Surface Elevation Change Processes in the Snohomish River Estuary

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EXECUTIVE SUMMARY

Estuaries provide crucial ecosystem functions and contain significant socio-economic value. Within Washington State, estuaries supply rearing habitat for juvenile salmon during their transition period from freshwater to open sea. In order to properly manage wetland resources and restore salmon habitat, the mechanisms through which estuaries evolve and adapt to pressures from climate change, most notably eustatic sea level rise, must be understood. Estuaries maintain elevation relative to sea level rise through vertical accretion of sediment. This report investigates the processes that contribute to local surface elevation change in the Snohomish Estuary, conveys preliminary surface elevation change results from RTK GPS monitoring, and describes how surface elevation change will be monitored with a network of RSET-MH's.

Part of the tidal wetlands within the Snohomish River Estuary were converted for agricultural and industrial purposes in the 1800's, which resulted in subsidence of organic soils and loss of habitat. The Tulalip Tribes, the National Oceanic and Atmospheric Administration (NOAA), Northwest Indian Fisheries Commission (NWIFC), and the Environmental Protection Agency (EPA) are conducting a large-scale restoration project to improve ecosystem health and restore juvenile salmon habitat.

A study by Crooks et al. (2014) used ^{210}Pb and carbon densities within sediment cores to estimate wetland re-building capacities, sediment accretion rates, and carbon sequestration potential within the Snohomish Estuary. This report uses the aforementioned study in combination with research on crustal movement, tidal patterns, sediment supply, and sea level rise predictions in the Puget Sound to project how surface elevation will change in the Snohomish Estuary with respect to sea level rise.

Anthropogenic modification of the floodplain has reduced the quantity of vegetation and functional connectivity within the Snohomish Estuary. There have been losses up to 99% in vegetation coverage from historic extents within the estuary in both freshwater and mesohaline environments. Hydrographic monitoring

conducted by NOAA and the Tulalip Tribe shows that 85% of the historic wetland area is not connected to the main stem of the Snohomish (Jason Hall 2014, unpublished data, NOAA). As vegetation colonization and functional connectivity of the floodplains of the Snohomish estuary is re-established through passive and active restoration, sediment transport and accretion is expected to increase.

Under the Intergovernmental Panel on Climate Change (IPCC) "medium-probability" scenario sea level is projected to rise at a rate of 4.28 mm/year in the Puget Sound. Sea level rise in the Snohomish Estuary will be exacerbated from crustal deformation from subsidence and post-glacial rebound, which are measured to be -1.4 mm/year and -0.02 mm/year, respectively. Sediment accretion rates calculated by Crooks et al. (2014) and RTK GPS monitoring of surface elevation change of the Marysville Mitigation site from 2011-2014 measured vertical accretion rates that range from -48-19 mm/year and have high spatial variability. Sediment supply is estimated at 490 thousand tons/year, which may be an under-estimate because of the exclusion of tidal transport in this value. The higher rates of sediment accretion measured in the Snohomish Estuary suggest that the Snohomish will likely match or exceed the pace of sea level rise under "medium-probability" projections. The network of RSET-MH instruments will track surface elevation change within the estuary, and provide a more robust dataset on rates of surface elevation change to quantify how vertical accretion and subsidence are contributing to surface elevation change on a landscape scale.

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INTRODUCTION

Statement of purpose: In order to properly manage wetland resources and restore their vitality, the mechanisms through which they evolve must be understood. The survival of estuarine habitat and vegetation depends on the ability of wetlands to accrete sediment at a rate proportional to global sea level rise. The projected effects of climate change combined with anthropogenic modification from pre-settlement or historical condition of wetlands exacerbate the potential loss of wetland area relative to sea level rise. In the Puget Sound alone, it is estimated that tidal wetlands currently occupy 17-19 % of their historical extent (Collins and Sheikh 2005). Interactions between sea level, vertical land movement, sediment accretion, and primary production control surface elevation and maintain wetland acreage relative to water levels (Morris et al. 2002).

This report analyzes surface elevation change in a tidal estuary of Washington State by reviewing studies that describe the processes responsible for localized elevation change in Puget Sound estuaries and introduces how surface elevation change will be measured in the Snohomish Estuary. A study by Crooks et al. (2014) analyzed sediment accretion processes in the Snohomish estuary as a component of a project that investigated carbon storage capabilities in wetlands. A newly developed network of Rod Surface Elevation Table- Marker Horizon (RSET-MH) instruments will document spatial variation in surface elevation change in the Snohomish estuary. This report conveys sediment accretion rates from the Crooks et al. (2014) study and RTK GPS surface monitoring data to create an expectation for the dataset the RSET-MH's will collect.

Background: Estuaries provide crucial ecosystem functions and contain significant socio-economic value. They supply critical rearing and migration habitat for 75% of the U.S. commercial fish catch (Zackey et al. 2014). In Washington State, juvenile salmon use the brackish and low velocity side-channel slough and pool habitat within estuaries to adjust from freshwater riverine habitat to open ocean habitat. Estuaries create an erosional buffer zone between intercontinental land and open-oceans by dissipating water and energy from storm surges. Soft, unconsolidated soils and estuarine vegetation provide flood control and naturally filter contaminated upland run off.

Wetlands represent the largest component of the terrestrial biological carbon pool, therefore playing a fundamental role in global carbon cycles. The ability of estuarine wetlands to naturally sequester carbon has significant implications for global greenhouse gas management. Estuarine vegetation accumulates carbon within their biomass and eventually transfers carbon from biomass into long-term sediment storage. The wet and low oxygen soils in estuaries/wetlands are ideal for organic mass storage, and maintain the ability to store high volumes of carbon and nitrogen (Crooks et al. 2014). When wetlands are drained or converted for land use, accumulated carbon biomass is released to the atmosphere as carbon dioxide (Crooks et al. 2014). Pendleton et al. (2012) estimated that between 150 and 1020 million tons of CO_2 has been released into the atmosphere from the destruction of global wetlands.

In Puget Sound and the Snohomish Estuary, the potential for carbon sequestration and need to restore fish rearing habitat supports investments in wetland restoration. A study by Crooks et al. (2014) calculated soil carbon stocks and changes in carbon density from historical landscape conditions within the estuary. The study found the Snohomish estuary demonstrates a particularly strong capacity for high sediment accretion and carbon storage rates. The loss of rearing habitat has been identified as the primary limiting factor for the survival of the endangered Chinook salmon in Puget Sound (Zackey et al. 2014).

Sea level rise is predicted to increase three-fold over the next century, accelerating from 15 cm/century to 48 cm/century, which will initiate a global loss of estuarine wetlands and dramatically redefine wetland habitat zonation. From sea level rise projections alone wetland loss is estimated to be between 14-20% by 2080 (Nicholls 2004). A few centimeters of change in soil elevation results in large changes in flood quantity, quality, and frequency. Habitat communities have an optimum water depth tolerance, and will migrate inland to avoid prolonged submergence periods (Scavia et al. 2002). Prolonged submergence may also convert intertidal zones to permanent open water habitat (Scavia et al. 2002). Thus, quantifying processes controlling localized surface elevation change will enhance the accuracy of sea level rise predictions, and improve planning for restoration projects.

Surface elevation change in estuaries: Wetlands maintain their elevation by reaching equilibrium between sediment building capabilities and deteriorative processes, like tidal erosion (Reed 1995). This dynamic equilibrium requires sufficient sediment input and accumulation of organic matter to maintain the vertical height of the marsh surface relative to mean sea level (Stevenson et. al 1985; Cahoon et al. 1995). Organic and mineral materials vertically accrete above and within sediment surfaces on tidal flats (Reed 1995). Fluvial systems and tidal floods supply sediment and nutrients and encourage vegetation colonization.

Sufficient sediment input requires adequate sediment supply from inland sources, mainly rivers, and tidal transport from sediments of coastal origin. Estimating sediment supply budgets for estuarine systems is difficult because of the nature of riverine versus tidal transport processes, complexities in channel transport paths, and difference in timescales in fluvial and tidal sediment transport (subdaily for tides and multiweek high river flows) (Wright and Schoellhamer, 2004).

Tidal transport of sediments is particularly important in macro-tidal environments, where the tidal range difference is about 4.5 m. Studies on the macro-tidal Humber estuary on the coast of Northern England have been measured to contribute 98% of the total sediment supply compared to fluvial sources, with sediment loads that vary by an order of magnitude in response to tidal effects and river discharge (Christie et al. 1999). For at least part of the year, tides account for a greater fraction of energy that transports sediment than rivers (Wright 1977). In macro-tidal environments tidal velocities are higher velocities and of submergence is prolonged (Toublanc et al. 2013). Higher velocities create more transport per unit time, and may increase erosion on river beds, entraining and re-suspending more sediment (Strumpf 1983, Toublanc et al. 2013). The difference between maximum tidal currents and slack water between ebb and flood stages influences the flux of coarser suspended sediments and finer suspended sediments, respectively (Dronkers 1986). The period of slack asymmetry often creates a tidal “sediment trap” in estuaries that causes a net upstream transport of suspended sediment (Allen et al 1980). Sediment transport rate is highest during pronounced current and turbidity maxima at the flood tide stage in macro-tidal estuaries (Coleman and Wright, 1978; Allen et al., 1980; Toublanc et al., 2013). Dynamic surge events and interannual weather events impart additional variability in sediment supply to macro and meso-tidal environments, although limited data availability limits analyses on marsh sensitivity to such events (French and Reed 2001).

Plants augment sedimentation on intertidal marshes (Mudd et al. 2010). Marsh vegetation retains sediment through particle capture from the hydraulic effects of plant stems, attenuating the flow velocity of water to encourage particle settling, and contributing directly to organic sediment addition through root decay processes (Postma 1961; Strumpf 1983; Mudd et al. 2010). If marsh elevation is lower than optimum colonization elevation, increases in the depth and duration of flooding may lead to a decrease in plant productivity and in accretion rates (Mudd et al. 2010). Such principles explain the formation of levees along tidal creeks where particle settling is encouraged, explains low sedimentation rates observed on higher marshes that are removed from creeks, and encourages the succession of plant communities (Strumpf 1983).

The positive feedback cycle between sediment accretion rates and vegetation is useful tool in rebuilding sediment accretion processes in wetlands. Mudd et al. (2010) found an increase in sediment accretion rates of 2mm/year in fertilized sites compared to control sites in a South Carolina wetland. Organic matter from vegetation increases soil volume, contributes to soil strength from interlocking root networks, and is recognized as a key factor in vertical accretion (Nyman et al. 1990; Nyman and DeLaune, 1999; DeLaune and White, 2012). The emergent vegetation line, the elevation at which vegetation begins to colonize mudflats, represents a significant elevation for the surface building capacity of the marsh and in tracking variability in sediment accretion across estuaries (Nyman et al. 1990; Nyman and DeLaune, 1999; DeLaune and White, 2012; Crooks et al. 2014).

