MODELING GEOMORPHIC EFFECTS ON EELGRASS BEFORE AND AFTER RESTORATION, NISQUALLY DELTA, WASHINGTON

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by

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San Francisco, California

May 2012

CERTIFICATION OF APPROVAL

I certify that I have read *Modeling Geomorphic Effects on Eelgrass Before and After Restoration, Nisqually Delta, Washington* by Anna Elizabeth Davenport, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Geography: Resource Management and Environmental Planning at San Francisco State University.

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MODELING GEOMORPHIC EFFECTS ON EELGRASS

BEFORE AND AFTER RESTORATION, NISQUALLY DELTA, WASHINGTON

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Investigating native eelgrass (*Zostera marina*) distribution before and after a dike removal and estuary restoration in the Nisqually Delta, South Puget Sound, Washington, USA, through a comparison of mapping methods, provides a visible measure of geomorphic effects. Research aims were to use two mapping methods, image classification and digitization, to compare accuracy and efficiency at determining change in eelgrass distribution over time as a result of the 2009 Nisqually Delta dike removal and estuary restoration. Substrate analyses were used to show change before and after dike removal. Results found that supervised classifications of 2009, 2010, and 2011 false color near infrared aerial imagery of the tidal flats underestimated eelgrass presence while digitizations of dense eelgrass beds using a 30 meter minimum mapping unit overestimated eelgrass distribution. Central to the results of both mapping methods was that both the classification and the imagery were sensitive to eelgrass exposure at low tide. Because the IR band does not penetrate through water there was high absorption even at shallow depths. Varying amounts of eelgrass were detected by the imagery dependent on the tides when the imagery was taken, leading to inconsistency in determining eelgrass areal extent over time. Assessing changes in the distribution of eelgrass through these methods helps us to better understand how dike removal can affect important tidal wetland habitat, and findings may inform methods for eelgrass mapping and for monitoring eelgrass distribution over time.

I certify that the Abstract is a correct representation of the content of this thesis.

Chair, Thesis Committee Date

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INTRODUCTION

Native eelgrass, *Zostera marina*, like many seagrasses, is an important contributor to ecosystem services (Lyons et al. 2011). Eelgrass is an umbrella species, meaning that maintaining and conserving eelgrass will maintain and conserve all of the species that rely on it for food and shelter. Acting as a nursery for juvenile fish and a nutrition source for invertebrates (Blackmon et al. 2006), eelgrass supports cultural and commercial salmon fisheries by providing shelter and habitat for juvenile fish to rear in an estuary before entering the ocean where they become part of the fishery. In addition to the roles it provides for species in its ecosystem, eelgrass also prevents erosion by stabilizing sediment with its rhizome root system, which can help prevent flooding and losses from future potential sea level rise (Mumford 2007). Although eelgrass plays these significant roles, it is declining worldwide (Short and Wyllie-Echeverria 1996). As a result, it is a widely studied subject in the literature providing significant reasons for mapping and monitoring its growth and impacts from human and natural disturbances.

Removal of a barrier, such as the dike removal and estuary restoration of the Nisqually Delta in South Puget Sound, creates opportunities to investigate how changes in deltaic processes affect components of an ecosystem. Studies of eelgrass distribution can help us understand the impacts of dike removal. Although the eelgrass in the Nisqually Delta grows outside of the area directly restored by the Brown Farm dike removal and estuary restoration, the change in sediment transport from reopened tidal channels and increased tidal prism and the change in substrate type as a result of the restoration could be significant to eelgrass distribution within the tide flat. This study will examine the short-term effect of a dike removal on eelgrass distribution, as a result of a marked increase in sediment yield. Two eelgrass mapping methods, image classification and digitization from imagery, are compared for accuracy and efficiency at determining change in distribution over time.

