguamish River at Pioneer Highway Bridge. Linear trend lines were fit to the groundwater datasets after the last significant detectable response to pulses in river flow resulting from spring floods. Slope of the trend line is the groundwater table rate of decline. Generally, the three wells recorded water-table lowering at an average rate that slightly exceeds 1 foot per month.

Continued data collection at the groundwater sites through the summer and autumn of 2018 defines a relatively uniform pattern of groundwater response (Figure 6-5). The springtime decline in the groundwater table noted above at all sites continued almost unabated throughout the summer, showing maximum declines of 1 foot per month but with extended periods of near-static levels (particularly at the Oberg and Miller Road wells in the second half of the summer). The early June rainfall that produced a noticeable response at Eagle North on the Snohomish River had only a barely discernable impact on two of the four wells here, and none at all at the other two. The two upstream wells (Nygaard and Oberg) both showed a small (1.5-foot) response to the mid-September rainstorm; these wells had a much greater and more abrupt rise with the first high flows in the Stillaguamish River in early November. The Miller Road well also rose in response to the November river discharge, but more gradually and to a much more subdued extent, likely reflecting its significantly greater distance from the channel. The Miller Road well also showed no response to either of the earlier rainstorms in June and September.

Although data were recovered from the Shackel well beginning in early June, its recorded level never varied by more than 3 inches over the entire 6-month period of record. Its data are not considered reliable, although the reason for its static behavior is not known.

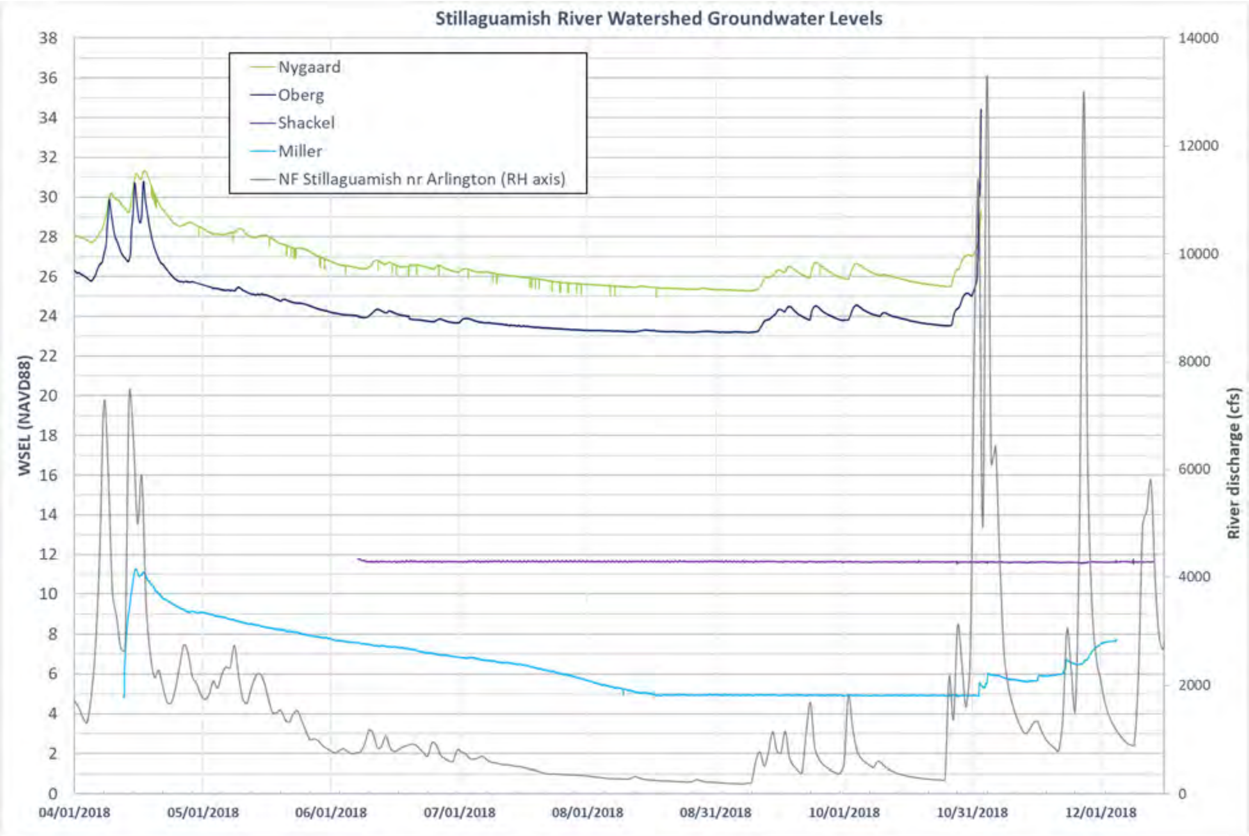


Figure 6-5 Selected groundwater data relative to WSEL of the Stillaguamish River at Pioneer Highway Bridge for the spring, summer, and autumn of 2018.

The effects of SLR on the timing of high groundwater conditions in the autumn are not likely to be significant. At the upvalley wells, the water table declined about 3 feet over the summer from its late-April, post-river-induced highstand, with significant rise only with the onset of the first high autumn river discharge. The timing of this transition will not be affected by an increase in sea level, because even a systemic rise in groundwater table of the magnitudes presently anticipated will not exceed the range of summertime groundwater levels already being experienced. At the downstream well (Miller Road), the spring–summer decline is initially more rapid, reaching its minimum value in mid-August. Its response to high river flows is slower, with recovery of a higher groundwater level requiring over a month following the first peak flow, and so a broadly higher groundwater level caused by SLR could advance the return date of problematically high groundwater levels. Because the initiation of this change is still triggered by mid-autumn flood flows, however, there is little likelihood that advancing the date when groundwater conditions became problematic would affect agricultural activities at the end of the growing season.

6.2 Lateral Extent of Tidal Influence to Groundwater

6.2.1 Snohomish River

Levees and roads prevent frequent marine and fluvial inundation within the lower Snohomish River basin. Tides still propagate upriver and are evident in the records of established USGS and Snohomish County gages. Tidal exchange is also readily observed by eye in surface waters when greater than about 0.5 to 1.0 foot of amplitude. Tidal propagation through and under levees and roads and into groundwater adjacent to tidal surface waterbodies, however, presents more challenges to observation. At the onset of this project, Cardno had expected to see a tidal signature in the wells located closest to the main channels of the rivers. However, none of the Cardno wells in the lower Snohomish River basin exhibited a tidal signature. The Eagle North well lies 915 feet south of the river’s edge, adjacent to RM 10.2. The river has 4 to 7 feet of tidal exchange here, but the levee, road, and train tracks apparently add sufficient resistance to groundwater exchange such that the Eagle North well did not display any tidal influence. The Eagle South well is even farther from the river’s boundary (8,000 feet south) and its WSELs also did not fluctuate with tides. The Grasslands and Craven Farms wells also did not show a tidal signature for spring 2018.

Because limited tidal exchange was observed at Cardno’s Snohomish River wells, we chose to utilize data from three Smith Island wells (SW-01, SW-02, and SW-08) to assess the extent of tidal influence to groundwater, since these wells were generally closer to their respective tidal boundaries and did display tidal fluctuation (see Figure 1-1 for the locations of these partner wells). Refer to Table 6-1 for a summary of each well’s tidal amplitude and distance from the tidal boundary at Union Slough. Tidal amplitude attenuated exponentially with increasing distance from the tidal boundary and is shown as a time series in Figure 6-6.

Table 6-1 **Union Slough Stage Gage and Associated Smith Island Observations of Shallow Well Tidal Amplitude, During Summer Conditions (constant river flow with 2,660 cfs near Monroe) and a Maximum Ocean Tide Close to MHHW (9.1 feet NAVD88 at Everett)**

Well Logger	Distance to Tidal Boundary (Union Slough), ft	Tidal Amplitude at ~ Mean Higher High Water (MHHW), ft
Union Slough	0	10.6
SW-01	448	2.2
SW-02	652	1.1
SW-08	1,700	0.5

Figure 6-6 presents the Smith Island well dataset selected for analysis of tidal attenuation into the groundwater table.

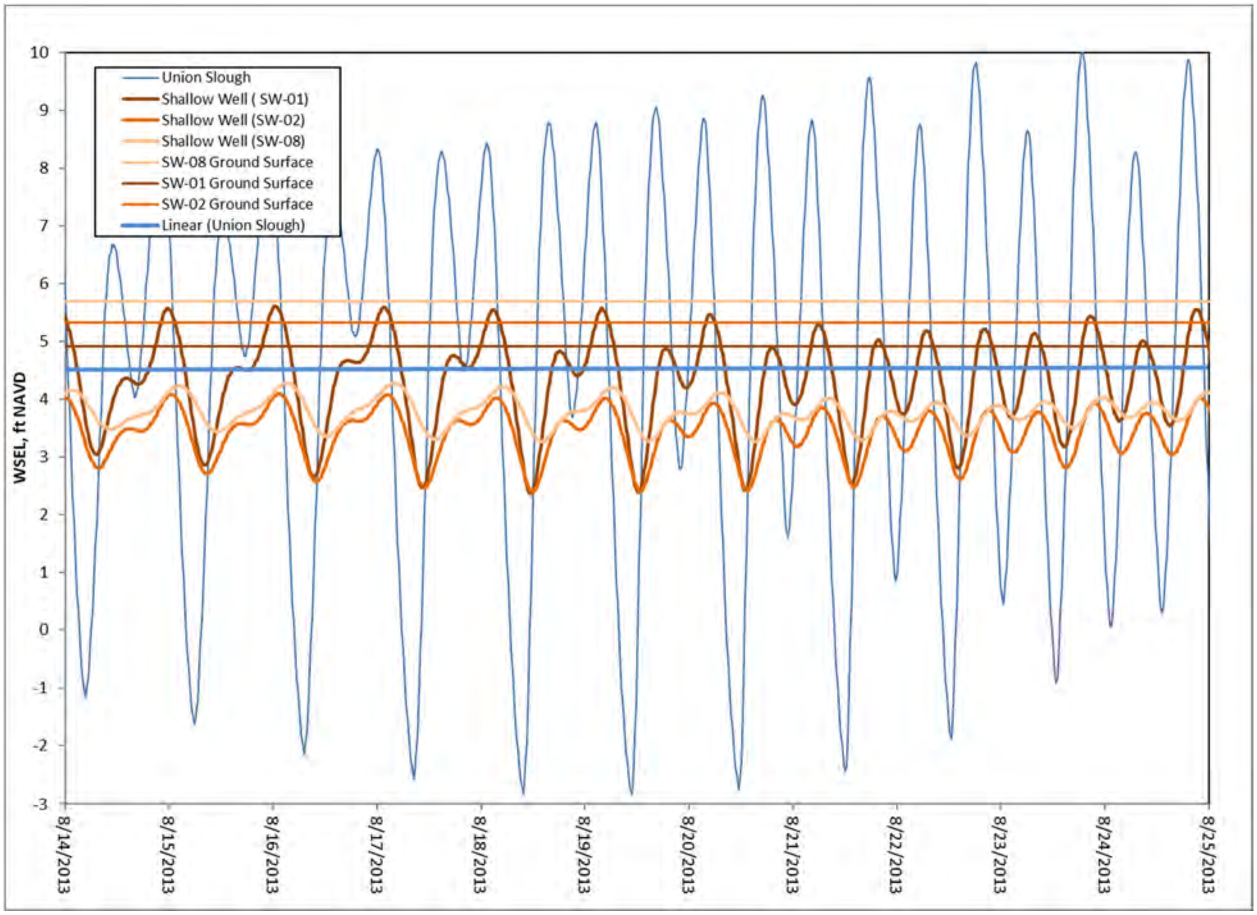


Figure 6-6 **Shallow wells SW-01, SW-02, and SW-08 on Smith Island (listed in order of increasing distance from Union Slough) were used to characterize tidal attenuation relative to tidal amplitude (as observed at Union Slough). Discharge near Monroe was a constant 2,450 cfs during this analysis time interval with no rain events in the basin. Plotted ground surface elevations are derived from 2009 Snohomish Estuary LiDAR; note period(s) each day when the water table at SW-01 was higher than the ground surface, implying artesian conditions. Data from 2013 were used to illustrate groundwater behavior without the effects of subsequent dike breaches (Tetra Tech 2013).**

Vertically, tidal oscillation in the groundwater table decreases moving upstream, and tides rapidly attenuate with increasing distance from the main river or slough channels. Tidal attenuation in the two river valleys was extrapolated using an exponential regression to identify the distance from tidal boundaries corresponding to 1% tidal influence (the ratio of well tidal amplitude to tidal boundary amplitude), based on the observations from the shallow wells on Smith Island. The projected extent of 1% tidal influence equals 3,260 feet, and this distance from the river was used to create a map of the expected area of tidal influence to groundwater lateral to the main channel, extending longitudinally from the coastline upriver to where no tidal fluctuation during spring 2018 was observed in the river (Figure 6-7). The extents of tidal influence to groundwater were cropped to exclude areas beyond the valley edge and to include tidal mudflats and estuaries based on ground observations, 2006 light detection and ranging (LiDAR) data, and 2017 aerial imagery. Spatially, tidal influence narrows across the floodplain with increasing longitudinal distance upstream.

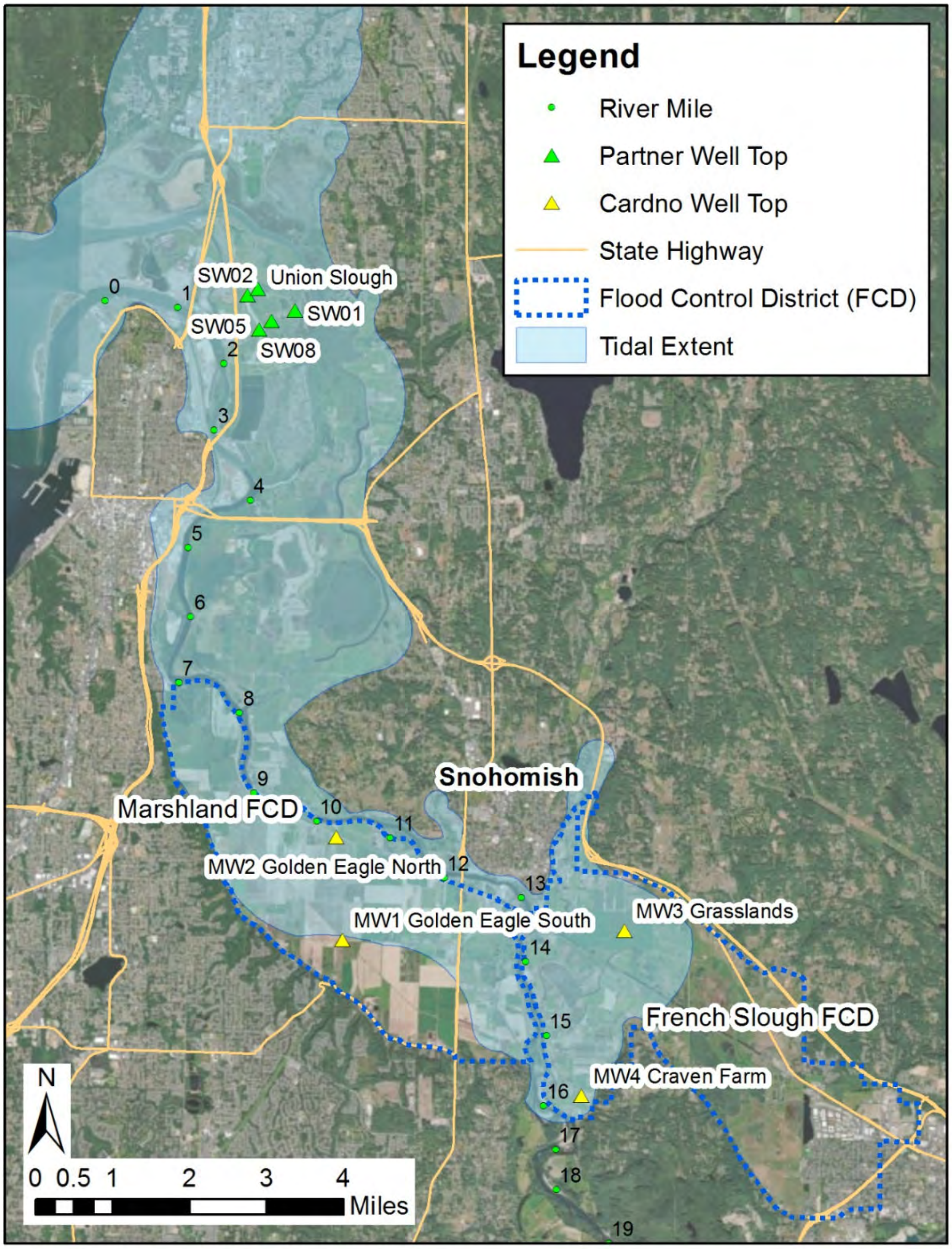


Figure 6-7 **Estimated extent of current spring tidal influence shown with a shaded light blue area for the lower Snohomish River basin. Yellow triangles represent Cardno wells (Eagle North and Eagle South at left, Grasslands Farm to the northeast and Craven Farm to the southeast).**

The Cardno wells Eagle North, Grasslands Farm, and Craven Farm did not show tidal fluctuation, although they still fall within the projected extent of tidal influence during the spring season. The method does not account for the effects of groundwater withdrawals, which may explain this apparent contradiction.

A few other areas express spring groundwater conditions that may not be fully explained by this geometric approach. The southern portion of Marshland FCD and eastern portion of French Slough FCD were predicted to have negligible tidal influence, given their distance from the river. Although no tidal signature would be expected here, these areas would be very wet from simple surface-water inundation under natural conditions. High pumping rates drain surface water and groundwater despite their low elevation (5 feet to 7 feet NAVD88) relative to the mean higher high water (MHHW) of about 9.1 feet. The FCDs would receive complete marine inundation frequently every month without protection from the pump systems and levees. Thus, under existing conditions of sea level, land elevation, and pumping, tidal effects to groundwater tables are limited to portions closer to the main channel.