Subsidence, which may counteract vertical accretion, describes all processes that lower surface elevation. Shallow subsidence is subsidence measured relative to a subsurface datum, the depth of which is determined by the technique used to measure surface elevation change (Cahoon et al. 1995). Shallow subsidence processes include soil compaction and settlement, the shrink-swell of soils, organic decomposition in soils, and reduced sediment supply (Cahoon et al. 1995, Lane et al. 2006). Soil compaction has two primary mechanisms that are described as consolidation from liquid expulsion between soil pore spaces and compression as soil volume is reduced from an increase in applied stress (French 1996**).** Deeper subsidence processes occur below the subsurface datum, and generally include deeper compaction, isostatic, and tectonic activity like faulting, (Cahoon et al. 1995). Coseismic subsidence and postseismic uplift may also lower or raise the base level of estuarine rivers, shifting the extent of tidal reaches, as documented in an Oregon estuary (Kelsey et al. 1998). Anthropogenic modifications to floodplains have encouraged subsidence by altering sediment supply and increasing surface pressure on wetland soils.

The anthropogenic modification of floodplains has led to reduced sedimentation. The filling and diking of wetlands fragments transport channels and disrupts the functional connectivity of estuarine systems by restricting sediment transport through deposition, hydraulic mixing, and pulsing events necessary for sediment delivery like overland flooding (Cahoon 1995). Fluvial systems are also often considered the most important source for mineral sediment (Hensel et al. 1999). Riverbank levees confine sediment to the river channels, preventing the supply of sediment to wetlands. Thus, the effect of human activities on estuarine response to sea level rise needs to be considered in wetland restoration planning efforts.

*Tracking elevation changes in estuaries***:** High spatial and temporal variability of sediment accretion in tidal marshes creates a need for site-specific data to accurately represent processes in models of tidal marsh sediment accretion (Simenstad and Thom 1996). Popular mapping techniques like airborne imagery, LiDAR, GPS technologies, and surveying may lack precision to accurately track surface elevation change in estuaries to millimeter scales appropriate to wetland surface elevation change (Webb et al. 2013). LiDAR also cannot penetrate water or vegetation, Woo et al. (2009) found error rates of +/- 15 cm when using LiDAR to measure surface elevation changes in tidal marshes. Soil compaction can affect the accuracy of topographic surveys, and benchmark instability and unconsolidated soils create laborious sampling conditions.

There are a few methods of measuring sedimentation at a localized spot over time. Sediment accumulation rate can be calculated from ^{210}Pb dating in sediment cores. Sediment poles show general sediment gain or loss through surface elevation changes relative to a fixed pole in the ground. Marker horizons show sediment accumulation, a thick marker material like feldspar is dispersed over an area and cored. GPS surveys are useful for measuring relative change in surface elevation in estuaries, although GPS data may not provide precision to the mm that is required for sufficient analysis of vertical accretion in estuaries. Enhanced satellite navigation systems used in conjunction with GPS systems like real time kinematic (RTK) systems enhance the precision of position data to within a centimeter level of accuracy,

The method of using dating horizons or radionuclide profiles may overestimate net accretion and neglect to include substrate compaction (French and Spencer 1993). The RSET-MH is a portable leveling device that measures relative sediment elevation change by providing quantitative measurements of both shallow subsidence and sediment accumulation. RTK-GPS surveys have generated preliminary data in the Snohomish Estuary to guide the development of a network of RSET-MH.

RSET-MH background: RSET-MH's measure surface elevation change, sediment accretion/erosion, and subsurface change with confidence intervals of +/- 1.3 mm when compared to global positioning data (Cahoon 2006). The source of the +/- 1.3 mm error was determined to be operator error through laboratory tests by Cahoon et al. (2006). The sedimentation-erosion table (SET) was originally developed by

Boumans and Day (1993) as a mechanical and portable device to measure elevation trends in estuaries at high resolutions. Cahoon et al. (1995) used the SET in conjunction with marker horizons (MH) to differentiate between what part of surface elevation change comes from subsidence or accretion. Donald Cahoon renamed the sedimentation-erosion table “the surface elevation table” (RSET-MH) and redesigned the RSET- MH to incorporate a benchmark pipe that incorporate a depth gradient and provide stable datum for data comparison. An illustration of the SET-MH is shown in Figure 2.

RSET-MH instrument design: RSET-MH’s use a platform for sampling. A benchmark rod is driven through the soil profile until resistance is met. The benchmark rod is constructed from several aluminum or stainless steel rods fashioned together, yielding a rod that typically measures 40” in length. Marker horizons are commonly feldspar or materials easily discerned from marsh sediment, and are established in each corner of the platform perimeter (Figure 2). The SET device is a portable horizontal arm attached at a fixed point to the benchmark to measure the distance to substrate surface using vertical pins. The mechanical arm spins around the benchmark in eight positions to provide subsamples within one RSET-MH station. Nine measuring pins on the arm measure distance to the marsh surface, and provide nine numbers as sub-sub samples within one subsample position. The pins are usually fiberglass, 1/4” or 3/16” in diameter, and 2.5-3.0 feet in length and held in place by badge clips. Marker horizons and RSET-MH readings are taken simultaneously.

STUDY SITE

Snohomish estuary: The Snohomish River basin is the second largest in the Puget Sound with an area of 4,807 km^2 (Haas and Collins 2001). The primary river drained by the Snohomish estuary is the Snohomish River, which is formed by the convergence of the Skykomish and Snoqualmie Rivers. The main channel of the Snohomish divides into distributaries and sloughs about 1.5 m above sea level

(Bourgeois and Johnson 2001). The town of Marysville is to the north of the estuary, and Everett lies to the south. A map of the estuary is shown in Figures 1.

As the Snohomish floodplain was settled in the late 1800's, wetlands were deforested, drained, diked, and converted to agricultural land (Collins et al. 2001). Agriculture is the major land use in the Snohomish Estuary. The secondary land uses are industry, municipal sewage treatment, waste disposal, and infrastructure, which constitute only 10% of the total land use. Prior to settlement, the Snohomish estuary included tidal wetland, mudflats, and side channel or backwater channel (slough) systems (Zackey et al. 2014). Today only 16% of the historic tidal wetland and 25% of the blind tidal sloughs remain (Haas and Collins 2001). Areas that have not been modified from their pre-settlement condition will herein be referred to as areas in their historic condition. The historic tidal wetland area is separated from the Snohomish River by seventy-one dikes (Zackey et al. 2014).

Vegetation in the Snohomish estuary includes emergent wetland, scrub/shrub wetland, forested wetland, scrub/shrub wetland, and unconsolidated shore (Figure 3) (Crooks et al. 2014). These vegetation types have decreased from their historic acreage on average by 85%, with the greatest vegetation type loss occurring in forested wetland at 95% (Jason Hall, NOAA, unpublished data, 2014).

Estuary salinity ranges from freshwater to polyhaline (over 18 ppt). The Snohomish estuary is a macrotidal environment with tidal fluctuations around 8 feet on average with a maximum range of 12 or 13 feet. NOAA operates regular tidal gauges. The estuary is home to several species of anadromous fish including the ESA-protected wild Chinook salmon and Steelhead.

Sediment supply to the Snohomish estuary is controlled by inland sources and tidal transport and was measured to be highly responsive to increases in water discharge by Nelson (1971). The modified maritime climate of the Snohomish River basin generally has heavy precipitation that peaks in November and December and declines in July and August. Streamflow and discharge are higher in the fall and decrease in the winter when precipitation falls as snow. Sediment discharge was measured by Nelson (1971) to increase with peak river flows from November to January and then in May or June during snowmelt. This follows suit with other west coast estuaries like the Sacramento- San Joaquin Delta where 82% of sediment supply and 85% of deposition occurred during wet seasons (Reed 2002).

Geologic setting of Snohomish River estuary: The modern landscape of the Puget Sound is largely a legacy of the Vashon stade of the Fraser glaciation, the most recent of several glaciations that shaped the region, and occurred between 15,000-20,000 calendar years BP (Booth 1994; Porter and Swanson, 1998). The Puget lobe, the southwesternmost extension of the Cordilleran Ice Sheet, depressed the Washington land surface. Subglacial water excavated deep linear troughs through the sediment transport of about 1000 km^3 of sediment (Booth 1994). Marine waters and lakes of the Puget Sound now occupy these troughs (Booth 1994).

The Snohomish River Estuary lies in an east-west trending glacial depression that drains the Cascade Range (Booth 1994; Collins and Montgomery, 2010). The estuary/river delta plain consists of horizontally to sub-horizontally bedded Quaternary alluvium of thickness ranging from 1-10 meters (Yount and Gower 1991). The estuary sediment contains discontinuous layers of organic silt, silt and clay, and clayey silt with intermittent lenses of fine-grained sand (Bourgeois and Johnson 2001). Everett and Marysville lie on top of thick unconsolidated Quaternary deposits containing till, outwash, and alluvium that are inferred to be greater than 30 m thick (Yount and Gower 1991). The unconsolidated soils of this region are susceptible to deformation from tectonic activity and display a paleo-seismic record of the active tectonics of the Puget Lowland region.

Tectonics: The active tectonics of the Puget Sound region creates vertical land movement that generates high spatial variance in surface elevation throughout the region. The Puget Lowland sits in a forearc of the North American plate over the Cascadia subduction zone. The Cascadia subduction zone is a complex plate margin, involving slip faulting on the Cascadia plate boundary, and deeper faulting (60km) that results from the oblique subduction of the Juan de Fuca plate, and shallow crustal faulting (Figure 5) (Bourgeois and Johnson 2001). The oblique subduction of the Juan de Fuca Plate and the northward migration of the North American forearc create crustal strain that accumulates in reverse faults and folds at shallow depths (Sherrod et al. 2008). Several E-W trending shallow crustal faults cross the Puget Lowland (Figure 5). Crustal faulting has produced notable changes in surface elevation, including an M>7 earthquake in 900 A.D. on the Seattle fault (Atwater 1999) that created an estimated 5.5 m of uplift (ten Brink et al. 2006). Crustal faulting and internal deformation actively compresses the Puget Lowland region in a north-south direction. The last great earthquake in the PNW (M>9) is estimated to have occurred about 300 years ago (Atwater 1987; Atwater 1992; Satake and Tanioka, 1996) current uplift rates have been estimated in studies from data spanning roughly over the past 100 years (Holdahl et al., 1989; Mitchell et al., 1994; Verdonck 2006). Active uplift in the western extent of the state on the Olympic Peninsula and subsidence in the Puget Sound vicinity is thus attributed to crustal deformation associated with loading between mega-thrust earthquakes (Verdonck 2006). The surface deformation is predominately controlled by coupling along plate interfaces and mirrors the direction of plate convergence (Verdonck 2006). Although there may have been post-seismic relaxation associated with the last mega-earthquake, deformation over the past 100 years is believed to be relatively constant (Verdonck 2006).