There is evidence that diking impacts eelgrass distribution as a result of dike construction and removal. The historical diking of parts of the Dutch Wadden Sea led to major losses in eelgrass beds from reduced tidal flow (Giesen et al., 1990). In addition to wasting disease making the population more vulnerable to disturbance, the construction of dikes meant substrate eroded from tidal channels, currents changed, and the tidal amplitude increased all leading to increased turbidity. Upon removal of the dikes, the sediment that was released buried the remaining eelgrass beds. Eelgrass traps sediment which helps secure the seafloor from erosion, but increased current action from the dike removal meant tidal channel erosion increased. The increased erosion led to sediment suspension and increased turbidity, blocking sunlight penetration through the water, crucial for eelgrass photosynthesis. Similar processes could be taking place within the Nisqually Delta with the removal of a dike and these may have at least a short-term effect on eelgrass distribution offshore. Tracking the change in sediment and the change in eelgrass and bare seafloor before and after dike removal and restoration will help us to better understand how successful this project is in improving tidal wetland habitats including eelgrass beds.

Within the Pacific Northwest, studies of eelgrass decline in estuaries are particularly important with encroaching urbanization and development's impact on distributions of eelgrass beds (Borde et al. 2003, Short and Wyllie-Echeverria 1996, Bulthuis 1995). Issues affecting eelgrass growth such as increased nutrient flux from dumping of pollutants, decreased light from overwater structures (docks, pilings) and damage from motorboat propellers have all been widely studied (Short and Wylie-Echeverria 1996). Both human and natural disturbances can impact turbidity, current velocity, dissolved oxygen, and nutrient abundance in the water column. While the nature of eelgrass disturbance is complex, this research will focus on how eelgrass distribution is influenced by increased sediment yield, and the associated change in substrate, resulting from a dike removal project.

Plant associations and primary productivity have been mapped and analyzed for the Nisqually Delta in the past (Burg et al. 1980), and vegetation within the former dike has been monitored and assessed before and after the dike removal (Nisqually Delta Restoration 2010). Data on current eelgrass spatial distribution in the Nisqually Delta outside of the former dike, however, is lacking. Mapping eelgrass distribution before dike removal and one and two years after will allow us to examine how eelgrass growing outside of the former dike is affected by the project.

Researchers from three United States Geological Survey (USGS) teams, as well as the Nisqually National Wildlife Refuge, the Washington Department of Fish and Wildlife and the Nisqually Tribe have been involved with monitoring both before and after the Brown Farm dike removal in early October 2009, in the Nisqually Delta inside and outside of the former dike to assess geomorphology, substrate, benthic invertebrate, fish, and hydrodynamic changes as a result of the estuary restoration. The eelgrass study is in concert with and contributes to the larger aims of this restoration monitoring research, focusing on the short term effects to eelgrass from the dike removal. The aim of this research is to compare mapping methods for determining if and how eelgrass distribution has changed from dike removal and restoration impacts. The hypothesis is that these changes could create new opportunities for expanded eelgrass distribution. The results gained through this research can be applied to inform other restoration projects in Puget

Sound and the Pacific Northwest and may illuminate short-term effects on ecosystems from the increasingly used practice of rapid dike or dam removal. This research uses the opportunity to look at effects on eelgrass distribution after dike removal at a time when the geomorphology of the site is suspected to be in a period of transition. Three dates; before dike removal, one year, and two years after, are used to determine the changes in eelgrass distribution as substrate changes with the possibility of the geomorphology stabilizing. Maps showing eelgrass distribution within the Nisqually tide flat will also support planning for the newly established Nisqually Reach Aquatic Reserve, as eelgrass is a primary consideration for monitoring efforts in the delta. These maps will provide context for where eelgrass is currently and how it has changed its distribution before and after the dike removal and estuary restoration.

The monitoring methods used in this research fall under tiers one and two of the hierarchical three-tiered seagrass monitoring system proposed by Neckles et al. (2012) to integrate monitoring seagrass at varying scales, dependent on the aim of the outcome. Originally based on a national monitoring scheme, this framework can be applied to individual ecosystems as well. The first tier of monitoring investigates large extents at coarse scales using airborne or satellite imagery analysis. The aim of this monitoring is to determine seagrass distribution and characterize limited ecosystem properties remotely across large regions. Tier two uses a higher resolution spatial scale and fewer sample points integrating ground monitoring methods to investigate specific environmental issues or ecosystem properties impacting seagrasses in smaller study areas. The integration of the scales of tier one and two monitoring with tier three intensive, fine scale, biophysical monitoring could allow for prediction and modeling of where seagrass could change. Tier three focuses on determining comprehensive drivers of change, ecosystem responses, and ecological processes by looking at the scale of individual shoots in order to determine causal relationships between drivers and vegetation change. The hierarchy of this three tiered monitoring allows for nested sampling to determine broad spatial distribution information, ground monitoring data, and specific factors of growth. Integrating just two of the tiers can still provide more information than focusing on only one form of monitoring. The scope of this research focuses on a combination of higher resolution imagery than that used in tier one and some ground monitoring methods as outlined in tier two to investigate spatial extent and distribution of eelgrass in the Nisqually Delta and determination of two ecosystem processes impacting these; percent cover and substrate type.