Smith Island experiences a demonstrated tidal influence on the groundwater table and, by extrapolation, Ebey Island is also expected to have tidal influence under existing conditions. Cultivated lands toward the centers of these islands may have small tidal signals in the groundwater table but will have high susceptibility to groundwater inundation as sea levels rise.

6.2.2 Stillaguamish River

The Stillaguamish River also has an observable tidal fluctuation (see Section 5). Assessing impacts of tidal fluctuation to the groundwater table, however, proved more difficult here because of the limited distribution of existing wells. The Schakel well exhibited about 2 feet of tidal amplitude during early summer (June 2018) and the Miller Road well had 0.1 foot of tidal amplitude for both spring 2018 (April to early June) and early summer (June 2018). The Schakel well lies 1,260 feet north of the main channel with tidal fluctuation up to 3 feet at RM 3.3. The Miller Road well lies 6,000 feet north of the main channel at RM 3.0 and exhibited no more than 0.1 foot of tidal fluctuation. The Stillaguamish Tribe wells (Nygaard and Oberg) did not have tidal signatures.

Because limited tidal exchange was observed at Cardno's Stillaguamish River wells and the Stillaguamish Tribe wells (Oberg and Nygaard), we used the Hatt Slough Snohomish County well dataset (wells B1, B2, and B3) to assess the extent of tidal influence to groundwater since these wells clearly showed tidal fluctuation (see Figure 1-2 for the locations of the three partner wells located at the Hatt Slough mouth). Refer to Table 6-2 for a summary of each well's tidal amplitude and distance from Hatt Slough, the tidal boundary. As with Smith Island, tidal amplitude attenuates exponentially with increasing distance from the tidal boundary (Figure 6-8).

Table 6-2 **Hatt Slough Stage Gage and Associated Shallow Well Tidal Amplitude During Summer Conditions (stable low river flow with no precipitation) and an Ocean Maximum Tide Close to MHHW of 9.1 Feet NAVD88 as Estimated for the zis a ba Estuary Restoration**

Shallow Well	Distance from River Boundary, ft	Tidal Amplitude at MHHW, ft
Hatt Slough Mouth	0	3.44
B3	157	1.76
B1	419	1.25
B2	1,106	0.35

Source: Cardno 2016

Figure 6-8 presents the Hatt Slough well dataset selected for analysis of tidal attenuation into the groundwater table.

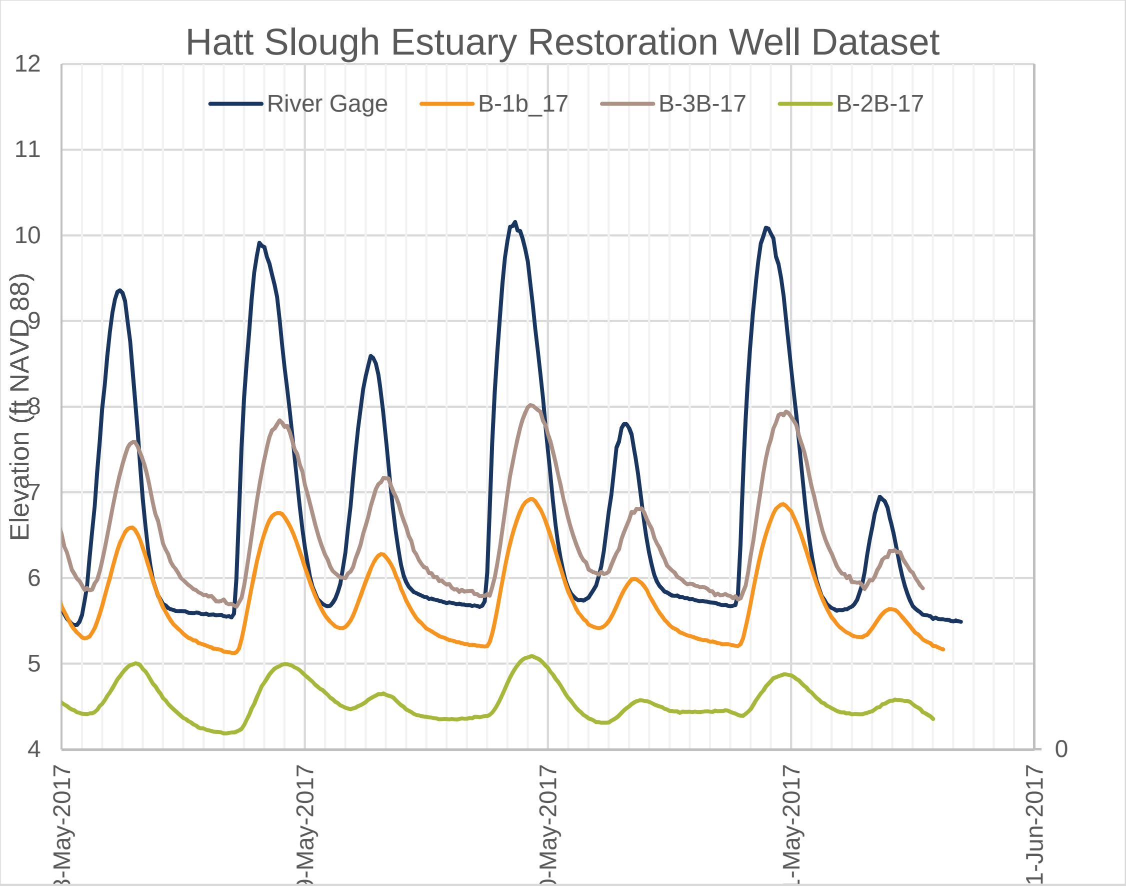


Figure 6-8 **Shallow wells B1, B2, and B3 were used to create tidal attenuation plots relative to the tidal amplitude observed at the adjacent edge of the Stillaguamish River. The river discharge was constant at 2,570 cfs near Arlington during this time interval with no rain events in the basin (Sources: Cardno 2017; Shannon and Wilson 2017).**

As with the Snohomish River data, tidal attenuation was extrapolated to identify a distance from tidal boundaries of 2,130 feet that corresponds to 1% tidal influence. The extent of 1% tidal influence was then used to create a map of the expected area of tidal influence to groundwater lateral to the main channel (Figure 6-9). The extents of tidal influence to groundwater were cropped to exclude areas beyond the valley edge but to include tidal mudflats and estuaries based on ground observations, 2006 LiDAR, and 2017 aerial imagery. The entire western half of the Stillaguamish FCD is expected to experience tidal influence on groundwater levels. Groundwater in the southern portions of Stanwood is expected to be influenced by tides; Stanwood runs extensive pump systems (Irvine Slough and Douglas Outfall) to stay dry.

The northeastern portion of the Stillaguamish FCD was predicted to experience negligible tidal influence. However, the FCD would experience complete marine inundation frequently every month without protection from the levees. Existing levees and drainage features (Jorgensen Slough and drainage canals that empty into the Old Main Channel near Miller Road) draw the water table down despite low elevations (5 feet to 7 feet NAVD88) relative to MHHW of about 9.1 feet NAVD88.

Given groundwater tidal fluctuation observations for Leque Island and adjacent farm fields south of Hatt Slough, Florence Island is presumed to have tidal groundwater influence under existing conditions. Florence Island will be especially susceptible to increasing groundwater inundation due to rising sea levels.

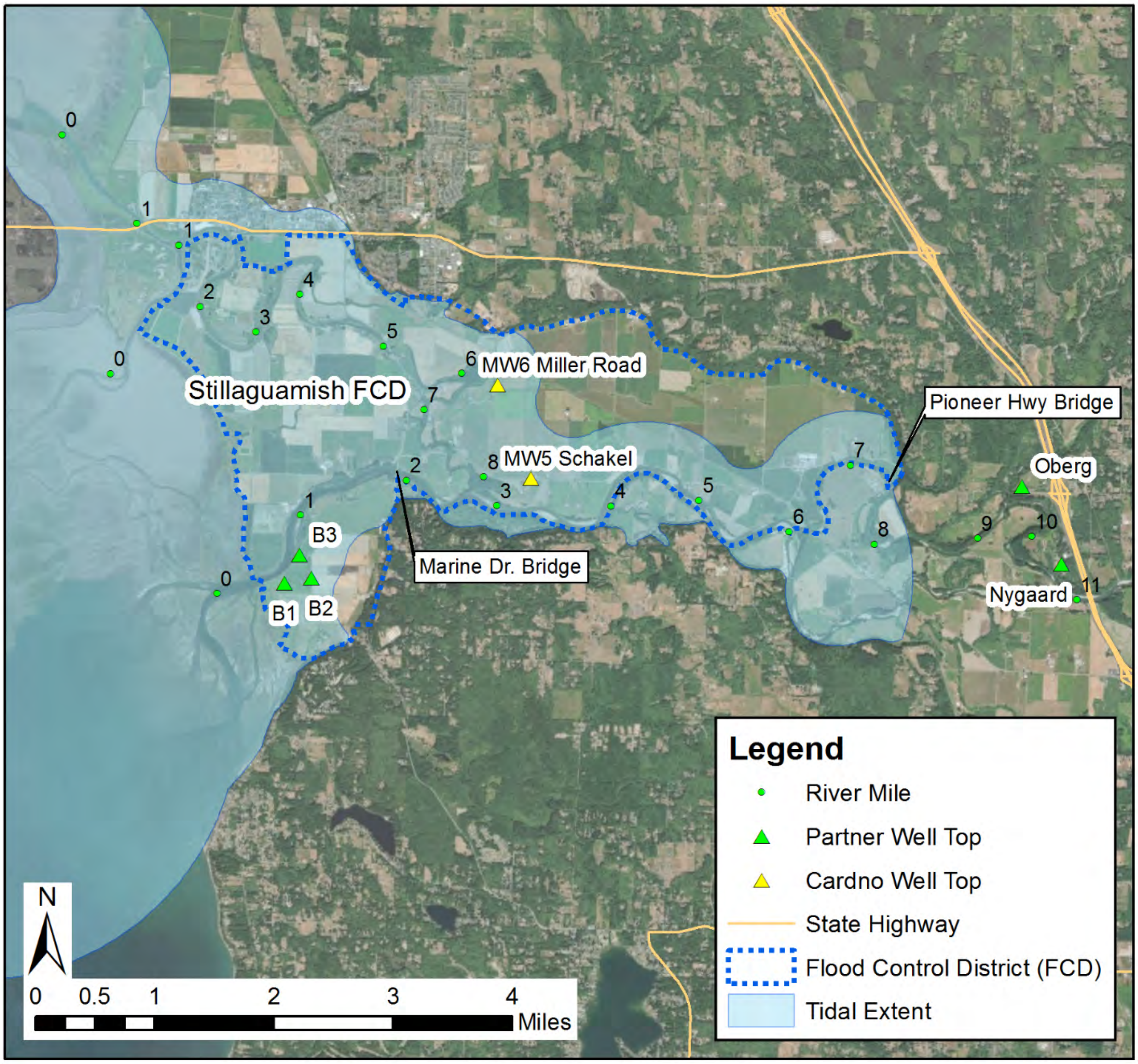


Figure 6-9 **Extent of spring tidal influence in the lower Stillaguamish Basin shown in shaded light blue polygon. Yellow triangles represent Cardno wells (Miller Road well to the north and Schakel well to the south). Green triangles represent the Snohomish County wells installed for the Hatt Slough Estuary Restoration Project. Note that the northeast portion of the Stillaguamish FCD is outside of the zone of anticipated tidal influence, but its low elevations (up to 4 feet *below* MHHW at present) render it susceptible to inundation from regional groundwater levels in the absence of pumping.**

6.3 Changes to Field Access Timing due to Sea Level Rise

Rising sea levels will delay the time when farmers choose to access their fields to begin cultivation activities. Farmers have already witnessed changes to their cultivation season, some of which relate to rising sea levels and a changing climate. According to Tristan Klesick who farms just east of Miller Road in the lower Stillaguamish River basin:

> “it seems that the weather is more severe right up to the time that the air temperature is about right to start to dry out the land. In the past we had a slower, more gradual start to working the fields. Now it feels like we just start and are trying to catch up because the

> work is backing up. Dairy farmers would first cut their grass and then move to spreading manure and then planting corn, and that order still happens, but it feels compressed" (Personal communication, email from Tristan Klesick to SCD, August 23, 2018).

Rising sea levels will exacerbate this condition and delay start times for working the fields as presented in Tables 6-3 and 6-4. Natural seasonal variation could delay start times on the order of weeks; thus, delays due to RSLR could disappear within this variation. But overall trends in increased delay of start times for working the fields will become more and more pronounced with time.

As discussed in Section 6.1, the autumn return of high groundwater conditions is triggered by rainfall and river flooding, with no discernable influence from sea level. Thus, the focus of this discussion of field access is limited to changes in near-surface groundwater conditions in the early spring.

The times at which farmers decide to access their fields depend on a variety of variables including crop types, farm equipment types, surface water from precipitation, and depth to groundwater. According to Brett de Vries of SCD, "farms with heavy equipment like dairies…will wait until the GW [groundwater] is at least a foot below the surface to avoid compacting soil and creating ruts. On smaller farms with smaller equipment, sometimes they can get out with a shallower GW level" (personal communication, email from Brett deVries to Cardno, August 23, 2018).

In spring 2018, farmers first accessed their fields in late March and early April. River flows were larger and rain events more frequent than when Cardno's CTD loggers were installed on April 12, 2018. Groundwater tables were likely higher prior to CTD logger installation. Hence, the CTD loggers did not capture the groundwater levels that actually prevented farmers from accessing their fields. Groundwater inundation maps calibrated to the Cardno CTD data would not represent the condition where groundwater inundation inhibits cultivation access.

Early spring inundation of the agricultural fields is a complex composite of ponding and saturation due to precipitation and high groundwater tables. Thus, Cardno chose to focus on the timing of inundation based on the actual measured rate of water table decline. Although the available data from "shallow" wells is still about 10 feet below the ground surface (and so obviously below the rooting depth of cultivated crops), it is judged to be an adequate indicator of water-level changes that can more directly affect the surface.

Table 6-3 **Predicted Timing Delay to Access Agricultural Fields of the Lower Snohomish River Floodplain within the Influence of Rising Sea Level Effects on Base Levels of the Groundwater Table**

Well Site	2050 Delay	2080 Delay	2100 Delay
Greenhouse Gas Scenario RCP 4.5 (Low Emissions):			
Craven Farm	< 1 Week	< 1 Week	< 1 Week
Grasslands Farm	1 to 2 Weeks	2 to 3 Weeks	3 to 4 Weeks
Eagle North	1 to 2 Weeks	3 to 4 Weeks	4 to 5 Weeks
Greenhouse Gas Scenario RCP 8.5 (High Emissions):			
Craven Farm	< 1 Week	< 1 Week	< 1 Week
Grasslands Farm	1 to 2 Weeks	3 to 4 Weeks	4 to 5 Weeks
Eagle North	2 to 3 Weeks	3 to 4 Weeks	5 to 6 Weeks

Table 6-4 **Predicted Timing Delay to Access Agricultural Fields of the Lower Stillaguamish River Floodplain within the Influence of Tidal Effects on Base Levels of the Groundwater Table**

Well Site	2050 Delay	2080 Delay	2100 Delay
Greenhouse Gas Scenario RCP 4.5 (Low Emissions):			
Nygaard	< 1 Week	< 1 Week	< 1 Week
Miller Road	< 1 Week	1 to 2 Weeks	1 to 2 Weeks
Hatt Slough B2	1 to 2 Weeks	3 to 4 Weeks	4 to 5 Weeks
Greenhouse Gas Scenario RCP 8.5 (High Emissions):			
Nygaard	< 1 Week	< 1 Week	< 1 Week
Miller Road	< 1 Week	1 to 2 Weeks	2 Weeks
Hatt Slough B2	1 to 2 Weeks	4 to 5 Weeks	6 Weeks

Note: The Schakel well late-spring average water table rate of decline was assumed to be similar to that of the Miller Road well.

Expected delays in start times were spatially represented. These maps account for large topographic features at the scale of miles of main channel river length and hundreds of feet of floodplain width, but they do not have sensitivity to smaller topographic features. They assume similar levee configurations and groundwater pumping rates into the future, and they are most relevant to the areas covered by the FCDs. Refer to Figure 6-10 for an example of mapped results of our first-order approximation to expected timing delays as influenced by RSLR for the year 2100. High-resolution maps for both river systems are presented in Appendix A.