The Seattle Fault, Tacoma Fault, and South Whidbey Island Fault are shallow crustal faults that cross the Puget Lowland and create significant earthquake hazard for the Seattle area. The Seattle Fault is a shallow thrust fault system that runs underneath the greater Seattle region in an east-west direction trending parallel to Interstate-90 (Figure 5). The Seattle fault forms the border between the Seattle Basin and Seattle Uplift, the two main shortening blocks attributed to the PNW north-south shortening (Booth et al. 2004). There is evidence for a similar magnitude east-west trending fault passing through Tacoma, the Tacoma Fault Zone. The South Whidbey Island Fault trends northwest from the city of Everett, passing through the northeastern margin of the Port Townsend basin to the city of Victoria, British Columbia. The SWIF crosses three structural basins, including the Everett basin adjacent to the Snohomish Estuary, exhibiting complex tectonic movement likely to not be synchronous across all three basins (Sherrod et al. 2008). Studies

(Kelsey et al. 1994, Johnson et al. 1996) have documented evidence that the SWIF produced up to M7 earthquakes in the Quaternary. The SWIF is the closest known fault to the Snohomish estuary, 13 km to the southwest of the Snohomish River Delta (Johnson et al. 1996). Excavations across fault scarps and Whidbey Island coastal deformation suggest that four earthquakes have struck the SWIF since the last deglaciation (Johnson et al., 1996; Sherrod et al. 2008). Recurrence intervals are believed to vary widely, with the longest recurrence interval between 9200-8800 years and the shortest recurrence interval at 470 years (Sherrod et al. 2008). Kelsey et al. (2004) estimate the SWIF was last active around 3000 years ago, causing 1-2 m of uplift in coastal marshes directly north of a projected fault location of the SWIF.

Post-glacial rebound: Isostatic rebound generally occurred in a south-north pattern in the Puget Lowland and radiocarbon dating of uplifted marine facies in coastal Washington and British Columbia suggest that post glacial field uplift was essentially complete 8,000 years ago (Thorson 1981; Clague et al., 1983; Thorson 1989), but varied in rate across the Puget Lowland according to the timing of local de-glaciation (Booth et al. 2003). The Puget lobe reached its southernmost extent near the city of Olympia, isostatically depressing the area to the north up to an estimated 300 m (Booth et al. 2003). As the Puget lobe retreated, glacial lakes that were dammed to the north were drained, and marine waters entered the Puget Sound. The release of pressure from draining water encouraged rapid postglacial rebound (Booth et al. 2003). Low mantle viscosities in the region also contributed to nearly complete post glacial uplift by the early Holocene (Clague et al. 1983, Booth et al. 2003). The shorelines of proglacial lakes record crustal tilt, which were compared to present day shorelines tilts, to yield a range of values of isostatic rebound. Isostatic rebound occurred at a S-N tilt that ranges from 0.85 m/km in the Southern Puget Lowland to 1.15 m/km in the Northern Puget Lowland (Thorson 1989; James et al. 2000). The S-N variance in rebound rate resulted in general land emergence in the north where rebound was the greatest, and submergence in the south (Thorson 1989). Present day isostatic rebound rates have been estimated in the vicinity of the Snohomish Estuary to be -0.02 mm/year (James et al. 2000).

Snohomish estuary restoration project: The Tulalip Tribes, National Oceanic and Atmospheric Administration (NOAA), Northwest Indian Fisheries Commission (NWIFC), and the Environmental Protection Agency (EPA) are collaborating on a long-term restoration project on the Snohomish River Estuary to recover salmon rearing habitat and restore environmental quality. The Snohomish estuary contains 1200 acres of restored wetlands or areas designated for restoration actions (Zackey et al. 2014).

The project includes sites of pristine or historic condition, and sites of active and passive restoration. In the Snohomish River Estuary active restoration includes dike breaching and setting levees back to increase land availability for the inland migration of intertidal wetlands. Management actions that promote or encourage natural recovery are referred to as passive restoration acts, such as protecting the naturally breached dike on Blue Heron Slough (Figure 1,4) and pristine areas of wilderness. Table 1 lists site names and stage of restoration for each site within the restoration project.

Monitoring is being conducted to track effectiveness of restoration projects and landscape changes as the estuary recovers back to tidal wetland conditions. Active monitoring efforts include fish sampling, hydrologic data collection, and establishing a network of RSET-MH's to measure sediment accretion and subsidence. Data collection occurs on a bi-weekly basis between June and September, and switches to a monthly basis between October and December and is conducted by the agencies listed above (Figure 4).

A network of RSET-MH instruments is being installed in the Snohomish River Estuary. There are ten RSET-MH's and several marker horizons installed currently in the estuary (Figure 4). Six more RSET-MH's are slated for installation. Data will be integrated with tidal gauges to compare vertical land movement to sea level rise.

Expectations: Expectations for surface elevation change in the Snohomish estuary are based on rates of sediment accretion, isostatic rebound, subsidence, and sea level rise. Sites with higher carbon densities will have higher rates of sediment accretion from a direct increase in organic input to sediment volume. We can expect from principles established by Postma (1961) that sediment accretion rates will be lower on marsh areas with higher elevations, and that rates will be higher along leveed areas closest to tidal creeks. The Snohomish basin has a high tidal fluctuation range and channels that provide consistent sediment supply to facilitate sediment accretion and encourage vertical growth of the marsh. Restoration actions will re-establish connections between restoration sites and tidal creeks and encourage growth of marsh vegetation. With consistent sediment supply, the Snohomish estuary shows potential to maintain vertical accretion at a rate sufficient to maintain elevation relative to rates of sea level rise.

METHODS

Office review: I summarized research on sediment supply, sediment accretion rates, wetland ecogeomorphic relationships, and crustal movement in the Puget Sound. There have been similar studies on surface change and estuarine responses to sea level rise in the Puget Sound estuaries (Thom 1992, Thom 2002, Woo et al. 2011) yet only preliminary research has been done in the Snohomish Estuary.

Crooks et al. (2014) published a study that evaluates the carbon sequestration potential of restoring wetlands within the Snohomish Estuary. Sediment cores were taken in 12 sites (Figure 3). Carbon densities were measured in all 12 sites, and sediment accretion rates were measured in 5 out of 12 sites (Figure 3). Carbon densities were measured in the top 30 cm of sample cores and lead 210 was measured to date sediment. Excess ^{210}Pb activity was plotted against depth and the slope of the natural log was used as the rate of sediment accretion. Historic wetland acreage was compared against existing wetland acreage to estimate the volume of soil subsidence that resulted from the drainage of wetlands. Historic wetland acreage was calculated from digital elevation data through the Puget Sound LiDAR Consortium and public records that detail the historical elevations of wetlands from the University of Washington Puget Sound River History project. The volume of subsidence was combined with soil carbon density values to project carbon emission from wetland drainage. They calculated mineral accumulation within the top 30 cm of their sediment cores and measured the elevation at which emergent tidal marsh vegetation colonize tidal flat surfaces (Crooks et al. 2014). This study uses their findings and preliminary surface monitoring data to create a foundation for the comprehensive dataset the RSET-MH network will collect in the Snohomish.

Hydraulic mixing boundaries and vegetation communities within the Snohomish Estuary were mapped by Jason Hall of NOAA. He used ArcGIS, historic and current vegetation classifications, and mixohaline boundaries established through hydrologic monitoring to delineate salinity profile boundaries. The boundaries were used to evaluate loss of current tidal mixing area compared to historic tidal mixing extents. I calculated changes in vegetation coverage and communities from his classifications.

I used data from studies on the glacio-isostatic response of the Puget Sound to determine how post-glacial rebound contributes to vertical land movement and surface elevation change in the Snohomish Estuary. The glacio-isostatic response of the Puget Sound has been determined in a number of different studies based on observations (Matthews 1970, Clague 1982, Thorson 1989) and postglacial rebound models (James 2000, Clague and James 2002). Three proglacial lake shorelines in the Puget Sound were distorted by isostatic response and exhibit a warped tilt that creates a regressional slope. Marine records that correspond to the time of deglaciation were used to yield local uplift values that were contoured. The postglacial rebound model considers a fixed value for the low viscosity mantle, maximum ice sheet elevations, ice sheet decay processes, and a smaller grid scale than previous models.

I used the results from studies on rates of tectonic uplift in the Puget Sound vicinity to determine how active tectonics may effect surface elevation in the Snohomish Estuary. Tectonic uplift rates have been calculated in a number of studies (Holdahl 1989; Mitchell 1994; Verdonck 2006) using data from tidal gauges that spans up to 55 years in the Verdonck (2006) and repeated leveling surveys. Data from repeated leveling surveys yield land motion across a gradient while tidal gauges measure eustatic sea level rise rates. After factors like seasonal fluctuations are corrected for, the coupling of land movement and sea level rise data shows relative land uplift rates from crustal deformation.

Data and information on sediment supply are less readily available. There is a comprehensive report published in 1971 by Leonard Nelson, USGS that estimated the suspended sediment load into the Snohomish basin during the 1967 and 1968 water years. The streamflow during the 1967 water year was slightly above the 30-year average and the suspended sediment load of the Snohomish basin was measured to be extremely sensitive to increases in discharge, with a 300% increase in suspended sediment concentration from 1967-1968. The USGS investigation installed two suspended sediment sampling stations that collected daily data on the Snoqualmie and Skykomish Rivers. The suspended sediment load in the Snohomish mainstem was not measured directly because of the backwater effect from tides. Suspended sediment was also measured from 27 reconnaissance sites at the mouths of selected tributaries at varying intervals and during storm run-off periods of intensified discharge. I evaluated how representative these values may be for the Snohomish, considering the lack of information on suspended sediment loads from tidal transport. I used a percentage of sediment flux into marshes calculated by Eric Grossman et al. (2014) on the Nisqually River Delta and Skagit River to estimate the percent of sediment that may flux into marshes and the percentage of sediment that may be transported seaward. Although the estimated sediment budget and annual discharge for the Snohomish basin is four times that of the Nisqually basin, the work done by Grossman et al. (2014) is a comprehensive example of estuarine sedimentation processes in a restoring floodplain of the Puget Sound. It is important to note that the studies by Grossman et al. (2014) were conducted during the 2010-2011 water year, which was a low flow year and may underestimate suspended sediment loads from decreased discharge.