Study Site

The study site (Fig. 1) is a tidal flat located northeast of Olympia and southwest of Tacoma, Washington in South Puget Sound with the center of the delta located at 47.1023°N, -122.7085°W. The Nisqually River on the east side of the delta and spring-fed McAllister Creek on the west side empty into Puget Sound depositing sediment to create the Nisqually Delta. The study site is bounded by a shellfish aquaculture company and private tidelands on the west at Hogum Bay north of the Nisqually Reach Nature Center, and Joint Fort Lewis-McChord Military base on the east near the city of Dupont, Washington onshore from Red Salmon Slough in the northeastern part of the delta (Fig. 2). The Nisqually Delta like most Pacific Northwest estuaries has a large tidal range with the mean higher high water (MHHW) level measured at 4.11 m (13.5 ft.) and the lowest tides occurring in the spring and summer as low as -1 m (-3.5 ft.) (Karlstrom 1971). Instantaneous annual stream flow from the Nisqually River measured at the McKenna

Gauging Station is 34.8 m^3s^{-1} and the climate is temperate with mean precipitation for this area in the Nisqually River watershed averaging 83- 127 cm/year (Nisqually River Basin Plan 2008).

The estuary restoration was a result of the gradual almost-complete removal of the Brown Farm Dike from the Nisqually National Wildlife Refuge that culminated in October 2009. This has opened up 762 hectares of newly restored estuary by allowing tidal flows to inundate the freshwater marshes behind the former dike (Nisqually Delta Restoration 2010). It has also possibly affected the tide flats outside of the formerly diked area where eelgrass is currently growing. In addition to this larger estuary restoration, starting in 2004 and continuing for several years about 56 hectares was also restored on the east side of the Nisqually River and its tributary the Mashel River by the Nisqually Tribe which increased the extent of restored estuary habitat.