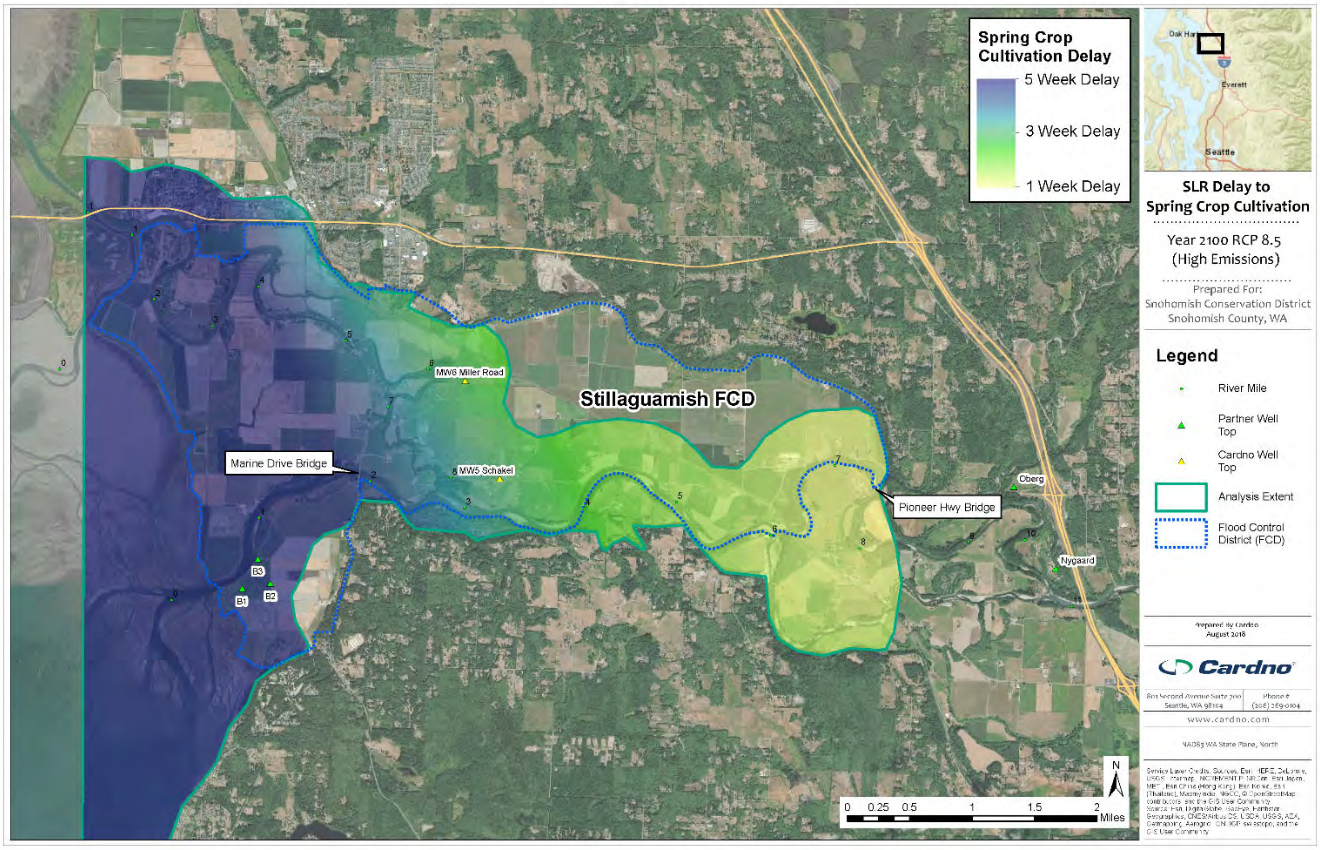


Figure 6-10 **Stillaguamish River basin example spatial output for the year 2100 with the ocean at RSLR of +2.2 feet (with a 50% probability of exceedance) under greenhouse gas scenario RCP 8.5. The map shows average weeks of start delay (with a 50% probability of exceedance) that farmers may experience to begin crop cultivation in spring, relative to their current experience.**

These maps provide a framework for planning the future of farming in the lower Snohomish and Stillaguamish River valleys. On average, areas relatively far from the Puget Sound coastline are unlikely to notice much systematic change in the dates of first springtime access to fields over at least the next several decades, at least as a result of sea-level-induced groundwater rise. Even closer to Puget Sound, changes over this time frame will be modest and unlikely to be noticeable above year-to-year variability.

In contrast, the acceleration in RSLR in the second half of the twenty-first century is likely to result in systematic delays of up to a month at the end of spring for achieving dry-land conditions, and an indeterminate (but likely similar) shortening at the end of summer. The magnitude of this time compression depends in part on the selected emissions scenario, but there is no alternative that avoids significant impacts over this longer time frame. Areas closer to the coastline will feel the greatest effects; those within a few miles are likely to experience significant changes well beyond those already recognized as a result of annual variability, with an overall magnitude of reduced access that is measured in many weeks to more than a month.

Several additional factors complicate this relatively simple picture, although they do not contradict its overall trend. Although the upvalley extent of changing riverine water levels is well constrained, lending confidence to the prediction of upvalley groundwater changes from rising sea levels in the alluvial aquifer, the lateral (i.e., cross-valley) extent of this influence is poorly defined. Available data only characterize the degree to which the daily tide cycle can be recognized in progressively more distant wells, but this is unlikely to be a perfect analog for predicting the effects of a long-term, systemic rise in the overall level of Puget Sound. Thus, the predicted zones of influence mapped on Figure 6-7 and Figure 6-9 are truncated at the edge of 1% tidal influence, but the lateral effects of long-term, non-oscillating SLR are likely to extend beyond these limits. Their precise boundaries, however, would require hydrogeologic modeling beyond the scope of this initial analysis.

A second complication is the effects of drains, pumping, and RSLR on groundwater levels, which cannot be predicted without a more complex groundwater model. In particular, pumping can (and does already) locally depress the water table far below its undisturbed, “equilibrium” level. Some portions of the study area already lie so low that they avoid diurnal inundation by sea water during every high tide only by virtue of dikes and levees (e.g., Smith Island, Marshlands FCD, French Slough FCD, and the Stillaguamish FCD, especially Florence Island). These areas of sub-tidal land will expand in the coming decades. Increased pumping rates (and, possibly, additional locations) will be required if these areas are to remain in cultivation, but predictions of the magnitude of required pumping or the potential increase in dry-land durations that might be gained are also beyond the scope of this analysis.

The viability of these areas (southern Marshlands FCD on Figure 6-7 and northeastern Stillaguamish FCD on Figure 6-9) may depend on the effects of pumping, which are not incorporated into the present analysis. Therefore, they have been left outside of the areas of predicted start-date delays. However, they will only escape the consequences of a higher Puget Sound (and a correspondingly higher regional groundwater table) with an even greater magnitude of pumping than at present.

7 Ebey Island Groundwater Levels

Because no groundwater data are available for Ebey Island, partner well data from Smith Island (Figure 7-1) were used as an analog to inform expected groundwater levels for Ebey Island. The Smith Island dataset was first used to predict Ebey Island groundwater levels under modern sea level but assuming no drainage or active pumping. These data were then used to predict future groundwater levels on Ebey Island with rising sea levels.

Figure 7-1 Close-up map of Smith Island and Ebey Slough, showing the three wells used and their relationship to the slough and coastline.

Given the proximity of both Smith Island and Ebey Island to the coast, and the obvious association of the Smith Island wells to tidal fluctuations and average sea level (Figure 7-2), potential secondary complications from fluvial or regional groundwater inputs were not assessed here. This stands in contrast to the approach taken for upvalley areas farther from direct coastal influence (Section 6), wherein the timing of field dry-out was dependent on the seasonal, regional decline of groundwater over the spring. Although sea level is expected to determine the baseline from which springtime groundwater levels fall through the summer, the absence of tidal signatures in the upvalley Cardno well data suggest a more broad-scale influence. Downstream at Smith Island, however, groundwater levels track the ocean tides almost perfectly, and the average groundwater levels are within a foot of the average water level in the slough during the summer months (Figure 7-2). Thus, present (and future) sea level appears to be an excellent predictor of the average groundwater level here, a relationship that is little modified by seasonal changes (refer to Appendix D for the full WSEL dataset of wells SW-01, SW-02, and SW-08).

The data also demonstrate that the daily tidal signal attenuates with distance from the slough, with the diurnal amplitude of groundwater-level oscillations decreasing in order of increasing distance from the Union Slough Gage (i.e., SW-01 to SW-02 to SW-08). This attenuation does not inform the long-term, time-averaged response of the groundwater table to an overall, non-oscillatory RSLR, but it does suggest a spatial pattern of short-term fluctuations declining with distance from a tidal waterway.

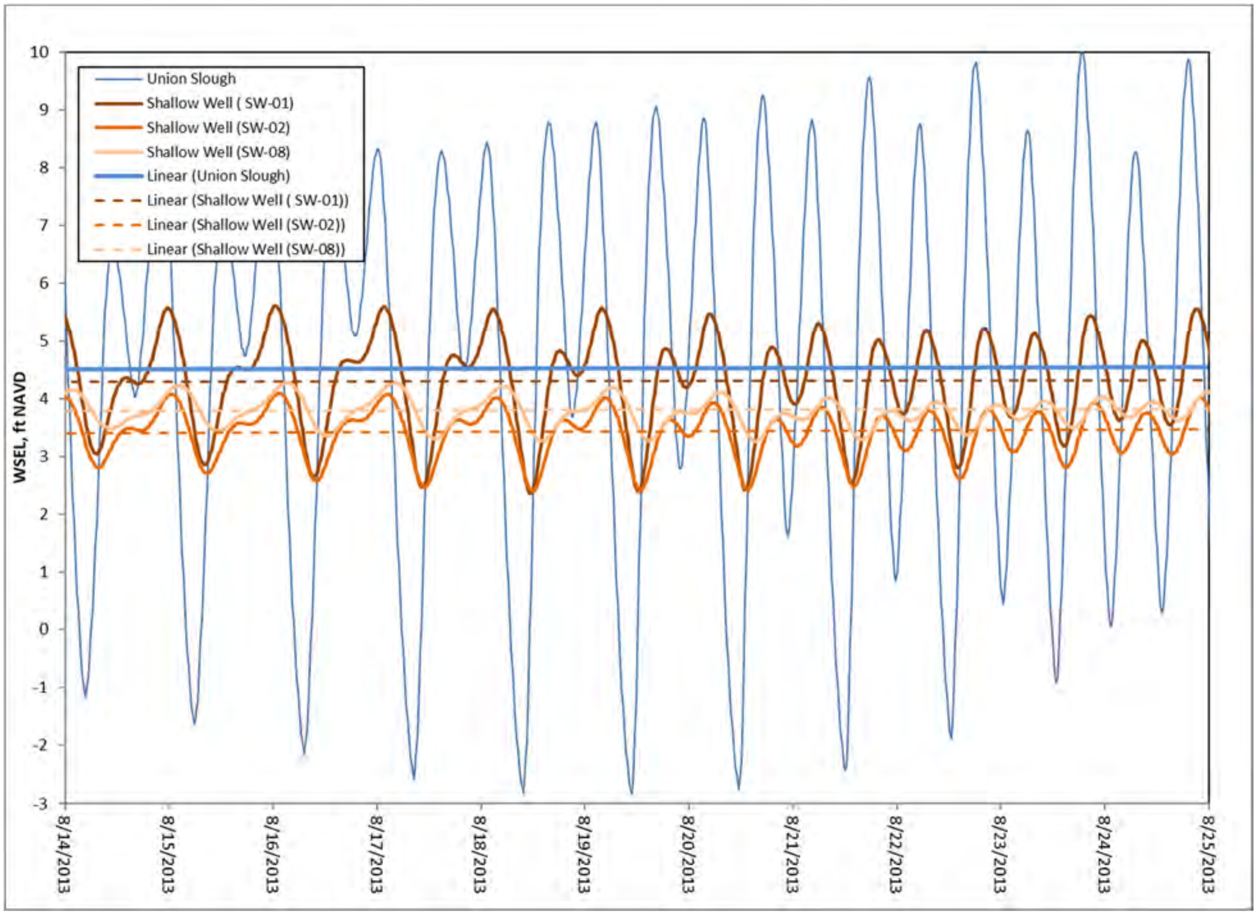


Figure 7-2 **The same dataset as Figure 6-6 with the addition of linear trend lines that represent mean WSELs for the time period (and including the mean WSEL for Union Slough). Data from 2013 are used to illustrate groundwater behavior without the effects of subsequent dike breaches.**

These water levels recorded at Smith Island were used to extrapolate an average groundwater table for summer conditions. The same pattern was then superimposed onto the topography of Ebey Island (Diking Districts [DDs] 2 and 4, and the area formerly known as DD 6 [northeast of the present-day Drainage Improvement District 13]). The result (Figure 7-3) indicates a number of areas across the island that would lie below the groundwater table and so be inundated, were it not for active drainage and pumping (which have been ignored for this analysis). RSLR was assumed to act uniformly over the analysis area as presented previously in Table 7-1.

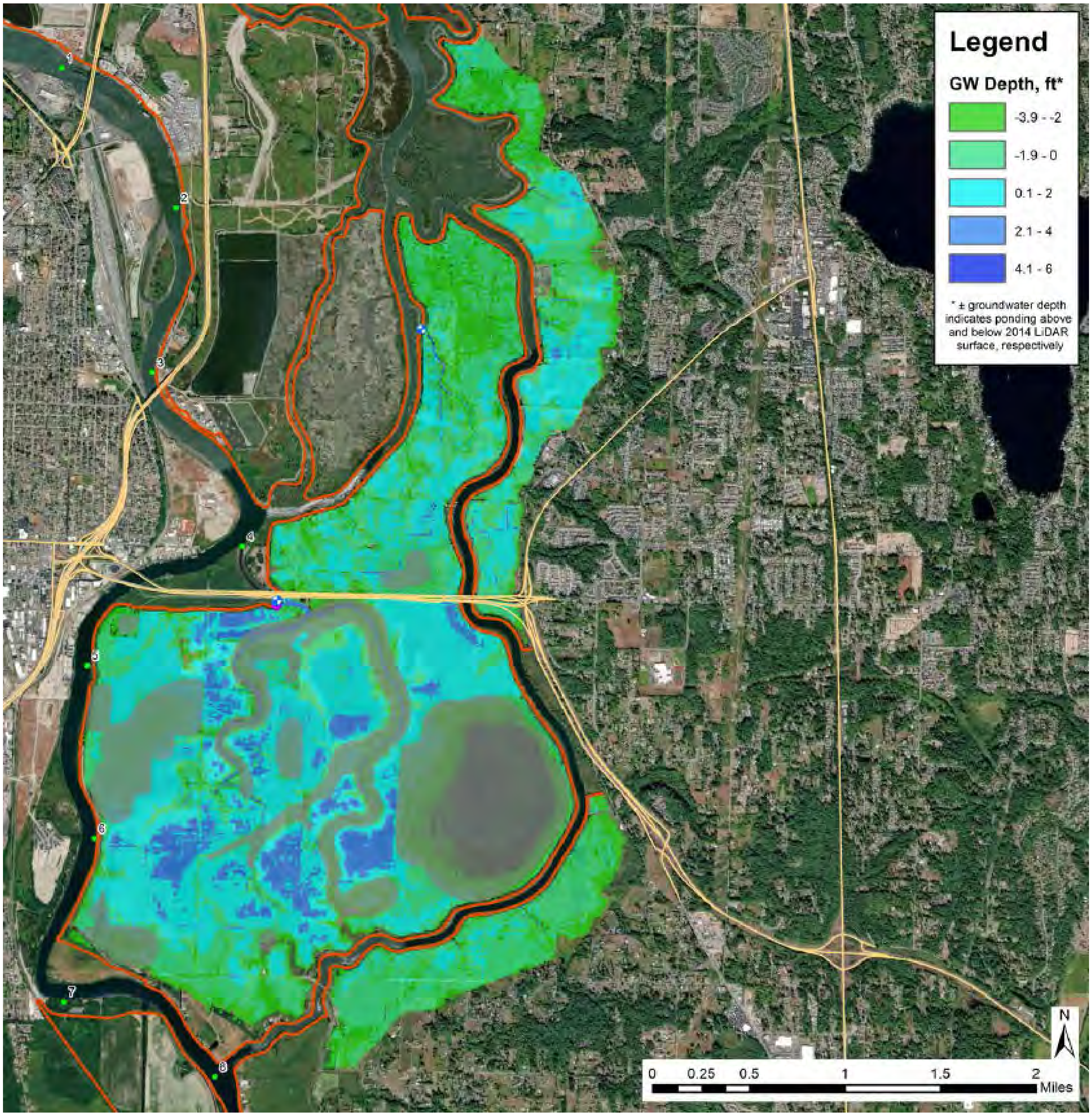


Figure 7-3 **Projected depth-to-groundwater map across Ebey Island under modern sea level and assuming no pumping. The blue areas lie at elevations below the assumed groundwater table, and so are currently dependent on active drainage measures to remain dry. In general, the darker blue areas closely correspond to wet areas or boils that are readily observed on aerial photographs.**

Although the data plotted in Figure 7-2 might suggest that the ground surface at SW-01 goes underwater, as this graph would predict, the interval of artesian conditions may be too short to force water to the surface. This is consistent with the assumption that average groundwater level, and so the separation between the groundwater table and the ground surface, is determined by tidally averaged sea level. If so, this gap should shrink over time by an amount equal to the projected SLR.

Table 7-1 **Assumed Average Summer Groundwater Table Elevations for Ebey Island, DDs 2 and 4, and Former DD 6**

Distance from Tidal Surface Waters	Existing Conditions	2050	2080	2100
Greenhouse Gas Scenario RCP 4.5 (Low Emissions):				
100 feet	4.3 ft NAVD88	5	5.6	6
450 feet	4.3	5	5.6	6
650 feet	3.6	4.3	4.9	5.3
Greenhouse Gas Scenario RCP 8.5 (High Emissions):				
100 feet	4.3 ft NAVD88	5.1	5.8	6.5
450 feet	4.3	5.1	5.8	6.5
650 feet	3.6	4.4	5.1	5.8

Groundwater surface elevations in feet NAVD88. Note that Ebey Island land surface elevations range from 0.5 to 8.5 foot NAVD88 (not including levees or areas of dense vegetation) compared to mean higher high water (MHHW) tides of 9.1 foot NAVD88.

The current distribution of observed Ebey Island groundwater ponding does not entirely match these predictions. The actual tidal attenuation is well-predicted by distance, but absolute groundwater levels are not. Farmers on Ebey Island have stated that pumping and drainage effectively dry out all cultivated areas, except for isolated areas where “boils” may puddle with high tides and dry with low tides. These conditions emphasize the critical role that pumping, not incorporated into this framework, plays in maintaining present agricultural viability, a role that will become even more important in a rising SLR future. The “no-pumping” groundwater inundation maps presented here, however, should prove useful for planning-level assessments, determining compensatory measures that may be needed to maintain agricultural viability into the future, and identifying opportunities for marsh restoration.

8 Effects of SLR on Shallow Groundwater Salinity

This section analyzes salinity data for the lower Stillaguamish and lower Snohomish River basins. Rising sea levels will raise elevations in the groundwater table and cause ponding delays for spring access to working farms as discussed in the sections above. Salinity intrusion associated with SLR, however, may also affect farming practices, by reaching into the rooting zone of crops.

The first subsection addresses salinity thresholds for significant and important crops in the study areas. Although prior analyses in this report first assess the Snohomish River before the Stillaguamish River, the lower Stillaguamish River has a wider distribution of relevant salinity data and so is considered first in this analysis. These data permit analysis of western Florence Island east to Miller Road within the bounds of the Stillaguamish FCD (Figure 8-1). For the Snohomish River basin, available data permit analysis of Smith Island, Ebey Island (DD1), DD2, DD4, Drainage Improvement District 13 (DID13), Marshlands FCD, and French Slough FCD (Figure 8-2).