I summarized findings from studies on projected local rates of sea level rise in the vicinity of the Snohomish Estuary. Finlayson (2006) combined tidal data from NOAA tidal gauges and a summary water level and regional air pressure change records from Elliott Bay during 1983 to 2001 to analyze the response of water levels to from weather patterns in the Puget Sound. Projected sea level rises from the IPCC reports were used by Mote et al. (2008) from the University of Washington Climate Impacts Group to model local sea level rise predictions in the Puget Sound. Mote et al. (2008) combined SLR effects from atmospheric pressure, vertical land movement, and global SLR to produce localized SLR projections in Washington.

Scope of field work: I worked as a restoration technician on the monitoring component of the restoration project. I researched the implementation of RSET-MH networks in other large estuaries/tidal wetland areas in an attempt to identify the spatial design that would maximize the usability of RSET-MH data for different analyses, including ecological, geomorphological, and analyses of how the stage of recovery may affect sediment accretion. I contributed to the site selection process by researching the physical site parameters that provide the greatest potential diversity for data analysis, and applied them to the Snohomish Estuary sites.

Although six RSET-MH's were installed during the summer field season of 2014, we were not able to collect measurements from them because of technical difficulties. They were re-calibrated and base surface elevations were measured with real time kinematic (RTK) device in conjunction with GPS systems during the 2014 summer field season. RTK-GPS measurements of surface elevation change from 2011-2014 were taken along transects at the Marysville Mitigation perpendicular to the Ebey Slough by the monitoring team (Figure 6).

RSET-MH's in Snohomish Estuary: Six RSET's were installed in 2013, and four RSET-MH's were installed during the fall 2014 field season (Figure 4). Four SETs are in the Quilceda Marsh, two in the Marysville Mitigation site, and four in North Ebey Island. A map of the restoration sites with the original RSET-MH locations is shown in Figure 4. The monitoring plan anticipates the installation of six more RSET-MH's.

The sites selected for RSET-MH monitoring in the Snohomish represent a mix of land uses and vegetation to track how restoration stage affects surface elevation changes. The Marysville Mitigation site and North Ebey Island are recovering from diked farmland to tidal wetland. North Ebey Island is passively recovering from a dike on the island that was breached sometime between 1965 and 1970, but estimated to have occurred in 1968 (Zackey et al. 2014). A dike on the Marysville Mitigation site was breached in 1994 and is recovering from diked farmland to tidal wetland. The Quilceda Marsh is in its historic state.

Vegetation communities are variable across the three sites that contain RSET-MH's. North Ebey Island's vegetation is scrub/shrub and forested, dominated by cattail and bulrush tidal marsh. The eastern and southern wetland margins are dominated by scrub-shrub and forested habitat. The vegetation of North Ebey Island has been of particular interest for other studies (Tanner et. al 2002) because it is a large-scale wetland in a re-generating stage post-restoration. The Quilceda Marsh has an emergent herbaceous wetland, and the tidal marsh complexes within this site are considered to be some of the most pristine in the region, maintaining the ability to support rare plant species and high-quality native plant species (Crooks et al. 2014). The Marysville mitigation site is predominately scrub/shrub vegetation.

FINDINGS

Current sedimentation rates in the Snohomish: Surface elevations were surveyed in the Marysville Mitigation site with RTK GPS units from 2011-2014. Elevation change ranged from -49 mm to 19 mm (Table 3). Out of the 15 monitoring stations, 2/3rds showed accretion. The mean value was 2.13+/-15.44 mm/year, and the standard error is 3.75 with a confidence intervals that of from -5.22 to +9.48 mm/year. Considering that only 8 out of 17 data points fall within the confidence interval, or two standard errors from the mean, it is reasonable to state that the spatial variance of the surface monitoring results is too high for the sample mean to accurately represent the parametric mean of surface change rates occurring at the Marysville Mitigation site. Data points were taken in transects perpendicular to the Ebey Slough (Figure 6), and the transect locations were largely confined by standing water from tidal channels that cut through the Marysville Mitigation site. The preliminary results agree with expectations of positive feedback cycles between vegetation and vertical accretion. Surface elevation is accreting near established communities of vegetation and subsiding closer to the inlet channel where water could be actively eroding the substrate (Figure 6).

The results from Crooks et al (2014) found high variability in sediment accretion rates, calculated over 100 years using decay rates of ^{210}Pb from sediment cores (Figure 3). They reported accretion rates ranging from 1.8 mm/year to 16.1 mm/year, with the lowest rate occurring at Heron Point and the highest rate at North Ebey.

Mineral accumulation rates were highly variable between study sites at the same recovery stage in the Crooks et al. (2014) study. The highest rate of mineral accumulation was at North Ebey, 7585 g/m^{2}yr. The Quilceda Marsh and Heron Point sites are in their historic condition, yet their mineral accumulation rates were significantly different, at 2134 g/m^{2}yr and 484 g/m^{2}yr, respectively (Table 2). North Ebey had a lower carbon density than Quilceda Marsh and the Marysville Mitigation site at 0.022 gC/cm^3, 0.024 gC/cm^3, and 0.032 gC/cm^3, respectively.

Sediment supply: I found that the Nelson (1971) report is a robust representation of sediment supply into the basin. Based on this study, the estimated annual sediment load for the Snohomish Estuary at 490 thousand-tons per year and the annual discharge is 10,000 ft^3/s (Nelson 1971; Czuba et al., 2011). The Nelson (1971) report gives annual suspended sediment concentrations at 19 different stations within the Snohomish basin during peak, transitional, and low run-off seasons. The 1967 and 1968 water years had average to above average streamflow, in the 1967 year was slightly above the 30-year average. The report lacks inclusion of estimates for tidal transport of suspended sediment. Recent work by Grossman et al. (2014) produced an annual sediment budget for the Nisqually basin that closely agreed with a similar sediment budget Nelson produced in the 1970's for the Nisqually, suggesting that the sediment budget he calculated for the Snohomish could still be an accurate representation of sediment supply. Nelson (1971) hypothesizes that anthropogenic changes to sediment supply will be negligible because the high vegetation cover within the Snohomish acts as a protective cover. Anthropogenic modifications to the floodplain may have not affected sediment supply over the last four decades.

It is likely that the Snohomish has sufficient sediment supply for marsh rebuilding capabilities. Grossman et al. (2011, 2014) estimate in other Puget Sound deltas up to 24% of the suspended sediment load is lost, tidally transported, or deposited. Wise et al. (2007) estimate that the Snohomish delivers 889 tons of sediment per year to the Puget Sound, which represents 0.18% of the estimated annual sediment load of the Snohomish and suggests that a large percentage of the sediment load is deposited within the basin or "lost" through another depositional mechanism. Estimates from Grossman et al. (2011, 2014) of sediment deposition into estuarine marshes and for the sediment available for vertical accretion may not be representative for Snohomish estuary marshes. Grossman et al. (2011, 2014) found that in the Nisqually basin, the net flux of sediment into the marshes was 370 m^3/year. This value is only 0.37% of the annual sediment 100,000 m^3/year. Applying a 0.37% net flux of sediment to marshes in the Snohomish Estuary yields a value of 1813 m^3/year. Grossman et al. (2011, 2014) found sediment accretion rates much lower, 0.12 mm/year, than the majority of the sediment accretion rates found in studies in the Snohomish estuary. Thus, 0.37% probably underestimates the net flux of sediments from the Snohomish river basin into the marshes. This number is also likely to be a gross underestimate of annual sediment loads because of the lack of data on tidal transport of suspended sediment. In macro-tidal environments like the Snohomish, whose semi-diurnal tidal range extends over 4 m, tidal transport has been found to contribute up to 98% of the suspended sediment flux (Dronkers, 1986; Christie et al., 1999).

The extent of tidal flooding and mixing zones within the Snohomish estuary (Jason Hall, unpublished data, NOAA) is shown on Figure 7 The Snohomish River Estuary hosts a suite of estuarine, palustrine, mixed salinity values, and freshwater habitats. From this data I calculated estimated that 85% of the historic wetland area is not currently connected to the main river stem, which suggests that the majority of the wetland habitat has limited sediment supply. The wetland types that experience the most prolonged periods of tidal mixing are mesohaline (5-18 ppt) emergent, scrub/shrub, and forested. Freshwater habitats experience the least tidal mixing. Mesohaline environments within the Snohomish could demonstrate highest rates of vertical accretion because of their higher inundation frequency and duration, which will increase with additional acts of restoration. Restoration actions will increase tidal submergence and encourage sediment settling/deposition within the estuary.

Vegetation and landscape changes: The Snohomish estuary has experienced dramatic losses in vegetation coverage since the floodplain was settled in the late 1800's and wetlands were diked and drained to support agriculture. The biggest loss in vegetation coverage is in freshwater settings with a 99.2% loss of freshwater scrub/shrub habitat and 98.6% loss of forested freshwater habitat. There are large losses in mixohaline environments, with an 82.1% loss in scrub/shrub habitat, and a 95.04% loss in forested habitat. Crooks et al. (2014) report that from 1885-2006 within the Snohomish River Estuary there has been a 234 hectacre (ha) increase in open water habitat, a 5 ha increase in aquatic bed habitat, and a loss of 1687 ha of wetlands. They also report that 374 ha within the estuary have been developed and 897 ha have been converted for agricultural use.

Crooks et al. (2014) found high potential for carbon storage within the Snohomish Estuary. They found that carbon storage processes began at an elevation of 0.9 m, which is the elevation of emergent vegetation colonization. Most drained or modified estuarine sites have subsided relative to natural tidal wetland conditions (Crooks et al. 2014). They found estuarine emergent marshes form at an elevation of 2.0 m and forested riverine/ tidal wetland zones form at 2. 6 m. In general natural areas had higher elevations, restoring wetland areas had intermediate surface elevations, potential restoration sites had the lowest elevations, and most wetland areas were at an elevation about the emergent marsh vegetation line.

Crustal movement: The active tectonics of the Puget Sound have a more dominant contribution than post-glacial rebound in surface elevation change in the Puget Sound and Snohomish Estuary. Holdahl et al. (1989), Mitchell et al. (1984) assume that no significant postglacial rebound component affected their comprehensive study on tectonic uplift within the past 100 years in the Puget Sound region. Studies

(Verdonck et al. 2006, Mitchell et al. 1994, Holdahl et al. 1989) and ongoing GPS measurements by Central Washington University measured a spatial gradient of vertical land movement, with a subsidence rate of -2.4 mm/year in the southern Puget Sound near Tacoma and decreasing north of Seattle to -1.4 mm/year, which is the value most spatially appropriate for the Snohomish Estuary (Mitchell et al., 1994; Verdonck 2006). West of the zone of subsidence the Olympic Peninsula and Vancouver have measured uplift rates up to >4 mm/year (Mote et al. 2008). Low-viscosity mantle values, rapid post-glacial adjustment, and a post-glacial rebound model (James et al. 2000) suggest a postglacial rebound rate of 0.1 mm/year in northwestern Washington State that decreases in the southern Puget Sound to around -0.02 mm/year in the region around the Snohomish Estuary (James et al. 2000). The work of James et al. (2000) is consistent with the 0.85 m/km S-N gradient of post-glacial rebound.