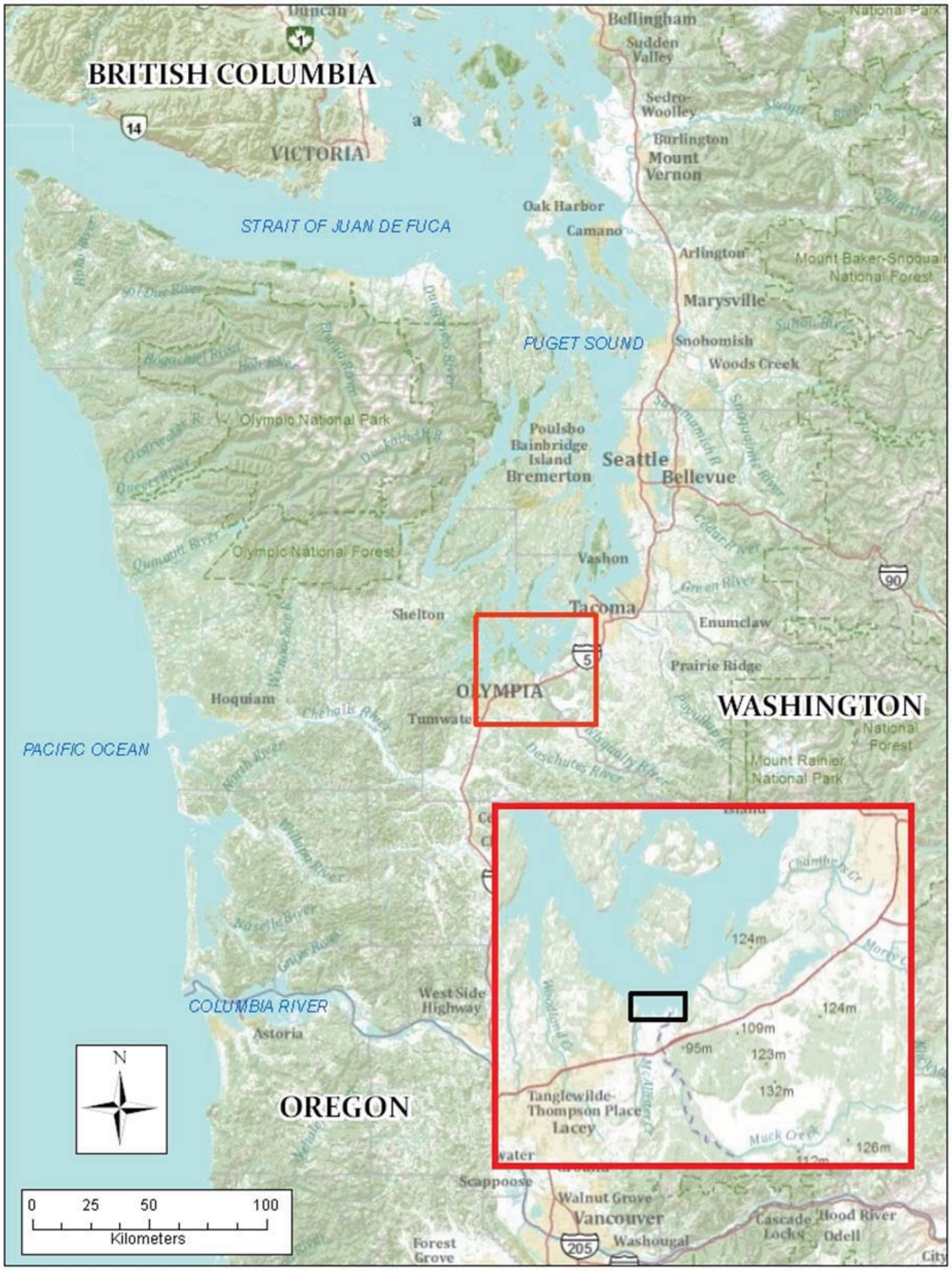

Figure 1. Pacific Northwest study area with study site extent inset (black rectangle) Base maps: ESRI, DeLorme, NAVTEQ, Tom Tom, Intermap, AND, USGS, NRCAN, and the GIS User Community. Labels and Graphics added by A. Davenport