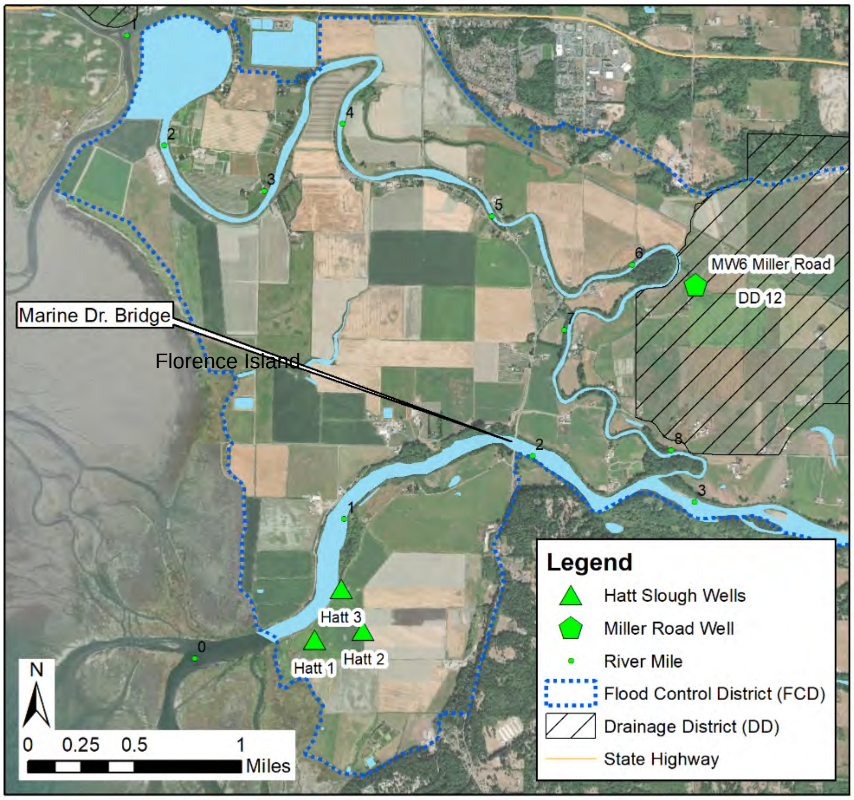


Figure 8-1 **Salinity analysis extents focused on SLR impacts to Florence Island for the lower Stillaguamish River basin, based on available shallow groundwater data.**

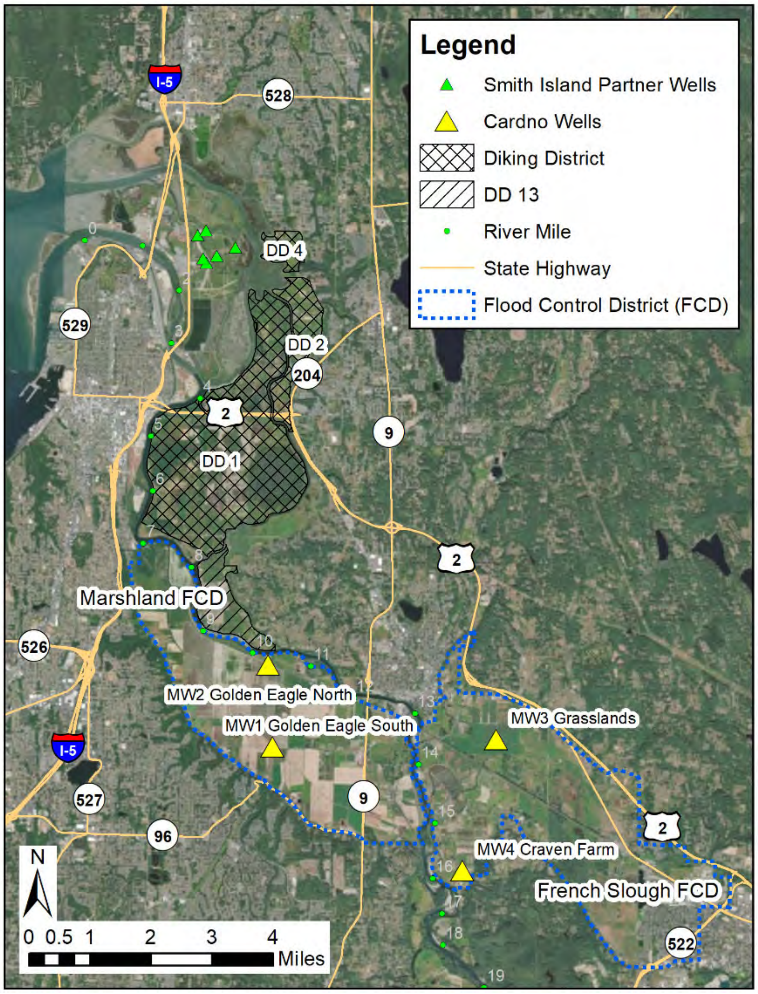


Figure 8-2 **Salinity analysis extents focused on SLR impacts to DD2, DD4, Ebey Island (DD 1), DID 13, and FCDs for the lower Snohomish River basin based on available shallow groundwater data (4 Cardno wells and 3 partner wells located on Smith Island).**

8.1 Background – Salinity Measurement and Crop Thresholds

Though salts (i.e., nitrates and potassium ions) are crucial plant nutrients, relatively high concentrations of any one salt or many different salts can be toxic to plants. Sodium and chloride, primary constituents of seawater, are the primary salt ions of concern under salinity intrusion. Although these ions can be measured directly through chemical analysis, the most practical method is to record electrical conductivity (EC), which is an excellent surrogate for the sodium and chloride concentrations in seawater, the dominant source of seawater salinity (e.g., In-Situ, Inc. 2011). The International System (SI) units of EC measurement used herein are milliSiemens per centimeter (mS/cm); salinity is typically measured in parts per thousand (PPT) or practical salinity units (PSU), with virtual equivalence between them. EC and PSU (or PTT) are closely related, with only modest variability in natural waters depending on the local temperature, pressure, and water quality. For example, the United Nations Educational, Scientific and Cultural Organization (1983) offered the following correlations:

- A salinity of 0.5 PPT (the average upper limit of freshwater values) at 25 degrees Celsius (°C) corresponds to an EC of 1 mS/cm.
- A salinity of 5.0 PPT (the upper limit of oligohaline waters, or the lower end of brackish water) at 25°C corresponds to an EC of 9 mS/cm.

Most salinity values are reported as “specific conductivity” (SC), which is simply the raw EC value adjusted to its value were the water temperature at 25°C (with the same unit as EC, mS/cm). This allows comparison of local data to various reference standards (e.g., Table 8-1), and of measured groundwater SC values to reported crop salinity thresholds (which are also reported as SC).

Table 8-1 **Cowardin Classification of Estuarine Habitats Compared to Agricultural Salinity Rating and Electrical Conductivity Value**

Coastal Modifiers[a]	Inland Modifiers[b]	Salinity (parts per thousand)	Approximate specific conductance (mS/cm)
Hyperhaline	Hypersaline	>40	>60
Euhaline	Eusaline	30.0–40	45–60
Mixohaline (Brackish)	Mixosaline[c]	0.5–30	0.8–45
Polyhaline	Polysaline	18.0–30	30–45
Mesohaline	Mesosaline	5.0–18	8–30
Oligohaline	Oligosaline	0.5–5	0.8–8
Fresh	Fresh	<0.5	0.8

Source: Cowardin 1979 and Agdex 2001

Notes:

[a] Coastal modifiers are used in marine and estuarine systems.
[b] Inland modifiers are used in riverine, lacustrine, and palustrine systems.
[c] The term brackish should not be used for inland wetlands or deepwater habitats.

Although the rooting zones of crops considered for this study are most likely within the upper 2 feet of soil, isolating the salinity of groundwater in just this narrow range was not practical for this study. Instead, the Cardno wells were screened from the ground surface to 10 feet below ground, providing critical information on the depth of the groundwater table but also mixing the rooting-zone groundwater with modestly deeper sources. Deeper soil levels are likely to hold water with progressively higher conductivity values without them being functionally “saline” (Agdex 2001). Thus, the salinities measured in these wells are likely modest overestimates of the salinity of water in the rooting zones of crops but should nonetheless provide a useful indication of the potential (or actuality) of seawater intrusion. The consequences of this uncertainty are discussed in the interpretation of results.

What levels of salinity may affect the crops of the lower Stillaguamish and Snohomish River valleys? Table 8-1 characterizes the range of generalized salinity ratings in terms of their SC values, which we assume are referenced to 25°C and, thus, represent SC. Table 8-2 presents general expectations for plant response to salinity values, thus translating the salinity ratings of Table 8-1 into potential impacts on crops. This provides the basis for evaluating the impacts of future projected salinity increases on agriculture in the Stillaguamish and Snohomish River valleys. The threshold salinity for spinach, cabbage, and garden beets, common crops in the region, is as low as 2 mS/cm (Figure 8-3) (Shannon and Grieve 1999). Corn has a salt tolerance of 4 mS/cm but may exhibit significant yield reductions at a salinity threshold of 2 mS/cm (Agdex 2001; Kotuby-Amacher et al. 2000).

Table 8-2 **General Guidelines for Plant Response to Soil Salinity**

Salinity (mS/cm)*	Plant Response
0–2	Mostly negligible
2–4	Growth of sensitive plants may be restricted
4–8	Growth of many plants is restricted
8–16	Only tolerant plants grow satisfactorily

Salinity (mS/cm)*	Plant Response
Above 16	Only a few, very tolerant plants grow satisfactorily

Source: Kotuby-Amacher et al. 2000

* EC_e (Electrical Conductivity of the extract) has units of dS/m (deciSiemens per meter), which are mathematically identical to mS/cm (milliSiemens per centimeter).

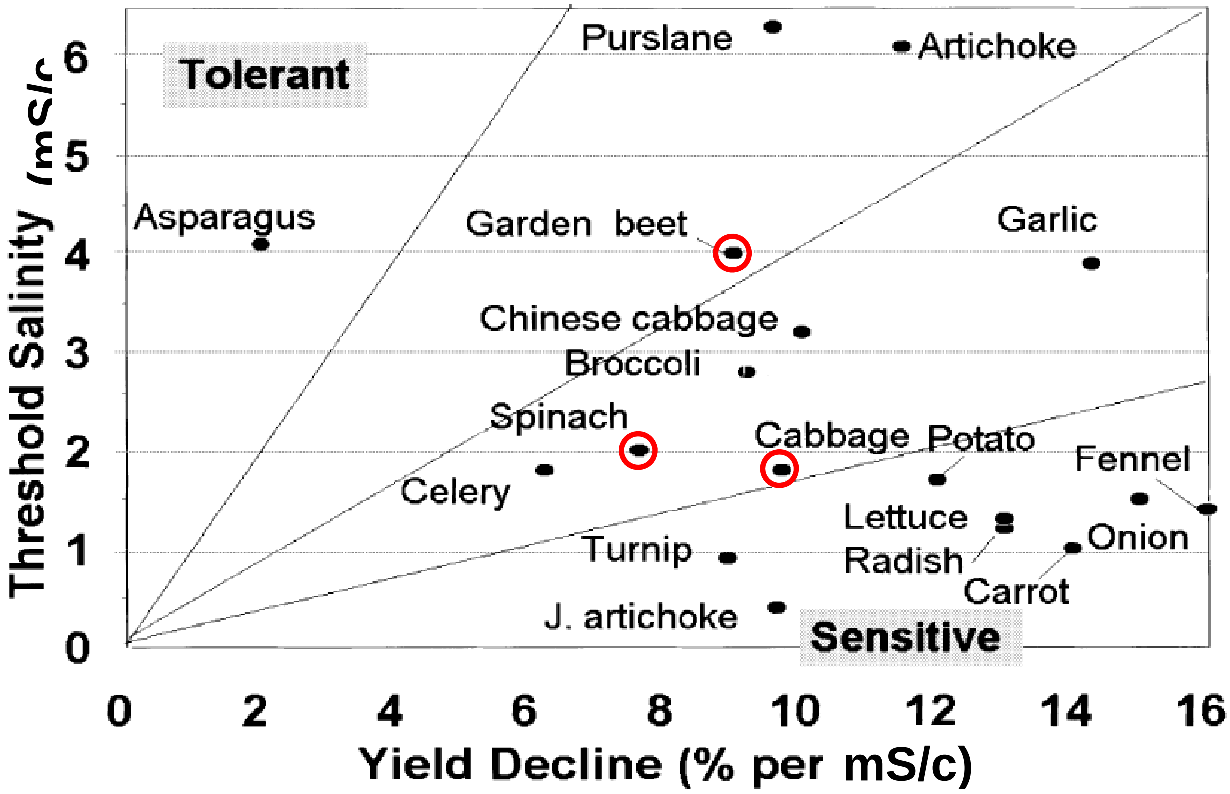


Figure 8-3 Salt tolerance of vegetable species, with red circles denoting vegetables of importance to the farmers of the lower Stillaguamish and Snohomish River valleys (Source: Shannon and Grieve 1999).

According to Eric Schuh of the SCD, the top two crops (by acreage planted) in the lower watersheds of both the Stillaguamish and Snohomish River valleys are corn and grass. Grass is grown either for silage (orchard grass) or for grass seed (lawns—perennial rye grass). Other significant crops are beet, spinach, cabbage for seed, and blueberries (mostly in the lower Marshland FCD). Table 8-3 summarizes the salinity threshold values for significant crops of the lower Stillaguamish and Snohomish River valleys, with increases as little as 0.5 to 1 mS/cm above a salinity threshold resulting in significant yield reductions.

Based on the data in Table 8-3, a future increase in rooting-zone salinity due to RSLR is likely to be “significant” once salinities surpass 2 mS/cm. Because the existing salinity measurements (and, thus, future projections based on those data) are not restricted to the rooting zone, however, a somewhat more liberal value of 3 mS/cm was chosen instead as the threshold for highlighting potential impacts of seawater intrusion.

Table 8-3 **Salinity Tolerance of Crops (mS/cm) Grown in the Stillaguamish and Marshland FCDs**

Crop	Threshold Value	Yield Loss		
		10%	25%	50%
Corn silage	1.8	2.7	6.8	8.6
Orchard grass	1.5	3.1	5.5	9.6
Perennial rye grass	5.6	6.9	8.9	12.0
Beet	5.3	8.0	10.0	12.0
Spinach	3.7	5.5	7.0	8.0
Cabbage for seed	1.8	2.8	4.4	7.0

Adapted from Kotuby-Amacher et al. (2000)

8.2 Methods

Cardno deployed six CTD-Divers manufactured by VanEssen Instruments that were capable of logging CTD. Special care was taken to record SC such that measured ECs were automatically compensated for varying water temperatures referenced to 25°C (Van Essen Instruments 2016), so that reported values reflected differences in salinity, not temperature.

Cardno CTD-Divers were checked against calibration standards twice during their 8-month deployment (Tables 8-4 and 8-5). Results of sensor checks against conductivity standards showed that MW5-Schakel had a faulty sensor and was removed from the analysis. Other standard readings were within ±0.3 mS/cm.

Table 8-4 **Cardno CTD-Divers Checked Against Calibration Potassium Chloride (KCl) Standards on June 5, 2018 (approximately 2 months after starting the well recordings)**

Well	CTD-Diver Serial Number	KCl Standard (mS/cm)	CTD-Diver Reading of Standard (mS/cm)
MW1 – Eagle South	R9205	1.413	1.5
MW2 – Eagle North	R9199	1.413	1.4
MW3 – Grasslands Farm	T2921	1.413	1.6
MW4 – Craven Farm	R9740	1.413	1.6
MW5 – Schakel	T1607	1.413	4.0 (faulty sensor)
MW6 – Miller Rd.	R9201	1.413	1.4

Table 8-5 **Cardno CTD-Divers Checked Against Sodium Chloride (NaCl) Calibration Standards Post-study Completion, December 5, 2018**

Well	CTD-Diver Serial Number	NaCl Standard	CTD-Diver Reading of Standard
MW1 – Eagle South	R9205	1.0	1.04
MW2 – Eagle North	R9199	1.0	0.7
MW3 – Grasslands Farm	T2921	1.0	1.11
MW4 – Craven Farm	R9740	1.0	1.1
MW5 – Schakel	T1607	1.0	0.04 (faulty sensor)
MW6 – Miller Rd.	R9201	1.0	0.94

Lower Stillaguamish River. Partner well datasets were presented with variety of salinity units depending on the goals of those studies, but the basic field measurement was always SC. The Hatt Slough well salinities were recorded as SC using identical instrumentation to the Cardno well instruments.

Salinity output from a hydrodynamic model was used to inform existing conditions groundwater salinity. Although the model output salinity in PSU in PPT, those values were converted to SC (with units of mS/cm) by multiplying by 1.2 using the relationship from Smith Island discussed in the next paragraph (Pacific Northwest National Laboratory 2015). This assumption falls well within the overall accuracy and precision of mapped salinity predictions of ± 0.5 mS/cm.

Lower Snohomish River. Cardno well data salinities were measured as SCs in mS/cm. Partner well data for the Smith Island well salinities were also measured as SCs. In the original report (Tetra Tech 2013), SCs were converted to PSU by accounting for temperature, pressure, and general ionic chemistry, providing a useful conversion between the two measurement systems that was also applied to the Lower Stillaguamish River dataset. Generally, measured Smith Island well SC values were an average of 1.2 times calculated PSU values, reflecting stable temperature recordings. Hydrodynamic model output (a separate and different model than the Stillaguamish River model) had salinity units as PSU in PPT (Hall et al. 2018). For the Smith Island dataset, Cardno chose to utilize the original measured values of SC in mS/cm for the lower Snohomish River analysis. Then, after vertical gradients and horizontal relationships were assessed, we created existing conditions and future salinity predictions in units of SC for ease of reference back to the prior section’s discussion of crop tolerances.

8.3 Lower Stillaguamish River Data Results

8.3.1 Cardno Data – Miller Road Well

The Cardno Miller Road well, located about 2 miles from the coastline (see Figure 1-2) and 1 mile north of the current main channel (Hatt Slough), had SCs between 0.6 and 0.7 mS/cm for spring and summer 2017 (Figure 8-4). The Miller Road well is located 550 feet from the Old Main Channel, which currently functions as a blind tidal slough unless flows exceed 26,000 cfs (Pacific Northwest National Laboratory 2015). The Old Main Channel generally flows as fresh water near the Miller Road well during high tide and low river flows (Yang 2008). Although the Miller Road well SCs lie well below a threshold of concern at present, they were included in this analysis to investigate upvalley extents of salinity intrusion.