Historical crustal displacements have produced abrupt changes in wetland surface elevation in the Puget Sound. Bourgeois and Johnson (2001) described stratigraphic evidence in the Snohomish Estuary for three episodes of liquefaction, one tsunami and one event of 750 mm subsidence within the last 2000 years. Within the stratigraphic sequence there is a tsunami-laid sand bed with intermittent sand volcanoes, and abrupt stratigraphic sequence changes that are interpreted as evidence for liquefaction. The relative recent timing of these events suggests that faulting could produce dramatic surface elevation change in the future of the Snohomish Estuary.

Sea level rise in Puget Sound: The strong effect of atmospheric forces on Washington sea levels is important to consider for localized forecasting of sea level rise, which could be exacerbated in the Snohomish Estuary (Finlayson 2006). During winter months, atmospheric pressure changes causing storm surges resulted in sea level changes between -400 mm and +600 mm. In spring and summer months, 99% of storm surges resulted in sea level changes between -300 and +300 mm. Finlayson (2006) observed that during El Nino winter months, sea level rose 100-200 mm. A Mote et al. (2008) study had higher estimates of seasonal sea level fluctuations, with a +500 mm winter sea level on Washington's coast and estuaries resulting from a coupling of prevalent northward winds and gravity.

The rate of sea level rise is projected to increase from rates calculated over the past century. NOAA has calculated a sea level rise rate of 1.98 mm/year in Seattle for the past 100 years from tidal records (Crooks et al. 2014). Sea level rise rates decreased slightly to a rate of 1.6 mm/year, north of Seattle near Everett for the same time period (Crooks et al. 2014). Mote et al. (2008) estimate that local sea level rise in Washington will closely match global average. SLR will have a reduced effect on the Washington Coast, where the rate of tectonic uplift is estimated to be 2-3 mm/year. The study reports a low estimate, medium estimate, and high estimate to correspond with the categories of SLR probabilities in the IPCC reports. Under very low SLR estimates, that assume no subsidence in the Puget Sound, there is 80 mm sea level rise projected by 2050, and 160 mm by 2100. Under the medium SLR estimate, again assuming no local subsidence, the Puget Sound SLR estimate is 150 mm by 2050 and 340 mm by 2100. Under the very high SLR estimate, assuming -2mm/year subsidence, there is a 550 mm SLR in Puget Sound by 2050 and 1280 mm by 2100.

Carbon sequestration in Snohomish Estuary: Crooks et al. (2014) measured carbon sequestration rates across 12 sites in the Snohomish. Current carbon storage capacity of restoring sites and projections of potential carbon storage rates of restoring sites were examined under several different IPCC sea level rise scenarios. Crooks et al. (2014) added one meter to the current elevation of the mean high higher water mark (MHHW), referring to the highest water mark at the highest tidal inundation stage, to correspond with a potential future MHHW under an IPCC "high-probability" sea level rise projection. This projection predicts a sea level rise of one meter by 2100, thus the MHHW projection is 3.76 m. They assumed historic wetland surface elevations of 2.76 m for emergent and scrub/shrub wetlands and 3.5 m for forested wetlands. A soil carbon density value of 0.025tC/m^3, calculated from field analyses, was used in conjunction with a calculated historic subsidence volume of 67.7 Mm^3 to estimate that estuarine soils in the Snohomish River Estuary have released 1.7MtC through drainage. They hypothesize that if the 4, 393 ha of marsh within the estuary was restored, and current carbon levels from in-situ plants were maintained, rebuilding marshes would sequester 1.2 MtC . There are planned restoration actions for 1,353 ha of land that should sequester 0.32 MtC. Crooks et al. 2014 calculated a marsh rebuilding rate of 16 mm/year from rates of sediment accumulation, mineral accumulation, and carbon density. This suggests that the Snohomish estuary wetlands will maintain elevation at pace with sea level rise even at the upper limit of global sea level rise predictions (Crooks et al. 2014).

SUMMARY

Sedimentation in the Snohomish River Estuary: Crooks et al. (2014) analyzed sediment accretion, mineral, and carbon accumulation rates pre and post restoration to correlate changes in land use with changes in surface elevation processes. Crooks et al. (2014) found no discrete trend between sediment, mineral, and carbon accumulation rates and restoration stage. North Ebey Island had a low carbon density value and the highest rate of sediment and mineral accumulation rate. The natural susceptibility to a high rate of sediment accretion indicates that North Ebey has a high potential for restoration.

The results from Crooks et al. (2014) and the high spatial variance in sediment accretion rates found through RTK GPS monitoring agree with spatial expectations for sediment accretion. The high sediment accretion rates on North Ebey Island are likely a result of its direct location on the Ebey Slough, which provides consistent sediment supply. In the Marysville Mitigation site, survey points closest to small tidal channels and vegetation communities, which create positive feedback cycles for sedimentation, (Figure 6) are showing vertical accretion and survey points farther from tidal inlets and vegetation are showing subsidence. The RSET-MH network will provide a more accurate quantitative representation of sedimentation within individual study sites.

With the tremendous acreage available for emergent vegetation growth and restoration projects slated it is reasonable to expect that increasing biomass through fertilization will increase sediment accretion rates. Although 98% of historically forested wetlands in the Snohomish Estuary have subsided, 58% of subsided lands lie above the elevation suitable for wetland re-colonization of emergent vegetation at 0.9 m (Crooks et al. 2014). The elevations of study sites that are in their historic conditions were higher than recovering sites, indicating their stability relative to fluctuations in sea level rise. Morris et al. (2002) also demonstrated a positive correlation between vegetation productivity and surface elevation change, high primary productivity increased surface elevation gain compared to non-vegetated controls. Mudd et al. (2010) used compressed carbon bulk density and known organic decay rates to estimate the volume of carbon that contributes to sediment accumulation, and found that 800 kg/m^3 of carbon in their study contributed around 2 mm/year to sediment accumulation rates. The low carbon density (0.00) in the Snohomish estuary and high losses of vegetation cover supports restoration investments in the Snohomish Estuary to encourage marsh re-building capacities.

Sediment supply data may significantly underestimate sediment supply because it does not include tidal transport, but it seems that the basin has adequate sediment supply to maintain vertical accretion rates relative to rates of sea level rise. From estimates on sediment transport in other rivers of the Puget Sound, and the sediment delivery of the Snohomish estuary to the Puget Sound by Grossman et al. (2011, 2014) and Wise et al. (2007), I estimate that 0.18-24% of the sediment from the Snohomish basin is transported and deposited in the Sound. This implies that a high percentage of sediment is retained within the Snohomish estuary. The 85% of tidal wetlands that are disconnected from the main stem of the floodplain suggests that with restoration encouraging functional connectivity, sediment supply and transport will increase. The macro-tidal nature of the Snohomish estuary necessitates data on the turbidity and suspended sediment concentration imported by tides to sufficiently gauge an annual sediment supply load and to partition deposition of sediment, especially considering that in other macro-tidal estuaries up to 98% of suspended sediment load was transported from tides (Christie et al. 1999).

Future expectations: Subsidence will exacerbate sea level rise in the Snohomish Estuary. Crustal deformation in the Pacific Northwest is the largest contributor to subsidence in the vicinity of the Snohomish Estuary, with at a rate of -1.4 mm/year (Mitchel et al. 1994, Verdonck 1995, Verdonck 2006), and deformation associated with post glacial rebound contributes -0.02 mm/year (James et al. 2000). The RSET-MH data will provide localized subsidence rates to improve surface elevation modeling in the Snohomish. In general, crustal deformation and elastic strain have been documented to produce abrupt surface changes in the Snohomish, and have a history that provides reason to expect similar tectonic events in the future.

With restored hydraulic connectivity and sediment supply, the Snohomish Estuary demonstrates a strong capacity for wetland rebuilding at a pace that will likely match or exceed projected sea level rise rates. Marsh rebuilding rates calculated by Crooks et al. (2014) and results from RTK GPS monitoring illustrated that the Snohomish exhibits some rates of sediment accretion sufficient to keep pace with rates of sea level rise. According to predictions from the Mote et al. (2008) study and the University of Washington climate impacts group, under a low – scenario sea level rise projection sea level rise rate is 2.28 mm/year, under a medium projection 4.28 mm/year, and under high-end prediction is 15.7 mm/year. The 2 mm/year subsidence rates in the Puget Sound are incorporated into the highest sea level rise scenario. Although there has not been enough data and data is too spatially variable to establish a good approximation for an estuary wide rate of vertical accretion, Crooks et al. (2014) reports marsh rebuilding rates 16 mm/year and RTK GPS monitoring found more positive accretion values than subsidence. The highest values of surface change values found through RTK GPS monitoring will exceed high-end predictions of sea level rise, and about 2/3rds of the values will exceed medium scenario predictions. High spatial variability in site-specific data and data among sites indicates that it may be more accurate to analyze accretion on a site scale rather than on an estuary-wide scale. The RSET-MH's network will provide a robust enough dataset to establish a better range or singular value for estuary averaged accretion rates. The RSET-MH data will eventually be integrated with tidal history to derive vertical land movement on an estuarine-landscape scale.

Tremendous improvements in such data will enhance predictions of estuary surface change in the Snohomish Estuary.

Future study suggestions: Freshwater marsh accretion dynamics are less understood than accretion dynamics in salt-water marshes. Tracking surface elevation changes within fresh and salt-water marshes in the Snohomish Estuary will offer data for future investigations into the effect of salinity on accretion processes. A comprehensive study on sediment supply loads from tidal transport is needed to improve sediment budgets for the Snohomish basin. Increasing the number of marker horizons in the estuary, and collecting seasonal measurements of vertical accretion from the marker horizons in accordance with project monitoring, will provide insight into seasonal sediment accretion fluctuations and surface elevation changes. Taking additional sediment core samples within the Snohomish estuary is an alternative to installing more RSET-MH's, which can be expensive and cumbersome to install. In general, installing more marker horizons and collecting more sediment cores, particularly in study sites at different stages of recovery, will improve understanding of the effect of restoration on different wetland environments and wetland rebuilding rates.