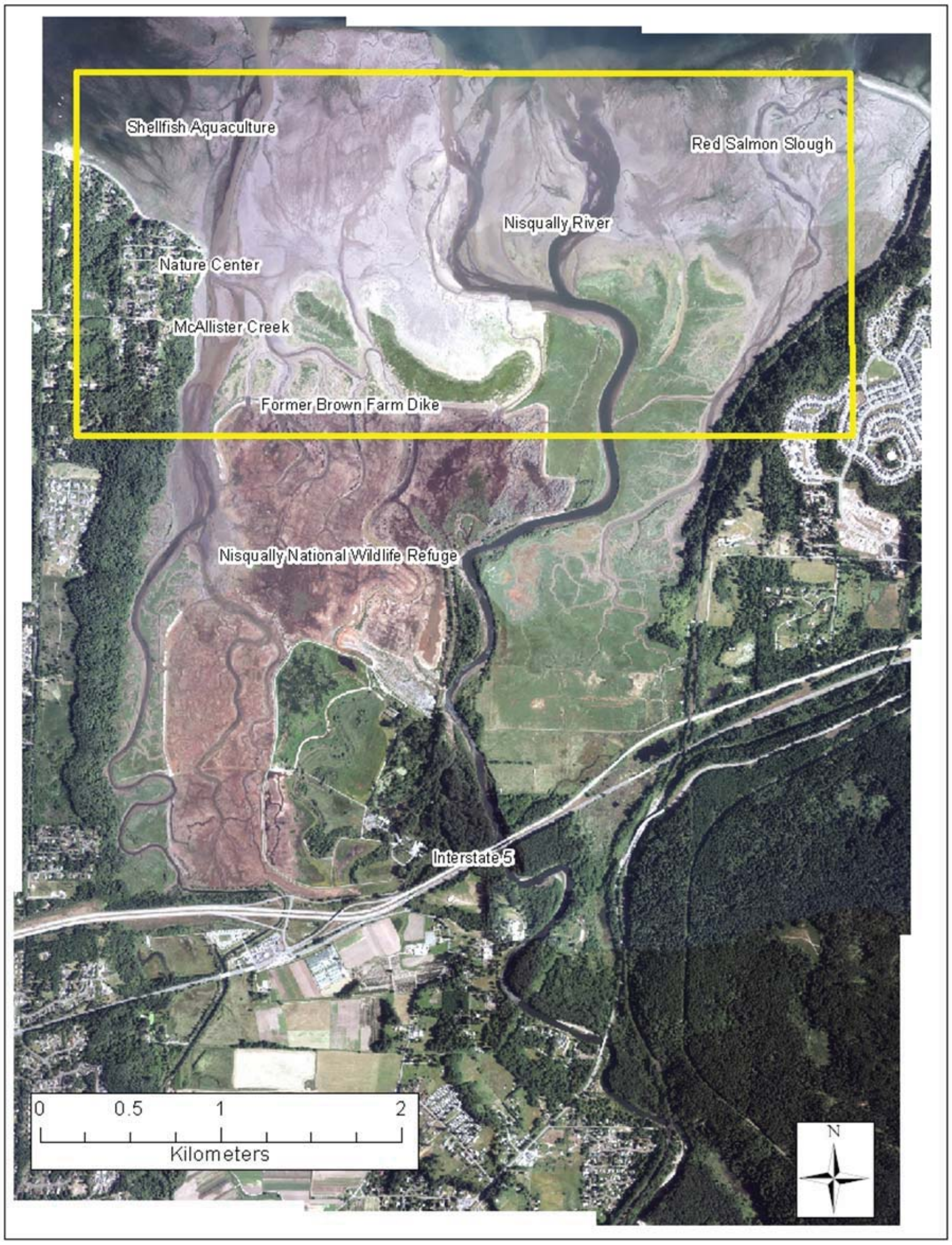

Figure 2. July 2010 true color mosaicked aerial photo of study site extent (yellow rectangle) and labeled landmarks within the Nisqually Delta. Imagery: USGS WERC 2010. Labels and Graphics added by A. Davenport

Background

The historical context of the Nisqually Delta provides a setting for the changes taking place today as a result of the dike removal and restoration. The Brown Farm dike was built by Alson Brown and his crew after he purchased 951 hectares of the Nisqually Delta for the purpose of reclaiming it from Puget Sound to use as farmland, dairy land, and orchards. The dike encompassed approximately 404 hectares of the former Nisqually estuary, completely blocking any tidal connection with Puget Sound. The 8 km long earthen dike was subsequently added to and reinforced over time, and in 1974 the land was bought by the United States Fish and Wildlife Service to become the Nisqually National Wildlife Refuge, for the protection and management of migratory birds (Nisqually National Wildlife Refuge 2009). Until 2009 the area landward of the dike was managed by the Refuge as freshwater marsh and supported a wide variety of bird and wildlife adapted to this habitat. The dike top supported a trail that was open to the public for wildlife viewing. The dike cut off flow from Puget Sound into the floodplain and estuarine wetlands, leaving the Nisqually River and McAllister Creek directly east and west of the dike respectively to flow to the delta tidal flats. The Nisqually National Wildlife Refuge made the decision to remove the Brown Farm Dike in 2009, after a lengthy planning process, which is the largest tidal marsh restoration project in the Pacific Northwest, to assist in the recovery of Puget Sound Chinook salmon and wildlife populations (USFWS 2004).