8.3.2 Hatt Slough Wells (Spring 2017)

The Hatt Slough wells are all located within 1,000 feet of Hatt Slough (Figure 1-2; see also Figure 8-5) and about a mile from the coastline, significantly closer to high-salinity water than the Miller Road well. The data spanned a broader range of SC values, as summarized by Shannon and Wilson in their 2017 Hatt Slough Estuary Restoration Project report:

> “During the spring monitoring period, the groundwater SC ranged from a low in shallow inland well B-2B-17 (1.7 to 2.0 milliSiemens per centimeter [mS/cm]) to a high in the deep shoreline well B-1A-17 (24.9 to 27.0 mS/cm). The river SC during this period was consistently low (below 0.3 mS/cm). These data indicate that the estuary at the project site was river-dominated. The SC may be higher deeper in the river, though…. [For example,] the river SC at the upstream USGS gage [Marine Drive Bridge] between April and October 2016 ranged between less than 0.1 and 6.7 mS/cm (in late August 2016). No SC data were available for this gage during the fall and winter months.” (Shannon and Wilson 2017)

Well pairs 1, 2, and 3 are progressively farther from the coast. Both the shallow wells (screened 5 to 10 feet below ground) and deeper wells (screened 25 to 30 feet below ground) show a similar trend of decreasing SC with increasing distance from the coast. The well 1 pair (B-1A and B-1B) was located 1,075 feet from Port Susan Bay MHHW shoreline. The well 2 (B-2A and B-2B) and well 3 (B-3A and B-3B) pairs were a similar distance from the shoreline at 2,335 feet and 2,345 feet, respectively (Figures 8-6 and 8-7). This trend is especially evident in Figure 8-7 Section B-B’, which displays the relationship of observed salinities at wells 1 and 2 along a cross section roughly perpendicular to the ocean boundary, terminating at the main river channel mouth (Hatt Slough mouth). These results are consistent with the intuitive understanding that farm fields lying closer to the ocean have higher salinity in their shallow groundwater wells.

These salinity data also show systematic change relative to their perpendicular distance to the river channel. SC is higher in well B-2A/B (1,070 feet from the channel) as compared to well B-3A/B (45 feet from the channel) for both deep and shallow wells (Section A-A’ in Figure 8-6). Both factors (proximity to ocean and proximity to the river) can influence groundwater salinity.

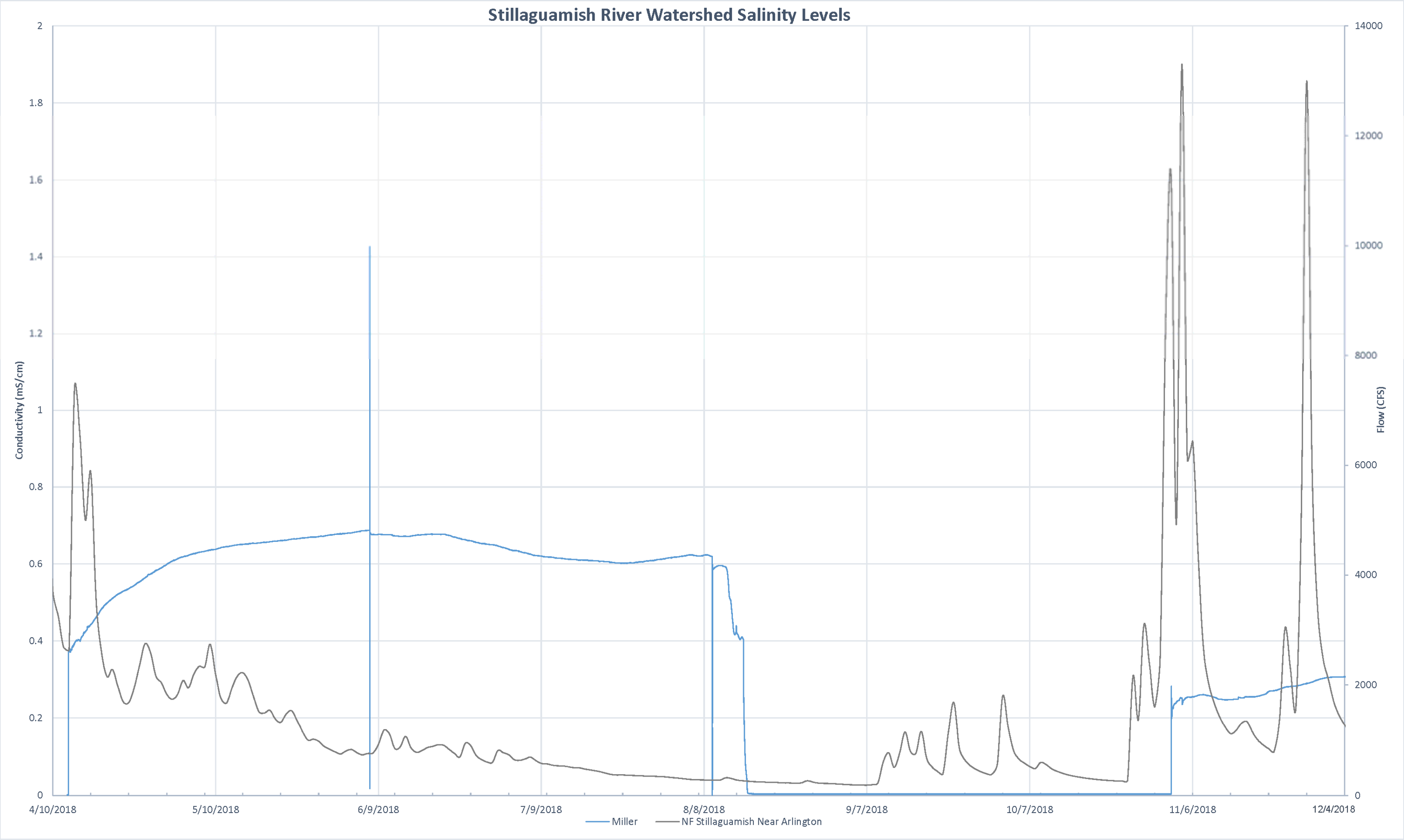
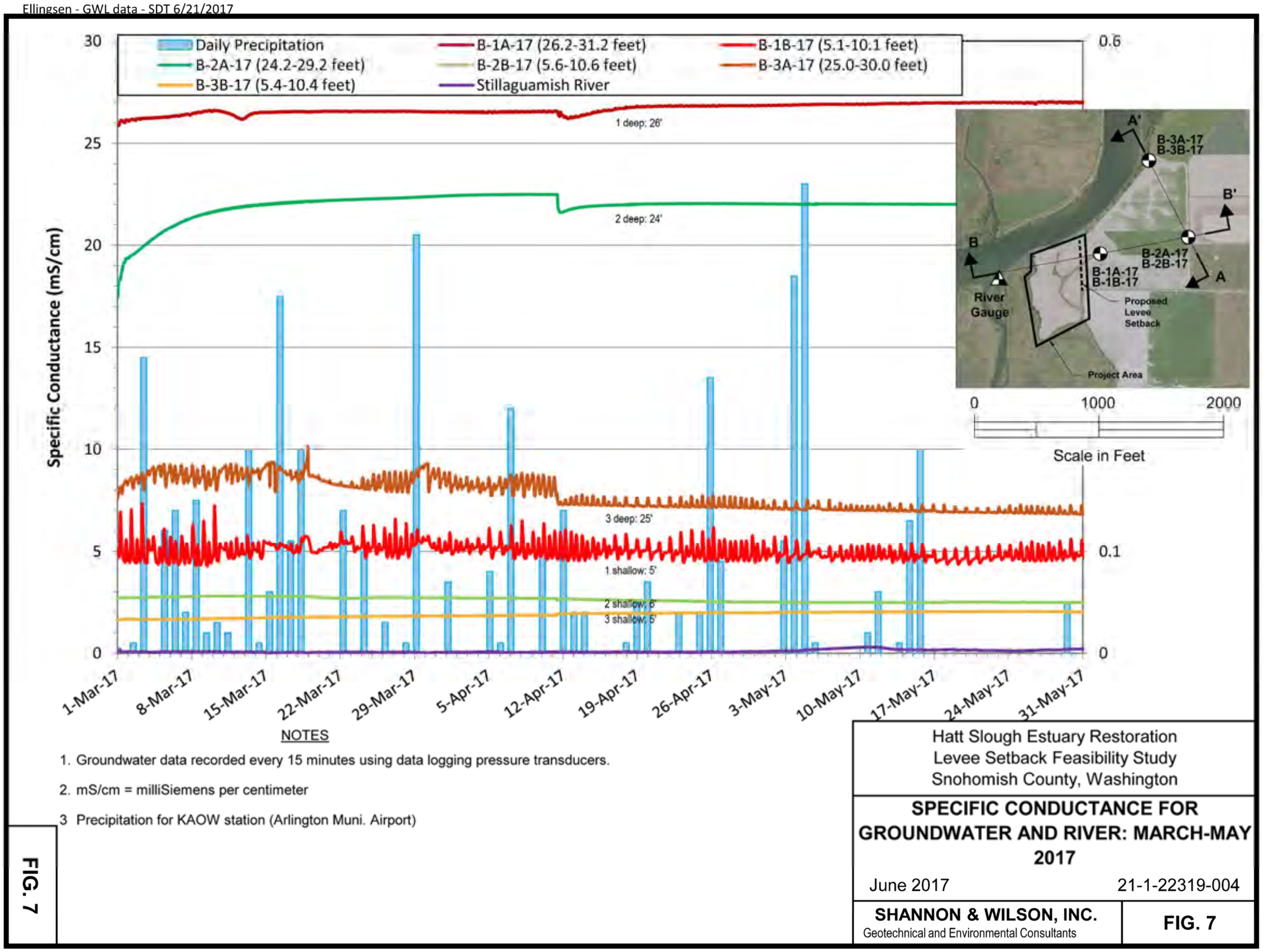


Figure 8-4 SC data for Cardno's Miller Road well in the lower Stillaguamish River valley showing a low but discernible level of saltwater intrusion to shallow groundwater. Salinity spikes near 1.4 mS/cm were the results of a physical test at the well site when the probe was placed in 1.4 mS/cm conductivity standard on June 6, 2018.



NOTES

1. Groundwater data recorded every 15 minutes using data logging pressure transducers.
2. mS/cm = milliSiemens per centimeter
3. Precipitation for KAOW station (Arlington Muni. Airport)

Hatt Slough Estuary Restoration
Levee Setback Feasibility Study
Snohomish County, Washington

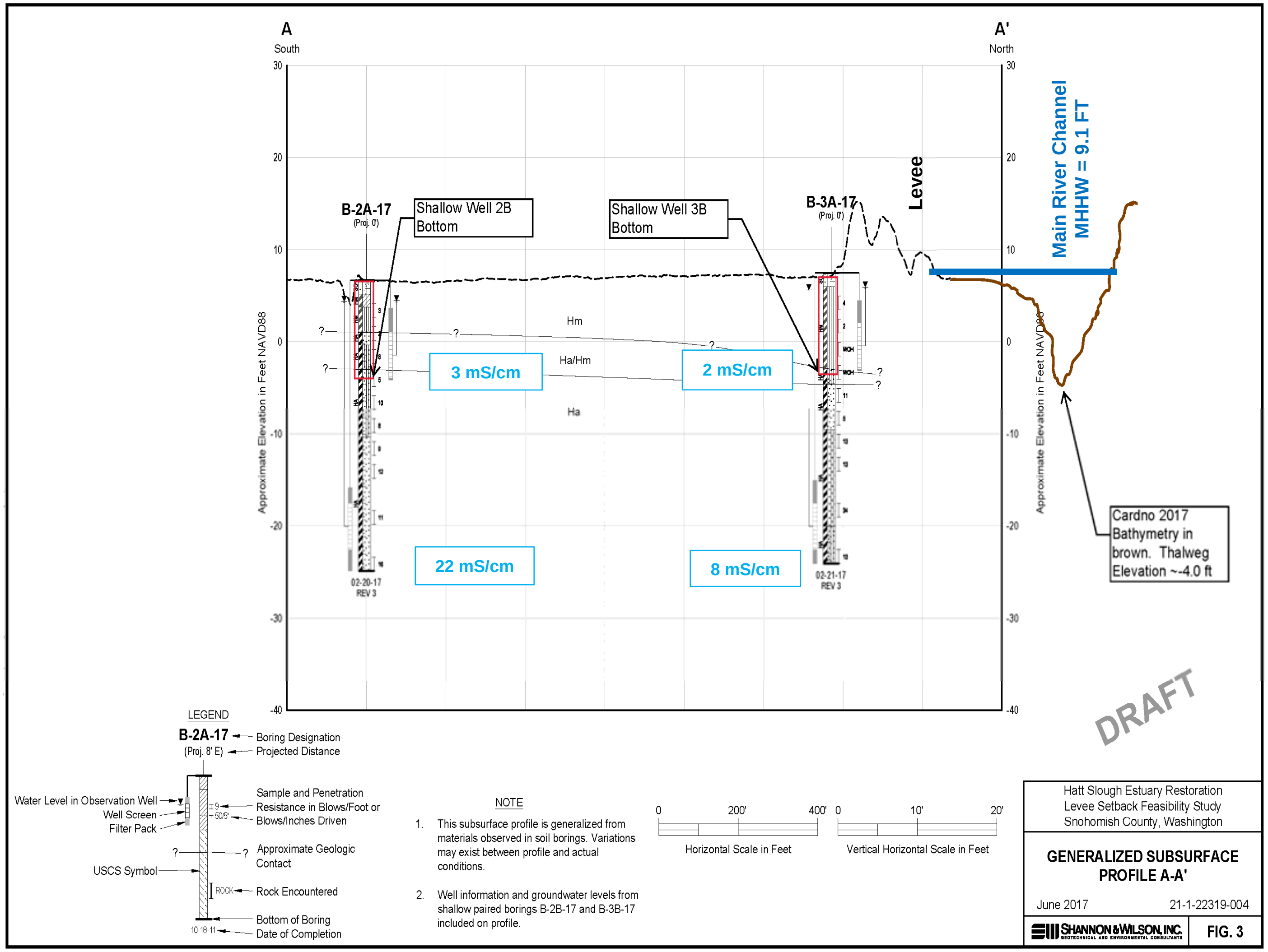
SPECIFIC CONDUCTANCE FOR GROUNDWATER AND RIVER: MARCH-MAY 2017

June 2017 21-1-22319-004

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. 7

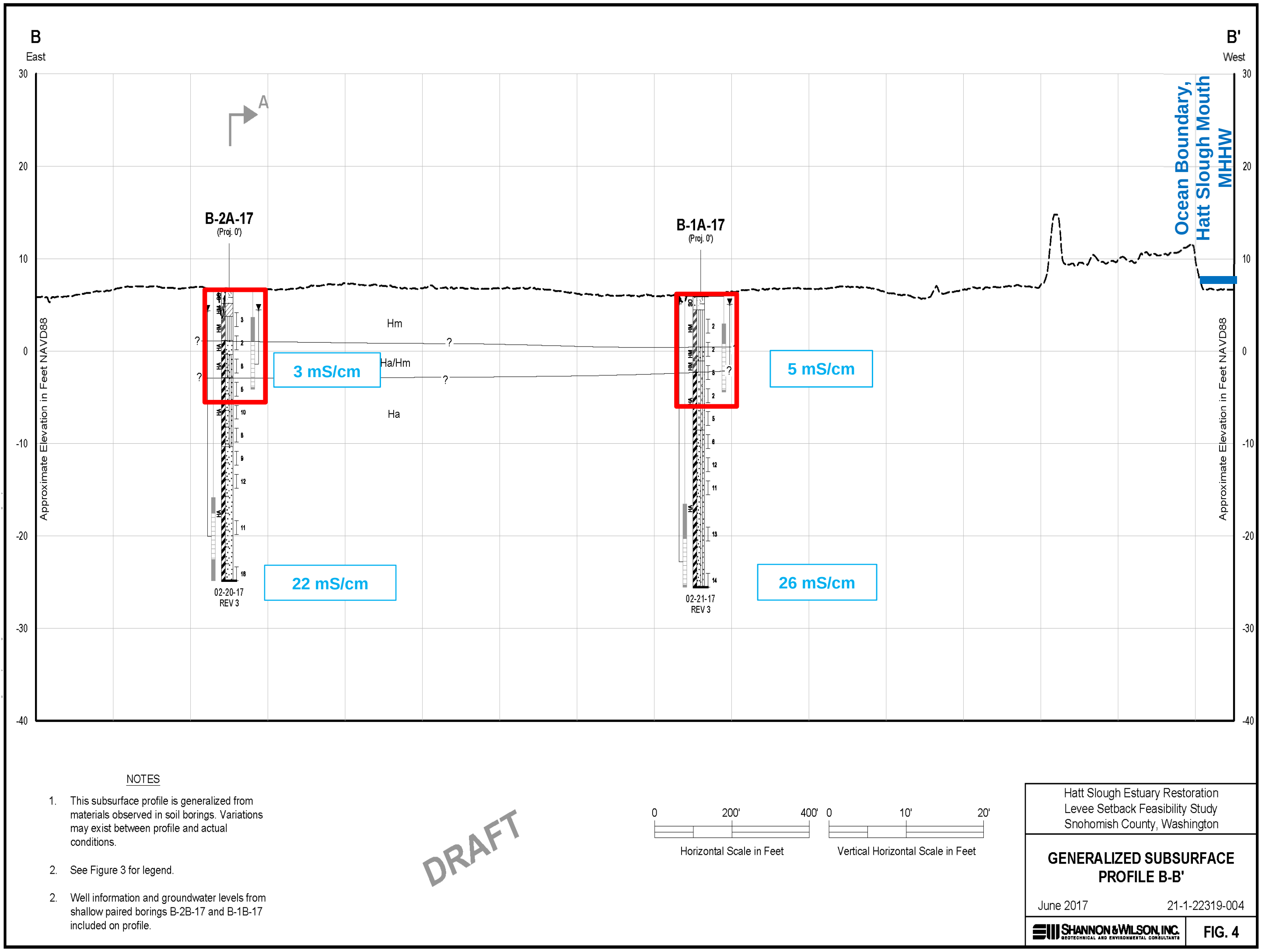
Figure 8-5 Salinity measured as SC for groundwater and river from March to May 2017. Topographic sections A-A' and B-B' also shown here. Plot adapted from Shannon & Wilson 2017.