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FIGURES

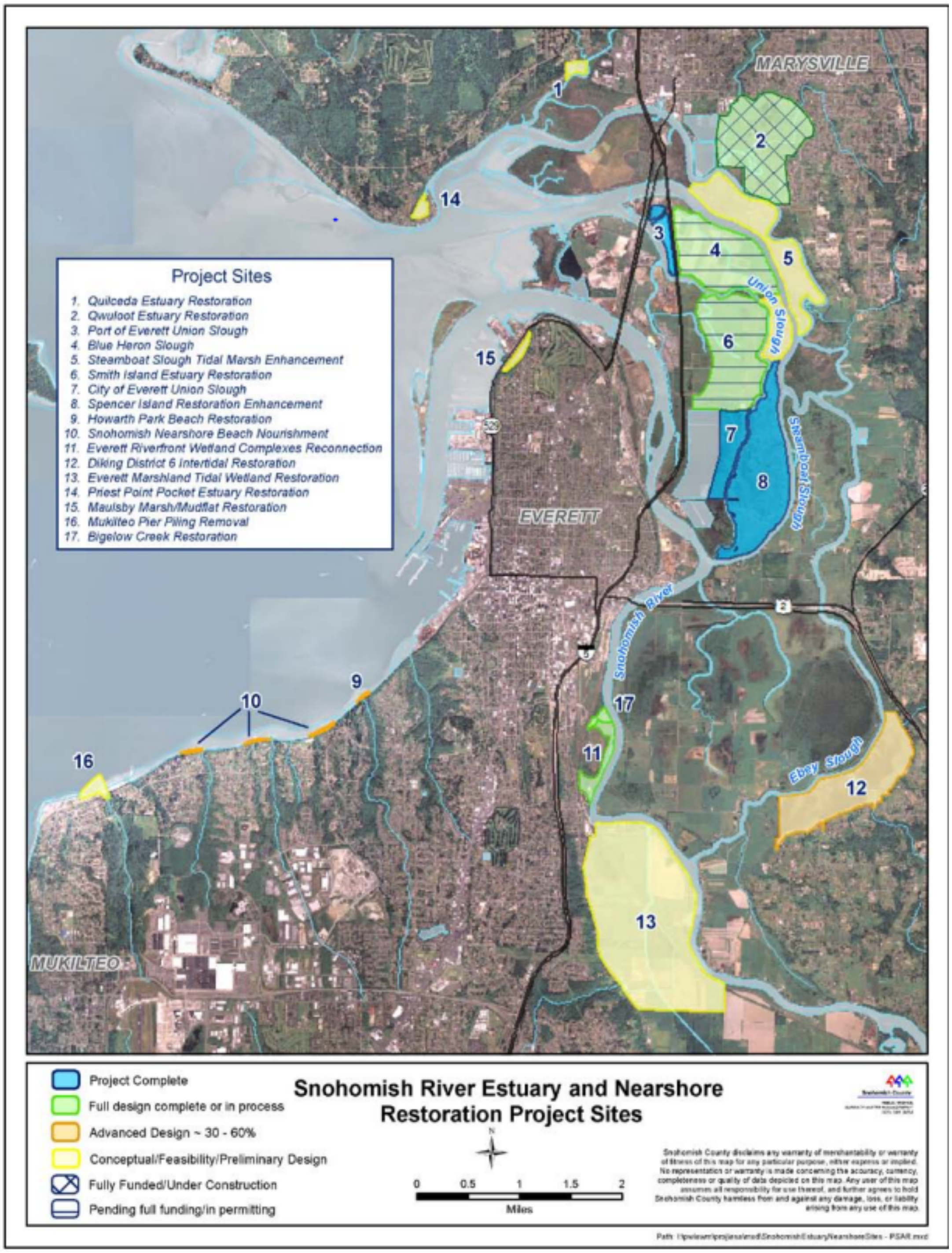

Figure 1: Map of the Snohomish River Estuary with restoration sites identifiable through the legend (Snohomish County, 2013; Zackey et al. 2014).

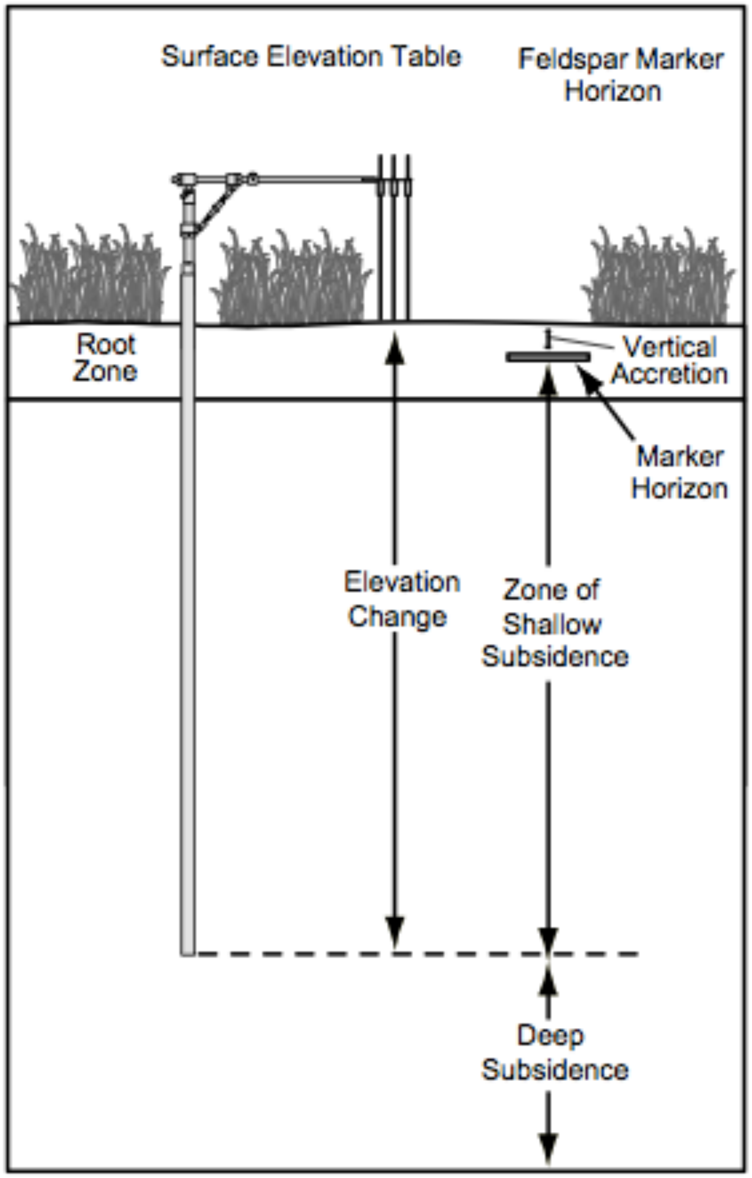

Figure 2- Illustration of the SET-MH, shows the basic design and depicts how the subsurface is measured. Source: Cahoon et al. (2006).

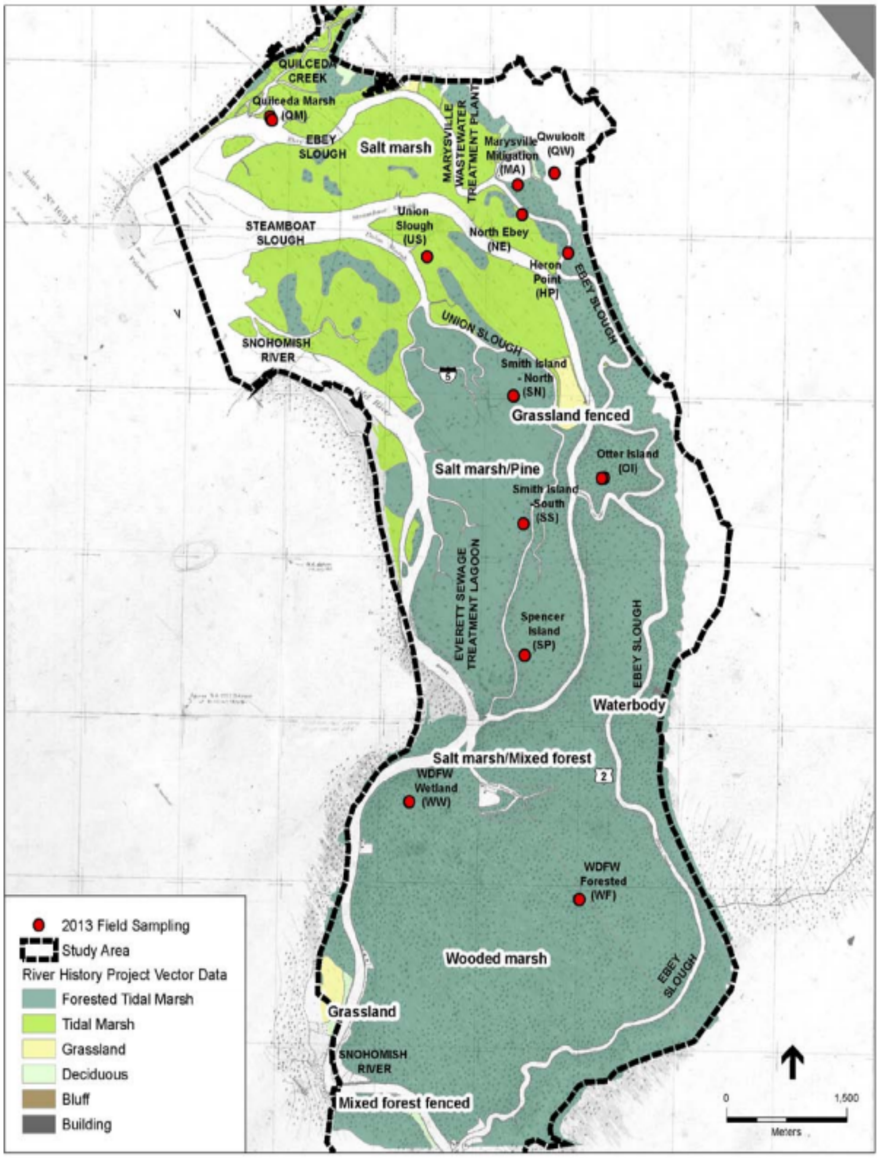

Figure 3: Historic Lower Snohomish River Estuary classified by habitat (Crooks et al. 2014). The sample sites for the Crooks et al. (2014) study are marked in red. Data from Haas and Collins 2001.