NOTE

1. This subsurface profile is generalized from materials observed in soil borings. Variations may exist between profile and actual conditions.
2. Well information and groundwater levels from shallow paired borings B-2B-17 and B-3B-17 included on profile.

Figure 8-6 Section A-A' showing shallow wells 2B and 3B (~10 feet deep) in red outline, assumed to represent salinities in the rooting zone for this study. Wells 2A and 3A are deep wells (~30 feet deep) immediately adjacent to the shallow wells. Average conductivities (mS/cm) for each well are shown in blue boxes. The brown line indicates bathymetry data of adjacent Hatt Slough, collected by Cardno in 2017. Geologic site conditions were interpreted as Holocene alluvium (Ha) and Holocene mudflat (Hm) deposits (adapted from Shannon & Wilson 2017).



NOTES

1. This subsurface profile is generalized from materials observed in soil borings. Variations may exist between profile and actual conditions.
2. See Figure 3 for legend.
2. Well information and groundwater levels from shallow paired borings B-2B-17 and B-1B-17 included on profile.

Figure 8-7 **Section B-B' (east to west) showing shallow wells 2B and 1B (~10 feet deep) in red outline taken to represent salinities in the rooting zone for this study. Wells 2A and 1A are deep wells (~30 feet deep) immediately adjacent to the shallow wells. Average conductivities (mS/cm) for each well are shown in blue boxes. Section B-B' terminates at the current mouth (Hatt Slough mouth), the ocean boundary (adapted from Shannon & Wilson 2017).**

Spring 2017 salinities in the shallow wells indicate that plants may already be stressed by existing conditions soil salinity. The shallow well B-1B had a maximum SC of 5 mS/cm, which would restrict the growth of many plants. Wells had stable SCs, with shallow well B-2B at 3.0 m S/cm (which may restrict the growth of sensitive plants) and shallow well B-3B at 1.5 mS/cm (which would induce a mostly negligible plant response to soil salinity, except for orchard grass).

The deeper wells (B-1A, B-2A, and B-3A) have consistently higher salinities than the shallow wells. This observed increase in salinity with depth is consistent with fundamental hydrogeological theory of circulation of fresh and saline groundwater at a zone of diffusion (sometimes referred to as the seawater interface) in a coastal aquifer (Figure 8-8). The Hatt Slough wells confirm that the depth to interface is 10s of feet and reflect basic theory that:

> “A mechanism that appears powerful enough to cause sufficient mixing is the reciprocative motion of the salt-water front resulting from ocean tides and from the rise and fall of the water table due to variations in recharge and other forces, including pumping. Palmer (1927, p. 51-52) and Wentworth (1948) theorized that this to-and-fro motion creates the zone of diffusion. The process by which two miscible liquids interfuse about their boundary when hydraulic flow causes the boundary to move is known as dispersion.” (Cooper et al. 1964)

The deep shoreline well B-1A had a maximum SC of 27 mS/cm, which is about half that of seawater; in contrast, the difference between shallow and deep salinities expressed in well B-3A and B-3B were much less dramatic.

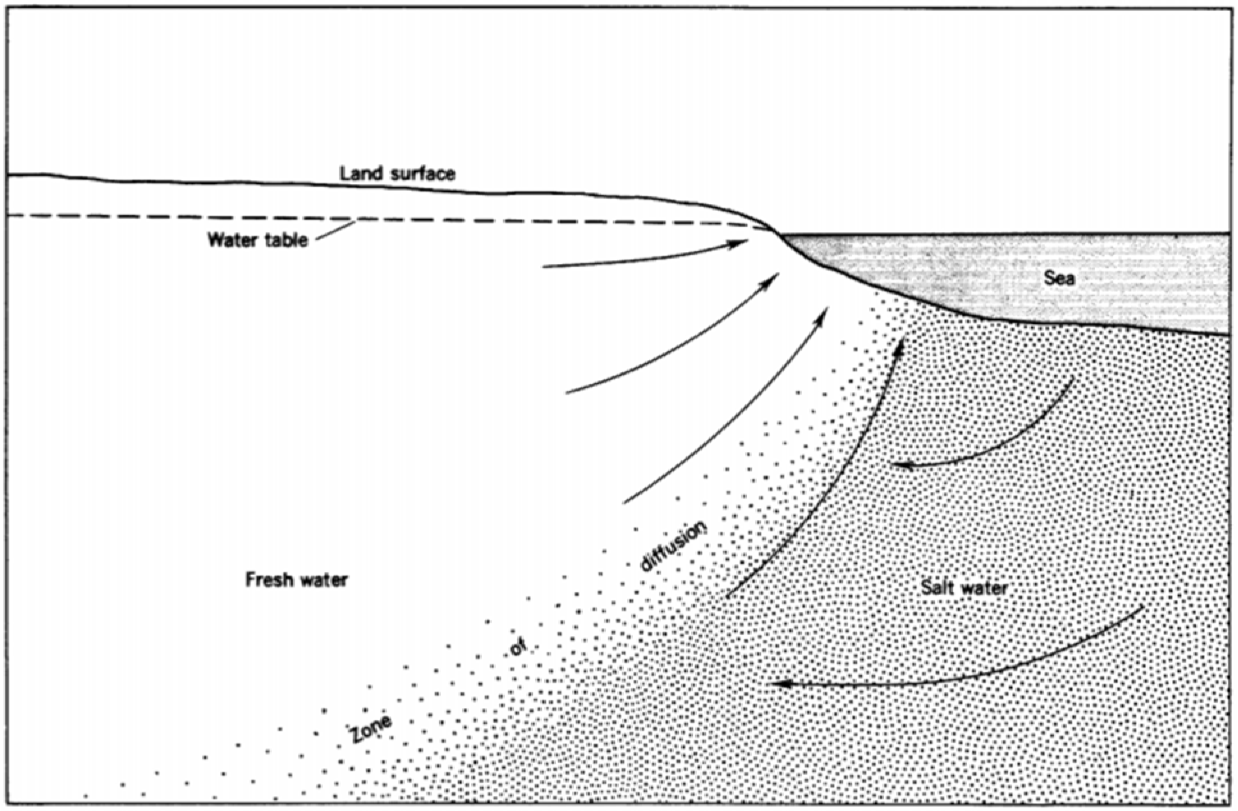


Figure 8-8 Conceptual diagram of the saltwater zone of diffusion for a coastal aquifer. Ocean at right. At any given distance from the shore, a deeper well should encounter water with higher salinity than a shallower well (Source: Cooper et al. 1964).

The Hatt Slough well data affirm the conceptual diagram of Figure 8-8, showing that a sharp interface does not exist between fresh water and salt water in the Stillaguamish coastal aquifer. Instead, a vertically wide zone of diffusion was observed. Hence, salinities were assumed to vary linearly over the relatively narrow range of depths between this study's shallow and deep wells, but exponentially over much larger separations governed by solute diffusion and fluid density gradients.

The consistent vertical behavior at wells 1 and 2 suggests that rising sea levels of 1 foot (projected to occur sometime between 2050 and 2080) will increase salinity by approximately 1 mS/cm (since a ~20-mS/cm difference is presently expressed over ~20 feet of separation). A complication is the proximity to the (freshwater) river, which in the case of well B-3A appears to largely overwhelm the pattern of increasing salinity with depth.

Rising sea levels also imply horizontally advancing coastlines that will presumably also follow linear trends over short horizontal distances but parabolic trends over long distances (Cooper et al. 1964). This dependency on distance to the coastline will affect the depth to the saline interface (see Figure 8-8), but this horizontal factor is not well resolved by the configuration of the available wells.

The Hatt Slough wells are generally within a freshwater river-dominated site where only well B-1B showed signs of semi-diurnal tidal fluctuation in salinity. Wells 2 and 3 did not show semi-diurnal variations in salinity, suggesting limited intrusion of seawater both up the channel and into the groundwater during the monitoring period. Despite variations in precipitation and river flows (e.g., Figure 8-5), the salinities remain relatively constant at all three Hatt Slough wells over 3 months of semi-diurnal tidal fluctuation to the groundwater table. Based on these data, shallow groundwater farther than 1,500 feet from the Port Susan Bay MHHW shoreline is not expected to express daily tidal fluctuations in salinity.

The consistent but small semi-diurnal variations in the shallow Well B-1B time series suggests a weak correlation with tidal exchange (1 mS/cm amplitude). Long-term migration of the saltwater/freshwater interface through the groundwater would presumably respond to net average SLR, but the zone of transient diurnal changes is apparently restricted to areas closer to the shoreline (e.g., well 1), at least during springtime discharges in the river. Shallow groundwater close to the shoreline, presumably within about 1,000 feet of the Port Susan Bay MHHW, is expected to exhibit daily tidal fluctuations in salinity.

The measured relationship between salinity and the monthly maximum tidal exchange provides a plausible basis for inferring future changes in average salinity as a function of SLR. Close to the shoreline, the observed semi-diurnal signal of salinity variation in shallow well B-1B (red line, Figure 8-5) correlates with semi-diurnal fluctuation in water levels within the same well (Figure 6-8). Late May 2017 had low levels of precipitation and stable river discharge, so inputs from the surface did not contribute to the semi-diurnal salinity signal. In shallow well B-1B, an SC increase of 1 mS/cm corresponded to a water-level increase of 1 to 1.5 feet—or 1 to 0.7 mS/cm rise per 1 foot of SLR (a magnitude of change projected to occur between 2050 and 2080). This result is consistent with the rate of salinity rise with rising sea levels that was deduced by the prior discussion of well separation.

In summary, salinity in near-coastal shallow wells is expected to rise about 1 mS/cm for every 1 foot of SLR. This likely represents the case of spring tides (full or new moons) and low stable river levels, and is representative of late spring and summer conditions where highest salinities may occur. On this basis, Table 8-6 presents the expected increase in salinity for a range of RSLR scenarios during low river flows.

Table 8-6 **Projected Increases in SC (mS/cm) Having a 50% Likelihood of Exceedance for Groundwater in the Lower Stillaguamish Basin during Low River Flows**

	Year 2050	Year 2080	Year 2100
Stillaguamish River Mouth:			
RSLR 50% for RCP 8.5	0.7	1.5	2.2
RSLR 50% for RCP 4.5	0.7	1.3	1.7

Note: All salinity values in units of mS/cm; by the relationship inferred above, these values are also equivalent to the predicted 50%-likelihood SLR in feet.

8.3.3 Eastern Camano and Leque Island Groundwater Study Wells

Groundwater in the northwestern and western portions of Florence Island (Figure 8-9) lacks proximity to a major freshwater channel, since the Old Main Channel typically flows as a blind tidal slough with little to no freshwater surface input except at very high discharges. Hence, proximity to the Port Susan ocean shoreline governs groundwater salinity. One well in the study from this area (Pacific Groundwater Group 2012) has relevance to this study's salinity predictions to the rooting zone: Camano Island shallow well S3s, located 1,150 feet north of the Port Susan MHHW shoreline and screened 8 to 13 feet below ground. For the November 2011 to April 2012 monitoring period, well S3s had SCs that steadily rose linearly from 7.4 to 10 mS/cm with no tidal signature, as salts concentrated to the groundwater with summer evaporation. Since the Stillaguamish River mouth (Hatt Slough) is relatively far distant from S3s, this salinity range presumably represents expected salinity for diked areas within 1,200 feet of the Port Susan MHHW shoreline absent any freshwater influence from a nearby river channel.

Other Camano Island and Leque Island wells were not relevant for inference of RSLR effects on shallow groundwater assessment because of screening depths more than 20 feet below ground, complex hydrogeologic interactions with Camano Island's aquifer, and the likelihood of seawater overtopping (PGG 2012, 2018).

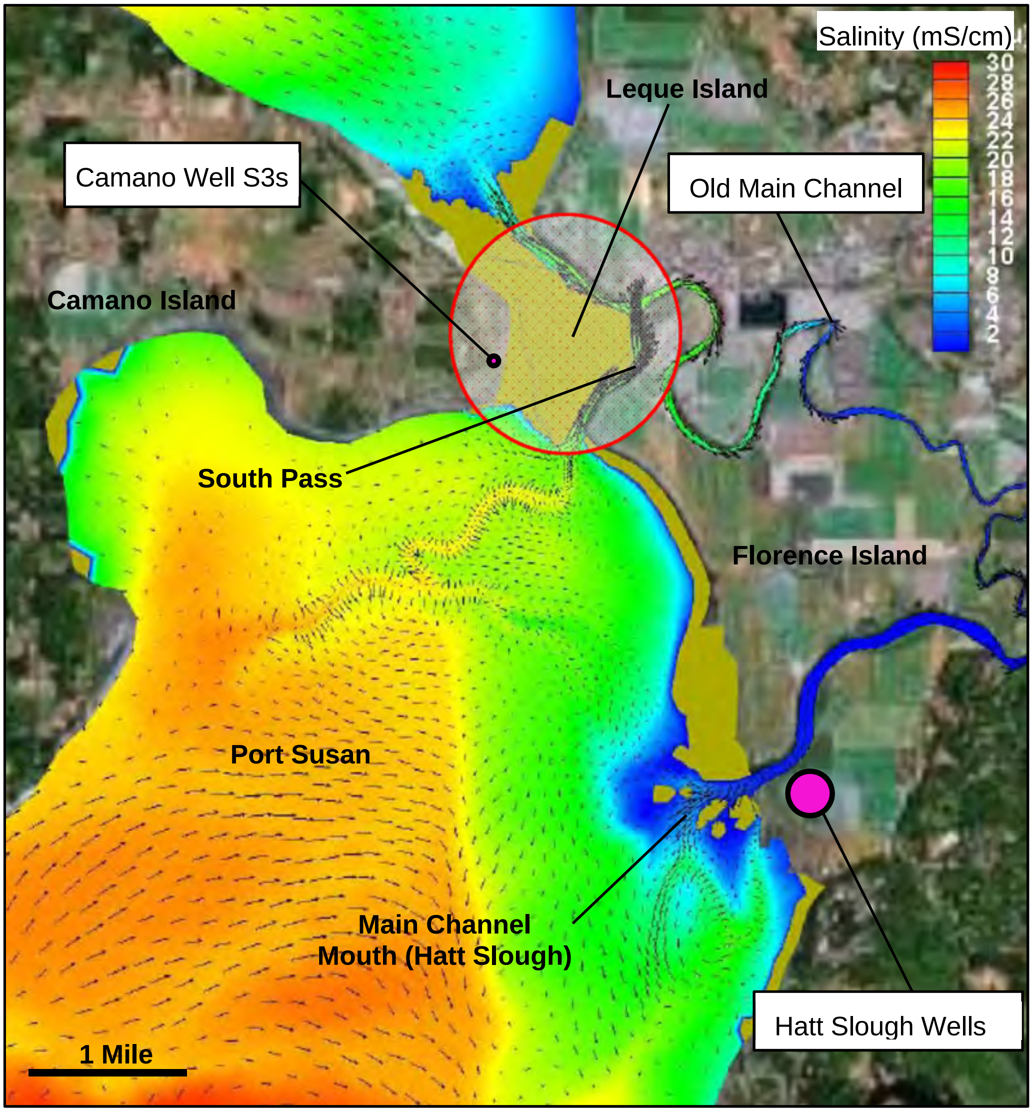


Figure 8-9 **Predicted surface salinities for existing conditions in northern Port Susan during high tide and low Stillaguamish River flows (~1,250 cfs). Leque Island (circled in red) is not inundated. Well S3s was 3 miles from a freshwater channel, the Stillaguamish River mouth (Source: Yang 2008).**

8.3.4 Florence Island Predictions

Surface waters adjacent to the northwestern portion of Florence Island have high salinities (16 to 22 mS/cm) during high tides and low river flows (see Figure 8-10). These are dilute compared to pure seawater (~50 mS/cm) but similar to general salinities for northern Port Susan, the ocean boundary in this study. Even during higher river flows above bankfull, when salinities are driven by fresh water, the northwestern portion of Florence Island is surrounded by brackish surface water (8 to 16 mS/cm) while Hatt Slough flows fresh (Figure 8-10). This study applies Camano Island well S3s to represent plausible shallow groundwater salinities for northwestern Florence Island close to the shoreline (here, assumed to be within 1,200 feet of Port Susan MHHW). For the southern portion of Florence Island, the Hatt Slough wells are in close proximity and are assumed to provide the best analog.

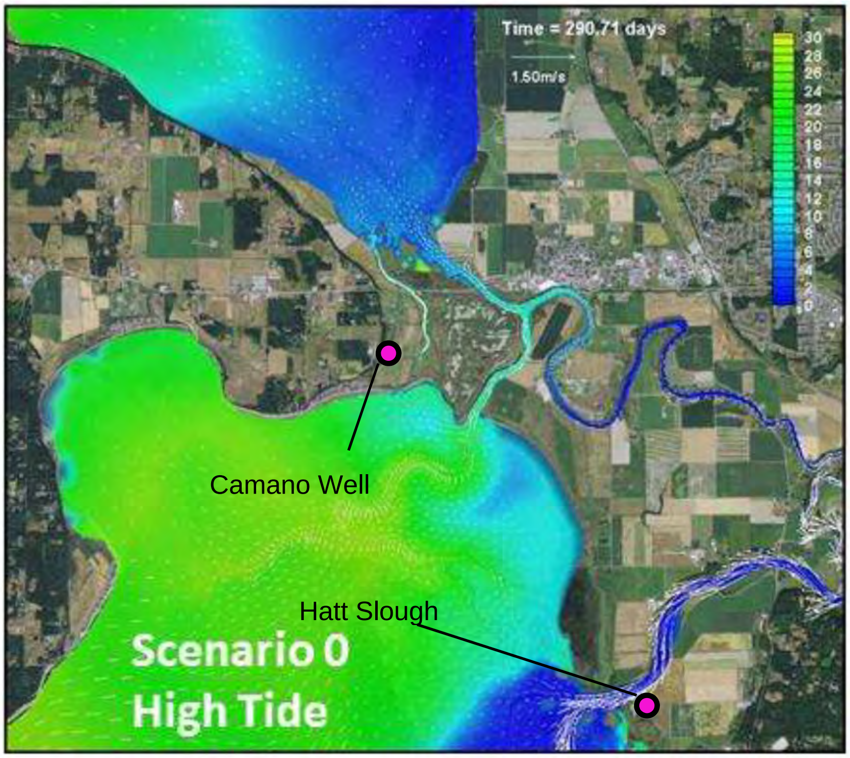


Figure 8-10 High tide at Northern Port Susan and Southern Skagit bay modeled with bankfull Stillaguamish River flows of ~26,000 cfs for October 17, 2005 (Pacific Northwest National Laboratory 2015). Hatt Slough (the current river mouth) flows fresh, whereas the Old Main Channel has brackish salinities even with fresh floodwaters flowing in from upstream.