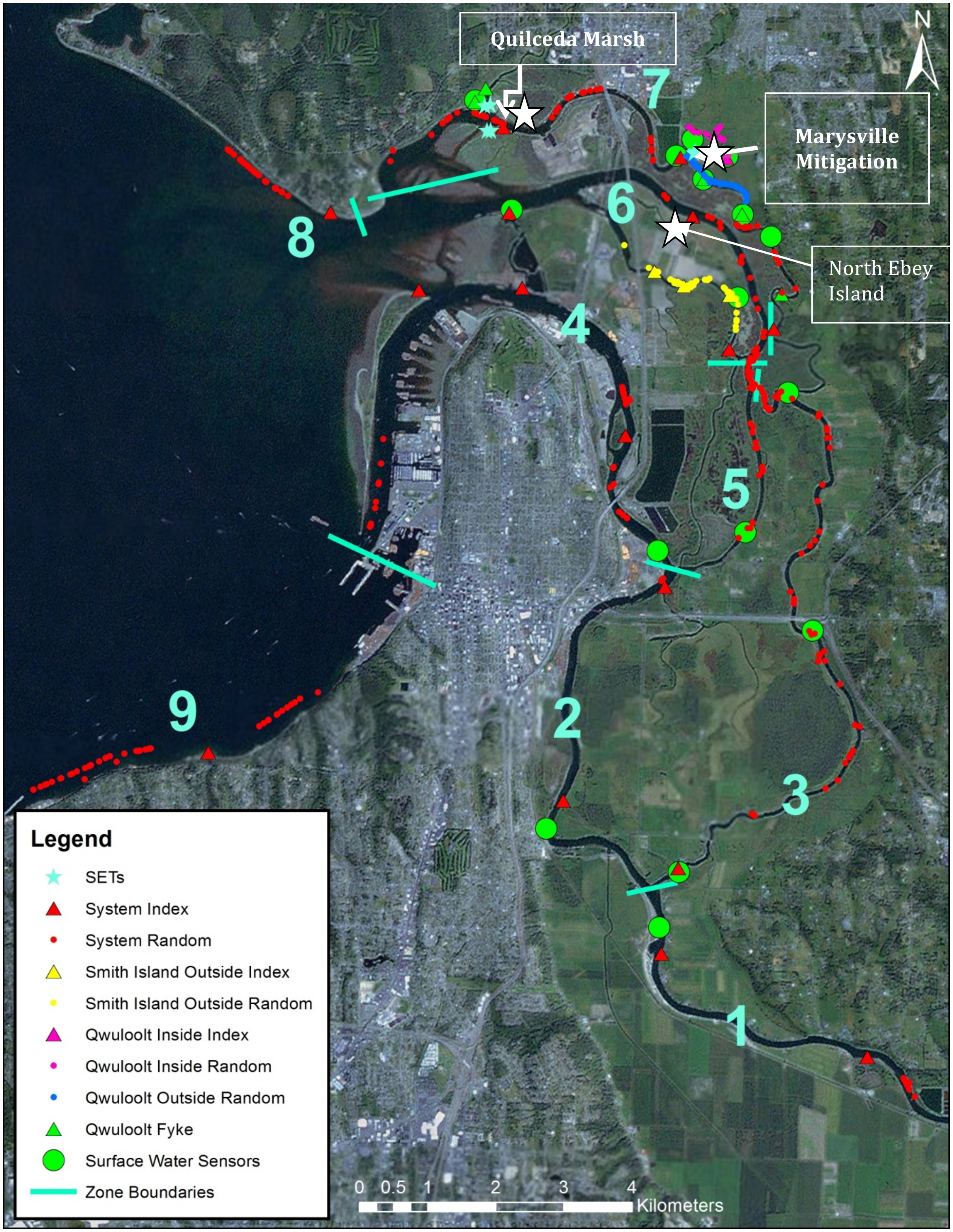

Figure 4: Map showing location of RSET-MH's and major monitoring sites for Snohomish Estuary Restoration Project. RSET-MH's are denoted by white stars. (Zackey et al. 2014).

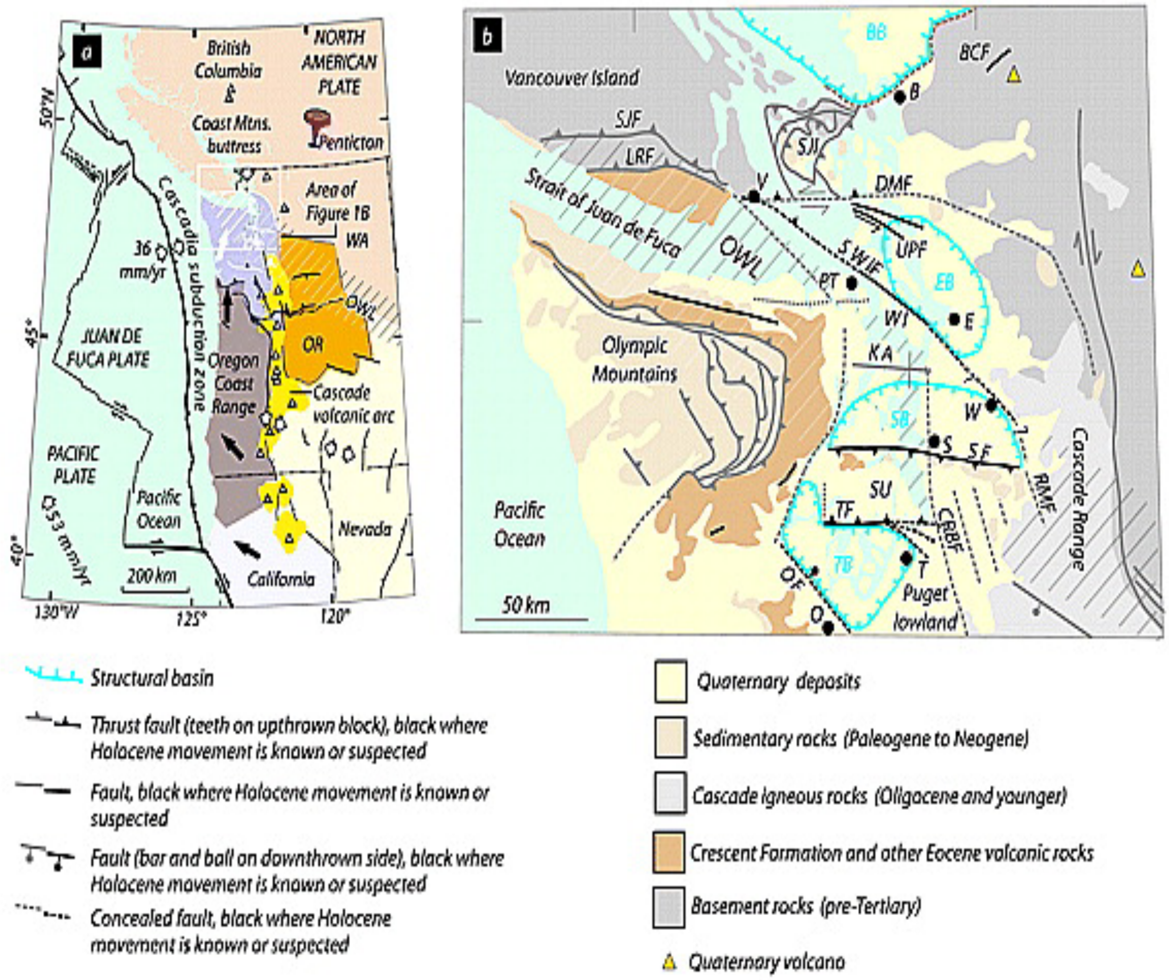

Figure 5 a) Kinematic model of Cascadia forearc (Sherrod et al. 2008), simplified from Wells et al. (1998) and Wells and Simpson (2001) b) Generalized map of Puget Lowland faults. (Sherrod et al. 2008, Brocher et al. 2001) BB, Bellingham basin; EB, Everett basin; KA, Kingston arch; SB, Seattle basin; SU, Seattle uplift; TB, Tacoma basin; BCF, Boulder Creek fault; CRBF, Coast Range boundary fault; DMF, Devils Mountain fault; LRF, Leech River fault; OF, Olympia fault; RMF, Rattlesnake Mountain fault; SJF, San Juan fault; SWIF, southern Whidbey Island fault; SF, Seattle fault; TF, Tacoma fault; UPF, Utsalady Point fault; B, Bellingham; E, Everett; O, Olympia; PT, Port Townsend; S, Seattle; T, Tacoma; V, Victoria; W, Woodinville; SJI, San Juan Islands; WI, Whidbey Island

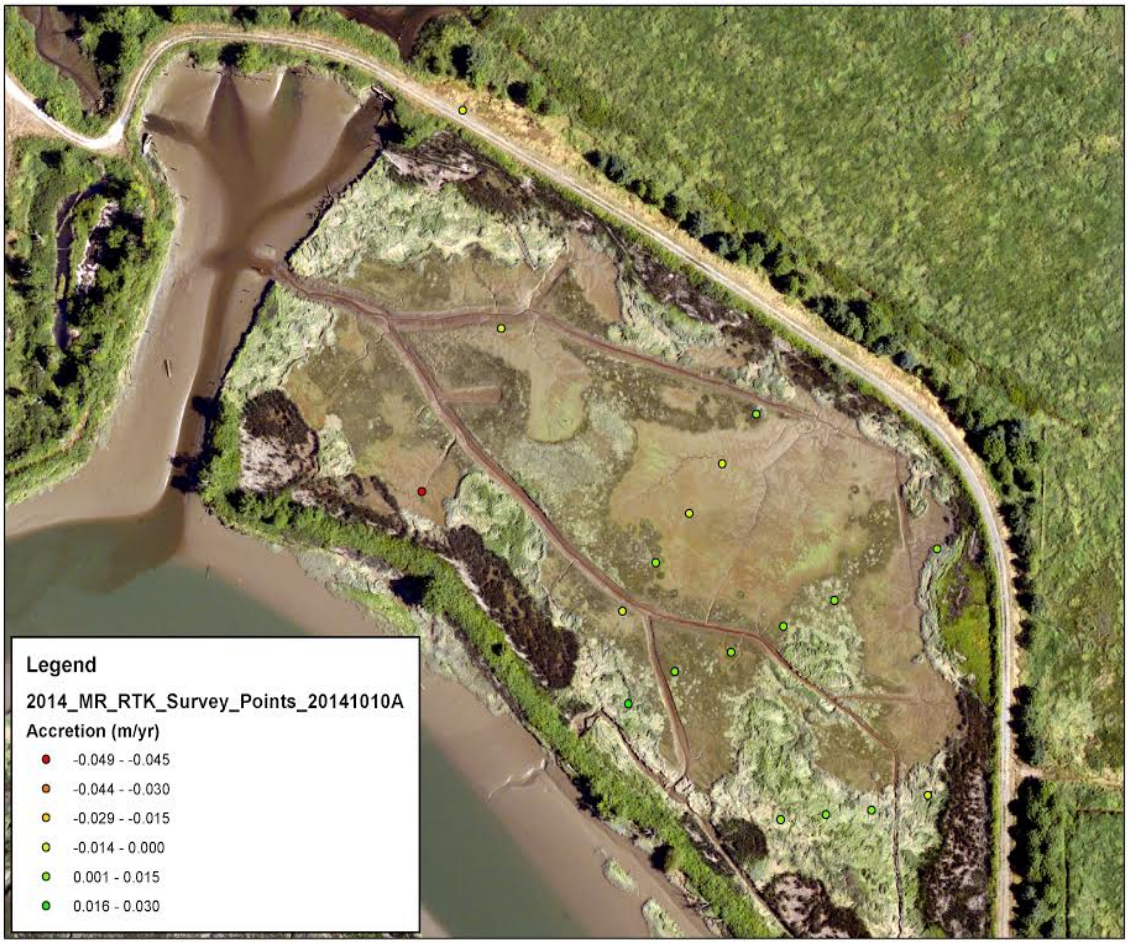

Figure 6: Map of accretion rates, reported in m/year, from RTK-GPS survey (2011-2014) in the Marysville Mitigation site Image: Jason Hall, NOAA.

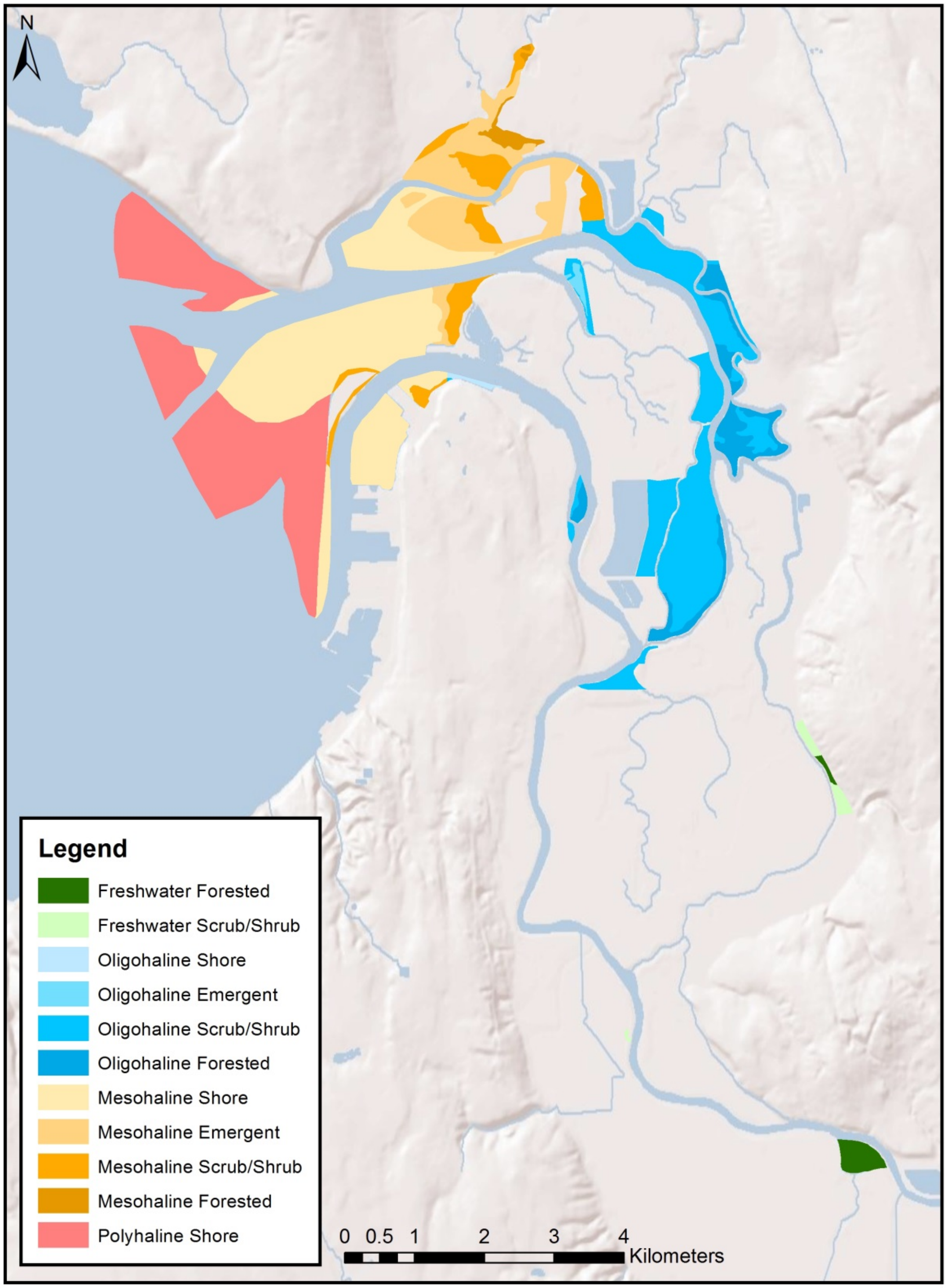

Figure 7: Current tidal flooding extent classified by mixohaline/salinity zones. The salinity values in the legend correspond to the follow numerical values: polyhaline (18 – 30 ppt), mesohaline (5 – 18 ppt), oligohaline (0.5 – 5 ppt), and freshwater (0 – 0.5 ppt) and current vegetation type. (Jason Hall and Casimir Rice, NOAA 2014 unpublished data)

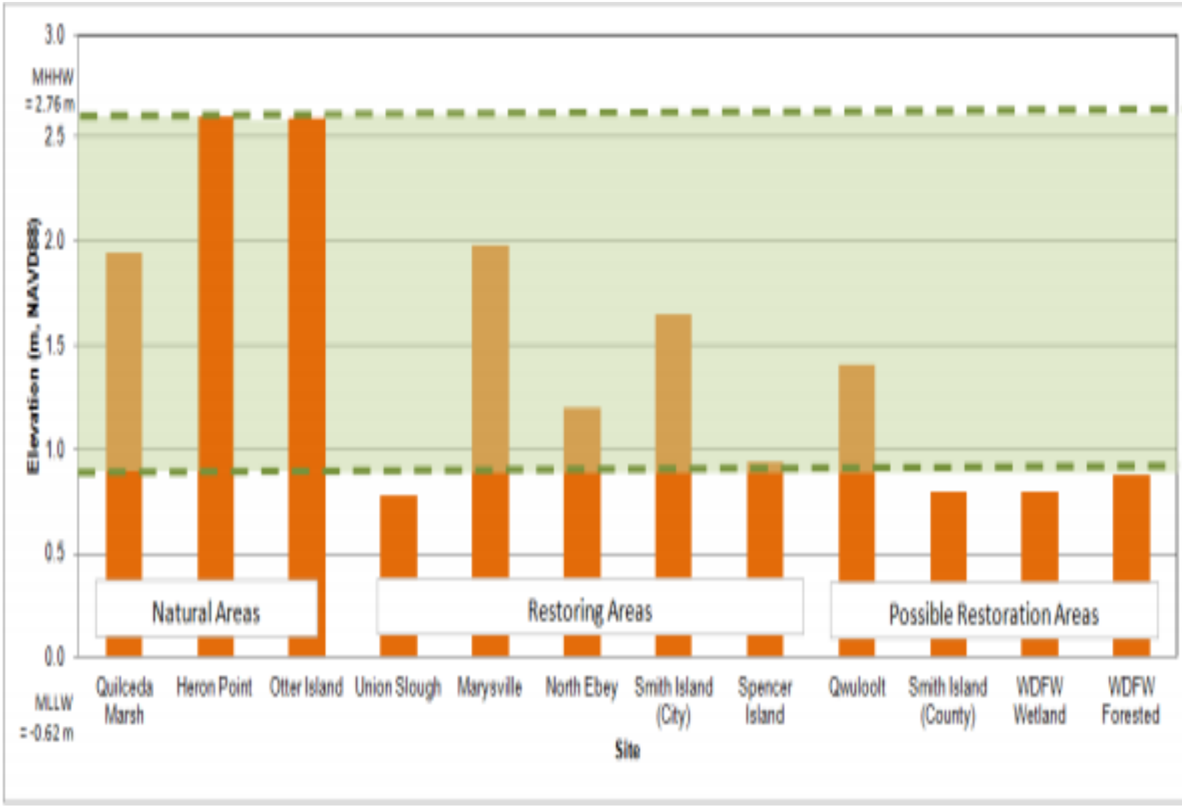

Figure 8: Existing elevation of sites is represented by orange bars. The first dotted green line at 0.9 m represents the elevation at which emergent vegetation can colonize mudflats. The second, higher green dotted bay at 2.76 m represents the line that tidal wetlands will be able to maintain their elevation relative to sea level rise under a medium-scenario of sea level rise as projected by the IPCC. Units are in m. (Crooks et al. 2014).

TABLES

Site Name	Stage of Restoration	Wetland type
Quilceda Marsh	Historic	Emergent herbaceous
Heron Point	Historic	Forested
Otter Island	Historic	Forested and emergent herbaceous
North Ebey Island	Restoring	Mixed herbaceous
Spencer Island	Restoring	Mixed
Marysville Mitigation	Restoring	Tidal
Union Slough	Restoring	Tidal/mudflats
Smith Island-City	Restoring	Tidal
Qwuloolt	Scheduled to restore	Drained wetland/agriculture
Smith Island County	Scheduled to restore	Drained wetland/agriculture
Blue Heron Slough	Scheduled to restore	Grassland
Quilceda Estuary	Design stage	Emergent tidal
Everett Marshland	Proposal stage	Drained/agriculture

Table 1: Restoration site name and corresponding restoration stage within the Snohomish Estuary

Site	Site Name	Sediment accretion rate (cm yr^{-1})	Carbon accumulation rate (g C m^{-2} yr^{-1})	Mineral accumulation rate (g m^{-2} yr^{-1})
QM	Quilceda Marsh	0.43	110.2	2134
HP	Heron Point	0.18	58.0	484
OI	Otter Island	0.58	173.1	2543
NE	North Ebey	1.61	352.1	7585
SP	Spencer Island	0.35	91.4	2148

Table 2: Results of Crooks et al. (2014) calculations of rates of sediment accretion, carbon accumulation, and mineral accumulation for five sites, labeled on Figure 2. Table sourced from Crooks et al. 2014.

Location ID	Sediment Accretion Rate (mm/year)
tran001	-48.90
tran015	-10.69
tran017	-10.01
tran002	-9.52
tran014	-0.89
tran009	-0.35
tran007	4.22
tran011	5.30
tran016	7.04
tran010	8.44
tran012	8.65
tran008	9.45
tran005	12.60
tran013	13.38
tran004	14.05
tran006	14.35
tran003	19.03

Table 3: Sediment accretion rates from RTK-GPS surveying in the Marysville Mitigation site in 2011-2014, taken by NOAA, reported by Jason Hall. Transect positions not specified, but general transects position are labeled on Figure 6.