Data from the three Hatt Slough wells coupled with the Miller Road well demonstrate the complex interplay of distance-from-river (Hatt Slough) and distance-from-shore (Port Susan). Shallow groundwater within 1,000 feet of the Port Susan shoreline and more than 400 feet from the river will have salinities of 5 mS/cm or greater (see Figure 8-7, Section B-B’). Twice as far from the shoreline and 1,100 feet from the river, shallow groundwater will have salinities of 3 mS/cm, whereas groundwater at a similar distance from the shore but immediately adjacent to the river will have lower salinities around 2 mS/cm (see Figure 8-6, Section A-A’). The Miller Road well defines a more distant, upland zone both far from the river (1 mile) and far from the shore (2 miles) where salinity intrusion is present but has declined to near-zero values. Fresh water presumably dominates farther upvalley. As future sea levels rise, groundwater salinities near the shoreline will increase and groundwater salinity will advance upvalley. Although speculative, plausible predictions of future groundwater salinities under high and low climate change scenarios for this study’s well locations are presented in Table 8-6.

Extrapolation of the existing pattern of salinity was completed by combining interpretation of shallow well salinities from the Cardno well near Miller Road, the three Hatt Slough wells immediately southeast of Hatt Slough, and southern Camano Island well S3s. After plotting these values and interpolating between them, a salinity “threshold” of 3 mS/cm was selected to discriminate areas with greater potential for significant effect of salinity on crops, with shallow groundwater west of this line predicted to have salinities greater than 3 mS/cm (Figure 8-11, “Modern Sea Level – No Drainage” scenario). Rising sea levels lead to an upvalley migration of this threshold level (Figure 8-11, future year scenarios) and permit the development of a speculative set of interpolated salinity intrusion maps for RCP 8.5, the high emissions scenario (Appendix C).

Table 8-7 **Selected Salinity Values Representative of Spring/Summer Existing Conditions used to Inform Future Salinity Intrusion Affecting the Rooting Zone of Crops for the Lower Stillaguamish River Basin under Climate Scenario RCP 8.5 (High Emissions) and RCP 4.5 (Low Emissions), both 50% Likelihood**

Well Name	Screen Depth (feet below ground)	Existing Salinity (mS/cm)	RCP 8.5 / 4.5 2050 Salinity (mS/cm)	RCP 8.5 / 4.5 2080 Salinity (mS/cm)	RCP 8.5 / 4.5 2100 Salinity (mS/cm)
Hatt Slough Well B-1B[1]	5.1 to 10.1	5	**5.7** / 5.7	**7.2** / 7	**9.4** / 8.7
Hatt Slough Well B-2B	5.6 to 10.6	3	**3.7** / 3.7	**5.2** / 5	**7.4 /** 6.7
Hatt Slough Well B-3B	5.4 to 10.4	2	**2.7** / 2.7	4.2 / 4	**6.4** / 5.7
Cardno Miller Rd – MW6	0 to 10	0.6	**1.3** / 1.3	**2.8** / 2.6	**5** / 4.3
Camano Island Well S3s[2]	8 to 13	7	**7.7** / 7.7	**9.2** / 9	**11.4** / 10.7

Notes:

[1] Original dataset from the Hatt Slough Estuary Restoration Project (Shannon & Wilson 2017)

[2] Well S3s data presented in PGG 2012 study. This well was taken to represent a lower limit of groundwater salinity for areas within 1,150 feet of the shoreline since the monitoring period (November 2011 to May 2012) was significantly different than for the other four wells. However, the salinity was very stable over a 5-month period (PGG 2012).

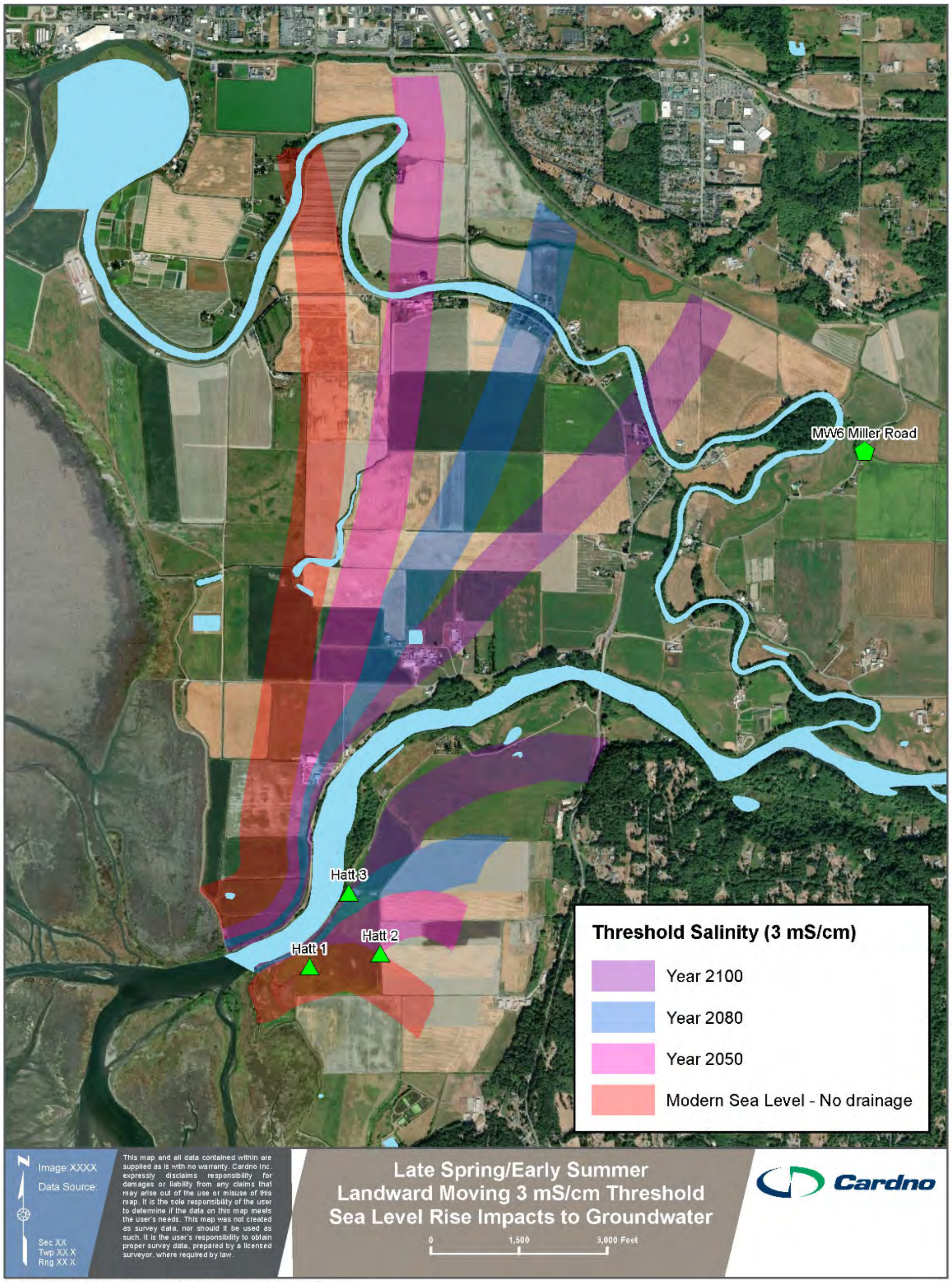


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Figure 8-11 Future landward advance of a 3 mS/cm salinity threshold for late spring and early summer shallow groundwater, driven by rising sea levels under conditions of low river flows, high tides, and future sea levels as predicted for climate scenario RCP 8.5 (high emissions).

8.4 Lower Snohomish River Data Results

8.4.1 Cardno Data – Marshland and French Slough FCDs

Relevant salinity data for the Lower Snohomish River valley are limited. The four wells installed for this study focused on achieving maximum spatial coverage of the Marshland and French Slough FCDs (Figure 1-2). However, these wells ranged 5 to 10 miles perpendicular distance from the ocean boundary (Everett, Washington, MHHW shoreline), a much greater distance than inferred to show any seawater influence based on the more proximal Stillaguamish River valley wells (Figure 8-12 and Table 8-8). The Snohomish River wells reported SCs ranging from 0.3 mS/cm to 1.2 mS/cm for shallow groundwater between April 2018 and December 2018. This range of salinities probably does not indicate salinity intrusion to shallow groundwater; instead, these SCs may reflect summer evaporative concentration of salts and dairy outfall contributions. As in the lower Stillaguamish River valley, SCs greater than a threshold of 2 to 3 mS/cm would be potentially problematic; this is not observed in the Snohomish River valley wells.

Cardno well MW1 Eagle South had very erratic SCs due to fluctuations in freshwater inputs from the steep drainages to the south. The well was not considered informative of salinity intrusion effects to the Marshland FCD.

Table 8-8 **Selected Salinity Values Representative of Summer Existing Conditions used to Inform Future Salinity Intrusion Affecting the Rooting Zone of Crops for the Lower Snohomish River Basin**

Well Name	Screen Depth (Feet below ground)	Screen Interval* (Feet, NAVD88)	Average Summer 2018 Salinity (mS/cm)
MW1 – Eagle South	0 to 10	5.8 to −4.2	0.4
MW2 – Eagle North	0 to 10	8.3 to −1.7	0.5
MW3 – Grasslands Farm	0 to 10	9.9 to −0.1	1.0
MW4 – Craven Farm	0 to 10	21.9 to 11.9	0.5

Note:

* Screen interval based on the survey ground elevation at each well site. Salinity measured near well bottom and likely represents an average over the full depth.

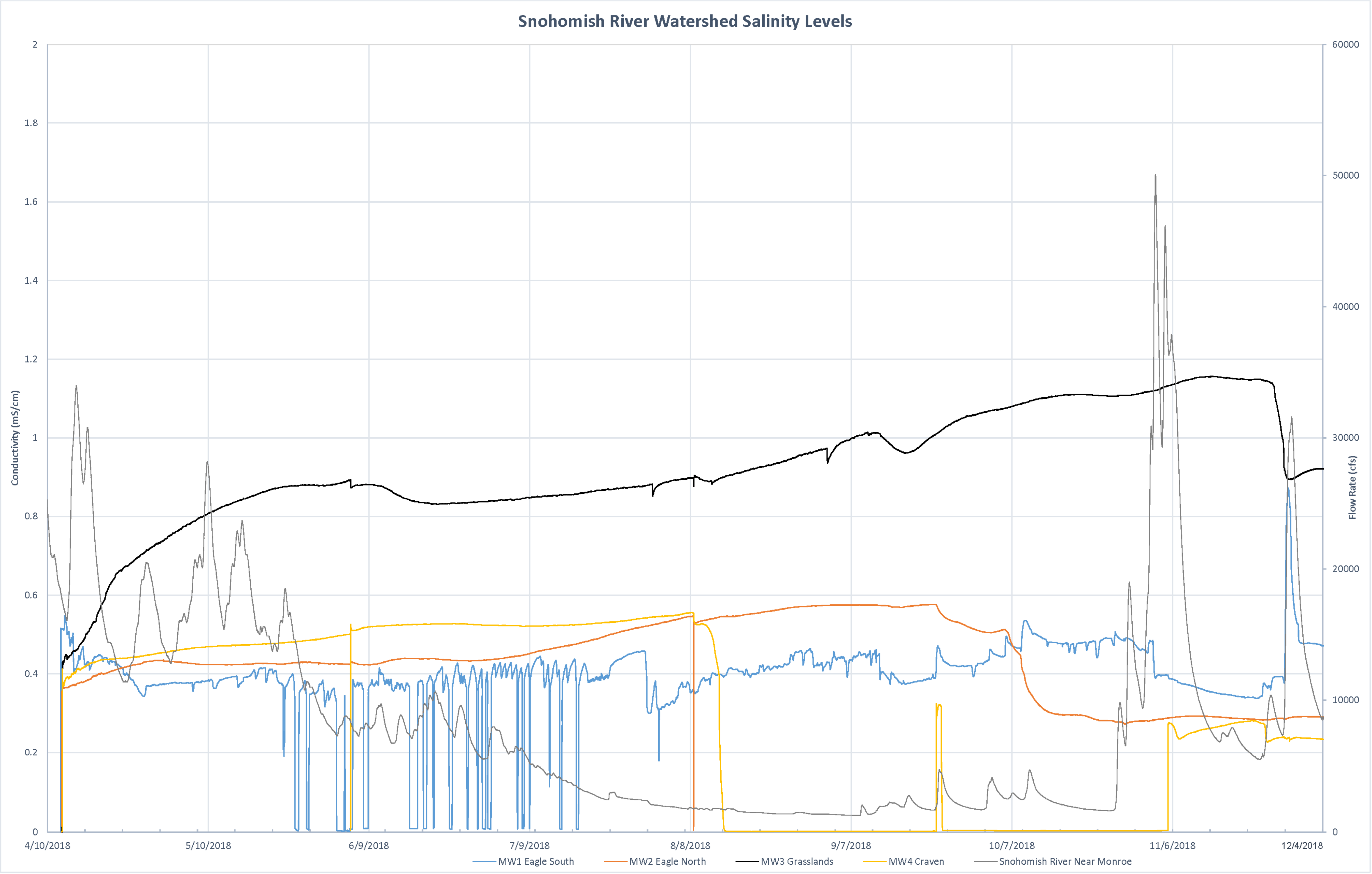

Figure 8-12 SC data for Cardno's 4 wells in the lower Snohomish River Valley showing relatively low salinity values than may increase due to saltwater intrusion associated with SLR. Salinity recordings of 0 in the Eagle South well occurred when the logger was exposed to air. Since all wells showed a steady exponential salinity rise in April, the well salinities were equilibrating with surrounding groundwater, and, thus, well salinities after early May are more representative of the surrounding groundwater system.

8.4.2 Smith Island Salinities

Data from wells discussed in Shannon and Wilson's groundwater study (Figure 8-13), previously used to extrapolate groundwater elevations on Ebey Island for modern and future sea levels, also included salinity data that can inform future conditions on Smith Island. Wells were within 3,000 feet of Union Slough (measured from the gage shown), within 3,700 feet of the Snohomish River main channel to the west and within 11,600 feet of the nearest ocean boundary (Everett, Washington, MHHW shoreline). The Union Slough surface water gage and wells SW-08, SW-09, and SW-05 reported salinities in both SCs and PSU (Appendix D). The wells were not originally installed for purposes of evaluating salinity impacts to crops and so they are screened as much as 30 feet below the surface, but they can nonetheless offer some indication of salinity patterns here.

The highest salinities were recorded in well SW-08, located 2,100 feet from the Union Slough surface water gage and screened from 25 to 30 feet below ground (Figure 8-13 and Table 8-9). Salinities had a semi-diurnal tidal signature with an average value of 19.3 mS/cm for summer months (July, August, and September 2013). SW-08 showed a modest decreases in the tidal salinity signature (to an average of 16.5 mS/cm) during periods of increased river flow in November and December of 2013.

Despite its closer proximity to the shore, SW-05 (screened 25 to 30 feet below ground, 2,780 feet from Union Slough) had somewhat lower salinity values than SW-08, averaging 12.7 mS/cm (July to September 2014) and with a more muted semi-diurnal amplitude. Clearly, the relationship between salinity, coastal proximity, and subsurface connectivity is complex and not fully discernible with available data, limiting the ability to quantify or predict the shallow groundwater salinities of surrounding terrain.

Shallow well SW-09 (screened 0 to 10 feet below ground) was the only well to characterize shallow groundwater salinities at Smith Island prior to levee breaching. Its shallow depth resulted in much lower salinities than at the other Smith Island wells (2.1 mS/cm for the summer monitoring period, July through September 2014). SW-09 salinities showed no tidal signature and WSELs were responsive to pulses in river flow, not tides, and so the influence of future RSLR and salinity rise cannot be inferred from this well.

Table 8-9 **Selected Salinity Values Representative of Summer Existing Conditions used to Inform Future Salinity Intrusion Affecting the Rooting Zone of Crops for the Lower Snohomish River Basin**

Well Name	Screen Depth (feet below ground)	Screen Elevation (Feet, NAVD88)	Average Summer Salinity (mS/cm)
SW-08	25 to 30	−19 to −24	19.3
SW-05	25 to 30	−20 to −25	12.7
SW-09	0 to 10	6 to −4*	2.1
Union Slough **	Surface water gage	x	7.1 and 14.4

Notes:
* Location of SW-09 was approximate and thus screen elevations were approximated from 2014 LiDAR
** Union Slough mid-summer average for 2014 (7/22/14–09/01/2014) and 2013 (7/22/13–09/01/2013)

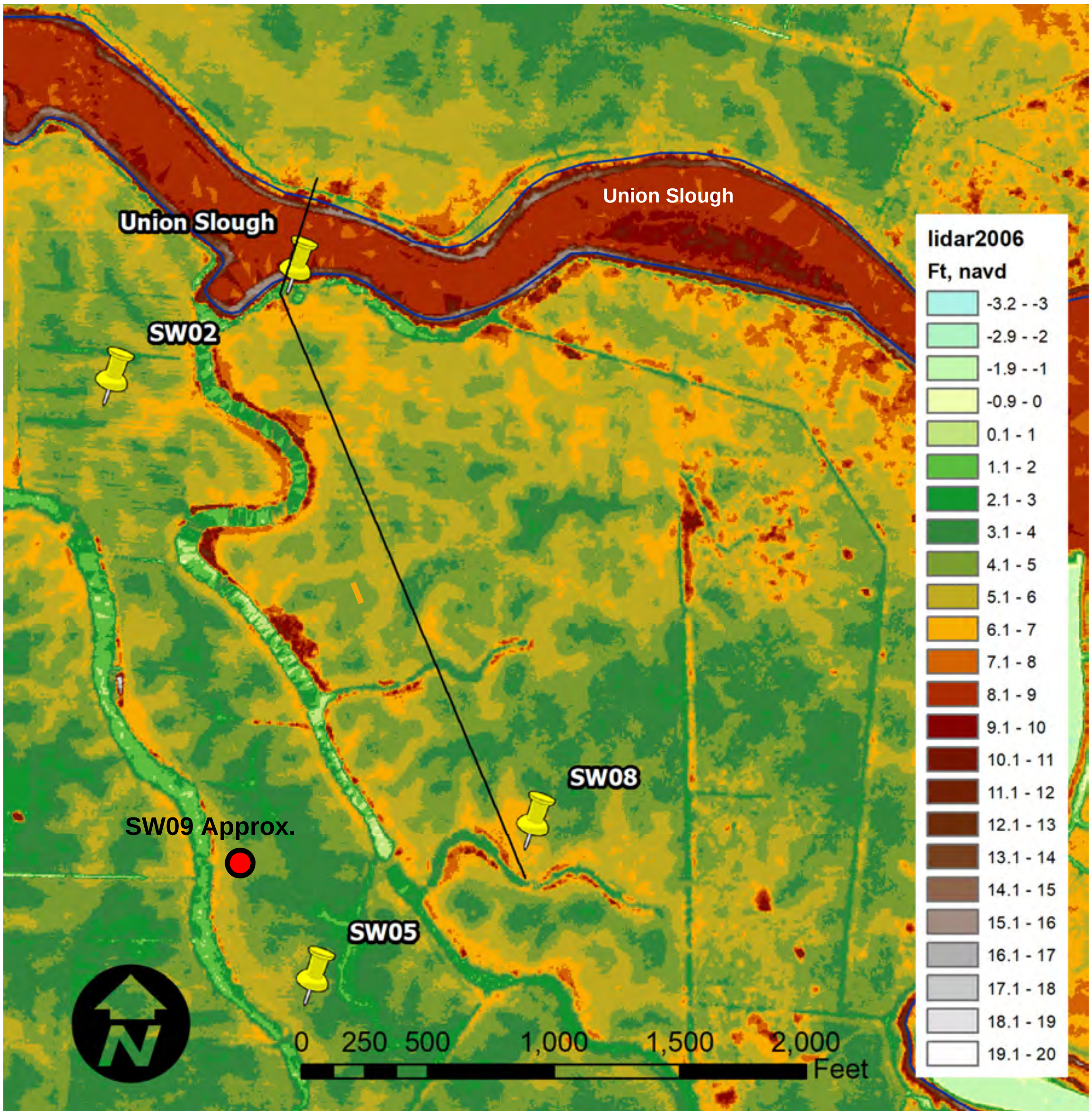

Figure 8-13 **Of the partner well dataset for Smith Island, only wells SW-09, SW-05, and SW-08 had CTD recordings. The surface water gage at Union Slough also recorded CTD values.**

8.4.3 Ebey Island and Drainage Improvement District 13 Predictions

Absent any salinity data measured on Ebey Island or DID13, the Smith Island dataset provides the closest reference with which to infer existing or future salinity conditions. However, only one Smith Island well (SW-09) measured salinities directly relevant to the crop rooting zone (i.e., upper 10 feet of soil). Inference of RSLR effects on salinity intrusion from the Smith Island well dataset is therefore not as robust as for the Stillaguamish River's Hatt Slough wells, since each Hatt Slough well point has a pair of shallow and deep wells.

Compiling well salinity datasets for the lower Stillaguamish and Snohomish River basins creates a basis for inferring RSLR effects on salinity for Ebey Island, Marshland FCD, French Slough FCD, and proximal drainage districts (Figure 8-14), if some broad degree of comparability between the hydrogeology of the two basins is assumed. The combination of all available data from both basins demonstrates that both depth and proximity to the shoreline play significant roles in predicting shallow groundwater salinity.

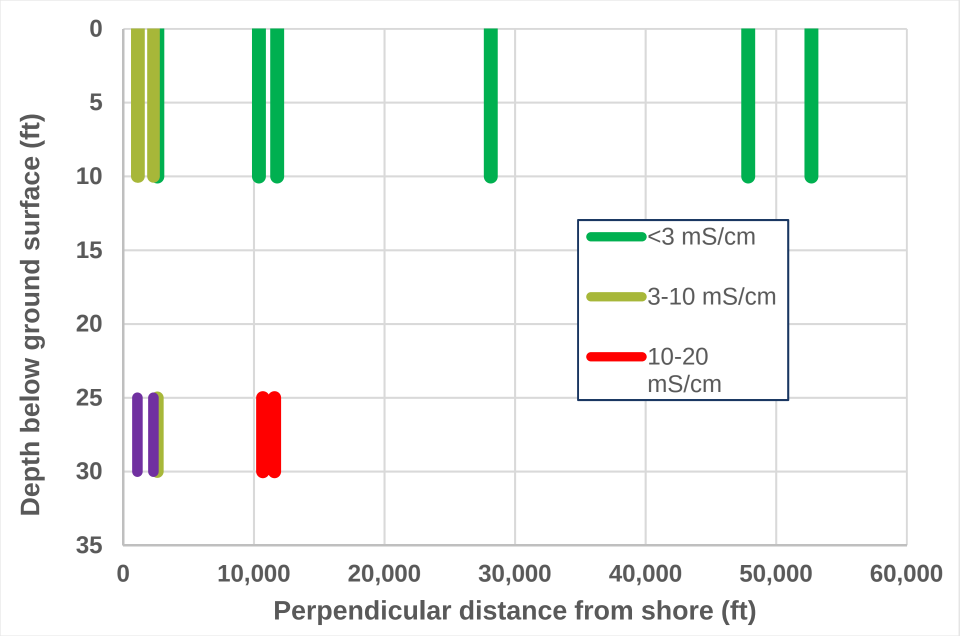

Figure 8-14 **Combined summer salinity datasets from both the lower Stillaguamish and lower Snohomish River basins. Shallow groundwater is apparently influenced by seawater salinity only within a few thousand feet of the shoreline. Although deeper groundwater has a potentially much more far-reaching influence, its relevance to agriculture is probably marginal.**

Areas within 5,000 feet of the shoreline commonly experience significant and measurable salinity intrusion effects (i.e., areas adjacent to Hatt Slough and Florence Island). For areas greater than 10,000 feet from the shoreline (which would include Ebey Island), however, the available data suggest that shallow salinity should be minimal. Even farther upstream (Eagle North, Grasslands Farm, and Craven Farm wells), summertime salinities are even lower (0.5 mS/cm to 1.0 mS/cm). Since Ebey Island and DID13 are likely to remain greater than 10,000 feet from the shoreline, even as sea levels rise and the shoreline encroaches landward, salinity intrusion into shallow groundwater is not expected to increase over the coming decades.

However, deeper groundwater on Ebey Island is presumably saline under modern sea levels and should further increase with rising sea levels. This saltwater connection is displayed in the Smith Island groundwater datasets, which display semi-diurnal tidal fluctuations in salinity. Kim Hendersen, Ebey Island Diking District Commissioner, corroborates this observation: “We have no data on the water on Ebey. The only anecdotal info is that when a few people have tried to drill wells for water for their property it comes up brackish and unusable …” (personal communication, K. Hendersen, with Cardno, November 14, 2018).

8.4.4 Flood Control District Predictions

The Marshland and French Slough FCDs are greater than 20,000 feet from the ocean boundary. Hence, Cardno does not expect RSLR to cause significant increases in salinity intrusion to shallow groundwater for these FCDs.

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9 Conclusions for Agricultural Resiliency and Restoration

9.1 Future Trends in Salinity

In summary, areas closest to the shoreline have the highest risk of increased groundwater salinity intrusion to due to rising sea levels. Areas within 5,000 feet of shoreline are especially vulnerable to groundwater salinity intrusion to the shallow rooting zone of crops, but areas within 10,000 feet may also experience measurable increases over time. To a high level of certainty, Florence Island (situated near the mouth of the Stillaguamish River and mostly within 10,000 feet of the shoreline) already experiences shallow groundwater salinities above crop tolerance thresholds, and those impacts to agriculture are likely to increase in severity within the next 50 years. In contrast, Ebey Island (mostly greater than 10,000 feet from the shoreline) may not experience significant increases in salinity intrusion to shallow groundwater.

9.2 Study Limitations

Although these predicted trends are well-supported by our limited analysis, two mechanisms not addressed by the available data may lead to underestimation of the impacts of elevated salinity. First, the short-term influence of high summer tides (during new and full moons) may increase shallow groundwater salinities beyond the averaged values used here to characterize impacts. If crops are sensitive to even brief exposure to increased salinity, impacts not anticipated by average values may result. Second, if levees were to overtop during the growing season due to rising sea levels combined with storm surge and/or large tides, highly saline water may infiltrate shallow groundwater from the surface and directly impact crops, regardless of predicted long-term values.

Conversely, this analysis has not incorporated other mechanisms that could lead to overprediction of future groundwater salinities. For example, future climate trends may increase the frequency and magnitude of late-spring peak floods, such that more freshwater flows overtop existing levees and reduce shallow groundwater salinities. Additionally, the data available for this study integrated groundwater conditions over the upper 10 feet of soil, but nearly all crops have an even shallower rooting zone. Thus, the available data may overestimate the salinities experienced by crops. Additionally, irrigation practices (such as the late spring flood-type irrigation water management strategy at Grasslands Farm) may further mitigate any impacts of apparent near-surface salinity.

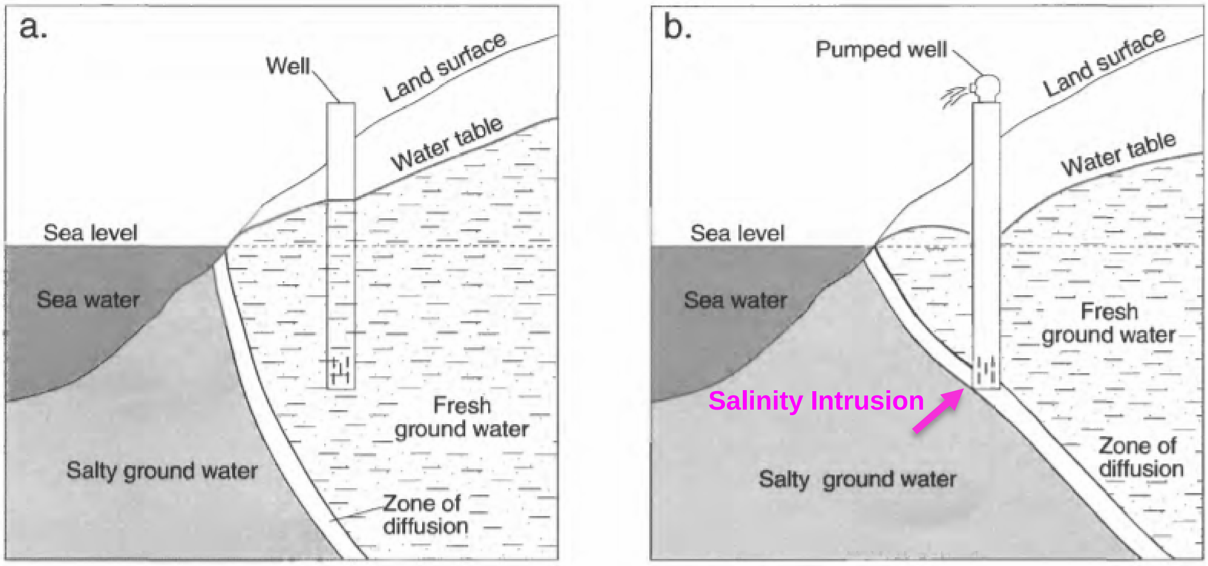
A final complication not addressed in this study is the additional chemical interactions that can be relevant to crop yields. For example, the *Leque Island Restoration 2017 Groundwater Monitoring Update* monitoring report noted that “The correlation between increasing EC and hardness is consistent with changes that occur when saltwater first begins to invade a freshwater zone. A ‘hardening front’ is created as the sodium displaces divalent cations like calcium and magnesium, thus causing them to go into solution” (PGG 2018). Increases in hardness may not affect crop yield while increases in sodium and chloride would certainly impact crops. Thus, similar salinity values but with disparate shallow groundwater chemistries may affect crops differently.

9.3 Future Planning

Working farms that are disaster-ready for RSLR can mitigate and adapt for future risks with planning and preparation. The most successful and cost-effective efforts are likely to be those that consider a strategic balance between natural areas restoration and improved infrastructure.

Natural areas restoration should emphasize the identification of those areas where the viability of farming is most uncertain, the value of the habitat for salmon and other native species is greatest, and the cost of maintaining infrastructure would be highest. Habitat improvements to benefit salmon can have synergistic and positive ecosystem services that benefit human infrastructure, such as reduced flood damage risks and the relocation of crops and infrastructure away from high-risk salinity intrusion zones. The loss of estuarine and brackish-water habitats over the last century has been identified as a key impediment for regional salmon recovery. The coincidence of areas that are most at risk for future agricultural impacts and of particularly high priority for resource-land acquisition suggest opportunities for mutually beneficial actions.

Infrastructure improvements to protect high-value agricultural land that can remain viable over time will also be a critical pathway to long-term solutions. Classic solutions from the past, however, may not provide adequate protection for the future. For example, installation of pumps and drainage to reduce flooding due to rising sea levels may draw deep salty groundwater upward, closer to the rooting zone of crops, increasing the area of surface drying but also decreasing the depth to saline groundwater (Figure 9-1). Since Florence Island will experience both increased groundwater ponding (increasing springtime delays in field access) and salinity intrusion from RSLR, increased pumps and drainage would likely increase salinity to the shallow rooting zone of crops. Ebey Island, DD2, and DD4 will experience increased groundwater ponding from RSLR, but saline groundwater intrusion may not increase greatly with RSLR. However, since shallow well data at Smith Island (SW-09) showed salinities near thresholds for some crops (2 mS/cm), any increase in pumping and drainage to address groundwater pumping risks “tipping the system” into a range of groundwater salinities with deleterious crop effects. Future improvements to pumps and drainage systems must consider both increased groundwater and salinity intrusion effects from rising sea levels.



Well tapping an unconfined (water-table) aquifer under conditions of equilibrium--no intrusion has occurred.

The same well under conditions of intensive pumping--intrusion has reached the well.

Figure 9-1 Increased pumping and drainage may cause further diffusion of salty groundwater upward (pink arrow at right) toward the rooting zone of crops (Source: Thomas et al. 1997).

Although methods exist for managing soil salinity, the most common approach will have little applicability here: “The first requirement for managing soil salinity is adequate drainage, either natural or man-made” such that farmers can “remove salts by leaching with clean (low salt) water” (Kotuby-Amacher et al. 2000). As sea levels increase groundwater levels, however, leaching salt via flood or sprinkler-irrigation practices will become increasingly difficult. Flood irrigation currently practiced in spring for the Grasslands Farm site may continue to work well for maintaining low salt levels there, but this approach will not be practical for Ebey Island, DD2, or DD4 due to poor drainage and increased groundwater ponding from RSLR. Furthermore, DD2 managers (Carlton Farms) have confirmed that some ditches are already saline in later spring and summer months, and so even these surface waters cannot be used for irrigation (personal communication, from Darren Carlton to Dan Elefant, Cardno, and Cindy Ditbrenner, SCD, February 20, 2019).

A focused data collection effort to evaluate the degree to which salinity already affects crop yields in the region would be an important next step. Cardno recommends that SCD and farm stakeholders undertake remote-sensing crop yield studies to verify whether and to what extent groundwater salinity may already impact crops.

The interplay of RSLR, groundwater, and surface water management for the lower Stillaguamish and Snohomish River basins is complex, and many uncertainties remain that have not been resolved by this or prior studies. For example, the *Saltwater Impacts Study for Smith Island Restoration* speculated that that the inundation resulting from this project might

> "…reduce the salinity of withdrawals from the well because Union Slough water has lower salinity than water in the main stem." (Tetra Tech 2013)

However, it also acknowledged significant uncertainty in their understanding of the complex hydrogeology underlying the coastal region:

> "Sufficient data do not currently exist to determine whether upward groundwater migration occurs at the Smith Island project site. If upward groundwater migration does occur at the project site, implementation of the restoration project could increase the piezometric levels in the marine sands aquifer and hence the magnitude of any upward groundwater migration. This effect is not expected to be large, and could be accommodated in the drainage facilities for the adjacent agricultural lands. The salinity of increased upward groundwater migration would be reduced by implementation of the Smith Island project. This is shown through the groundwater modeling discussed … which indicated a freshening effect to the groundwater from increasing the groundwater recharge proportion from Union Slough versus the Snohomish River or potentially the City of Everett Water Pollution Control Facility ponds." (Tetra Tech 2013)

Similar complexities may well exist for Ebey Island, and so a more targeted analysis will be needed to support any future drainage or restoration considerations. Available data, however, already suggest that tidal restoration of farms that risk losing economic viability with RSLR could have far-reaching benefits to both salmon and society. Tidal restoration in the Ebey Island vicinity may mitigate for burgeoning water quality concerns from increases in the amount of sewage disposed through septic systems and increases in the use of chemicals for agricultural, commercial, and industrial activities (Thomas et al. 1997). Agricultural and ecosystem restoration and tribe stakeholders need not represent mutually exclusive interests—their landscapes can provide multiple functions with synergistic benefits.

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10 References

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APPENDIX

A

MAPS – SLR DELAY TO SPRING CROP CULTIVATION

Please Respect the Environment

About Cardno

Cardno is an ASX-200 professional infrastructure and environmental services company, with expertise in the development and improvement of physical and social infrastructure for communities around the world. Cardno's team includes leading professionals who plan, design, manage, and deliver sustainable projects and community programs. Cardno is an international company listed on the Australian Securities Exchange [ASX:CDD].

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