The study site extent for this project, focusing on the tidal flats outside of the former dike was chosen from consultation of eelgrass video transect maps from the Washington Department of Natural Resources Submerged Aquatic Vegetation Mapping (SVMP) program which semi-annually maps eelgrass and other vegetation in Puget Sound. The 2004 and 2007 data in the

Nisqually Delta East and West sites were used as a basis for where to focus on eelgrass distribution for classification within the delta front (Figs. 3 and 4). These maps indicate eelgrass presence or absence for areas in Puget Sound through both video transect lines and polygons incorporating presence data. The area outside of the former dike is covered by the eelgrass bed sites Flats34 and Flats35. These site maps provided a basis for establishing the extent of the study area within the Nisqually Delta based on where eelgrass was present in the past. Areas were then analyzed within the study site extent using remotely sensed high resolution false-color infrared aerial photography. Flats34 and 35 are due to be sampled for eelgrass video transects again later this year (Jeff Gaeckel pers. comm. April 6th 2010). The results will also yield predictions for where distributions could expand in the future. These could then be compared with the 2012 SVMP sampling to gauge the validity of eelgrass distribution predictions gained through the classification and field sample analysis methodology of this research. Results will also provide key areas in which to focus further eelgrass research along the delta front. Areas of eelgrass farther out towards the Nisqually Reach in deep water that cannot be mapped using aerial photos will be mapped using sonar later this year (pers. comm. Andrew Stevens November 1st 2011) and by providing advance knowledge of where eelgrass is located at present, the mapping in the Nisqually Reach has the potential to create a complete assessment of eelgrass distribution throughout the Nisqually Delta front.

Figure 3. Map of sites Flats34 and Flats35 showing eelgrass presence and absence in 2007 within Nisqually tidal flats used to determine study site. Map: Washington State Submerged Vegetation Mapping Program 2011

Figure 4. Map of inset of Flats 35 showing eelgrass presence and absence within Nisqually tidal flat used to determine study site. Map: Washington State Submerged Vegetation Mapping Program 2011

In addition to past eelgrass presence and absence data, the limitations in the extent of the imagery data sources also determined the study site extent: for consistent classification all images (2009, 2010, and 2011) had to have the same extent, thus eelgrass beds along the delta front were excluded from this study as they were not included in all images. Within the tidal flats, some extensive eelgrass beds are located out from where McAllister Creek and the Nisqually River enter the delta, and those areas are near newly reopened tidal channels which may be where new colonization could occur. Observation on site has shown that these areas are experiencing the most change as a result of the dike removal and this is possibly where geomorphic and substrate change has been greatest since the dike was removed in early October 2009. Although these areas are experiencing the most geomorphic changes, classification will focus on change detection of the eelgrass beds located farther offshore and along McAllister Creek because of the imagery extent. Reconnected tidal channels experienced deposition at their mouths after dike removal (Nisqually Delta Restoration 2011) but are now being scoured out and areas in the tidal flat adjacent to these channel mouths could be impacted by increased sediment flow through the tidal channels.

Digital aerial imagery has been proven to be the best way for detecting aquatic vegetation as it has a higher spatial resolution than most satellite imagery, although it has lower spectral resolution (Valta-Hulkkonen et al. 2003). For the aims of this research however, determining change in eelgrass spatial distribution through classification, the four bands, red, green, blue, and near infrared are assumed to be sufficient for identifying vegetation. The imagery used for classification and analysis are three high resolution false color infrared (IR) digital aerial images taken by the USGS Western Ecological Research Center. These images were flown over the

Nisqually Delta over three time periods: prior to, one year, and two years after restoration (July 2009, July 2010, and July 2011). The July 2009 imagery had the coarsest spatial resolution at 1.25m by 1.25m but was resampled using cubic convolution to the same pixel size as July 2010 for consistency in classification analysis, .26m by .26 m. The July 2011 imagery had a pixel size of .25 m by .25 m. All images were taken at approximately the same conditions and the timing of imagery used was based on the plant only being exposed at negative tides; also ensuring homogeneity through seasons. The images were post processed and georectified by Bergman Photographic Services of Portland Oregon. The false color near infrared imagery utilized wavelengths in green (500–575 nm), red (575–675 nm) and near-infrared (675–900 nm) wavelengths. Of the imagery provided, the false color near-infrared imagery was used for analysis as the near IR band maximizes visibility of vegetation (McLeod and Congalton 1998, Baily and Pearson 2007). This was visible when inspecting eelgrass and marsh vegetation in truecolor versus IR imagery; the vegetation was more distinguishable from other land cover classes in the IR imagery (Figs 5, 6, and 7).

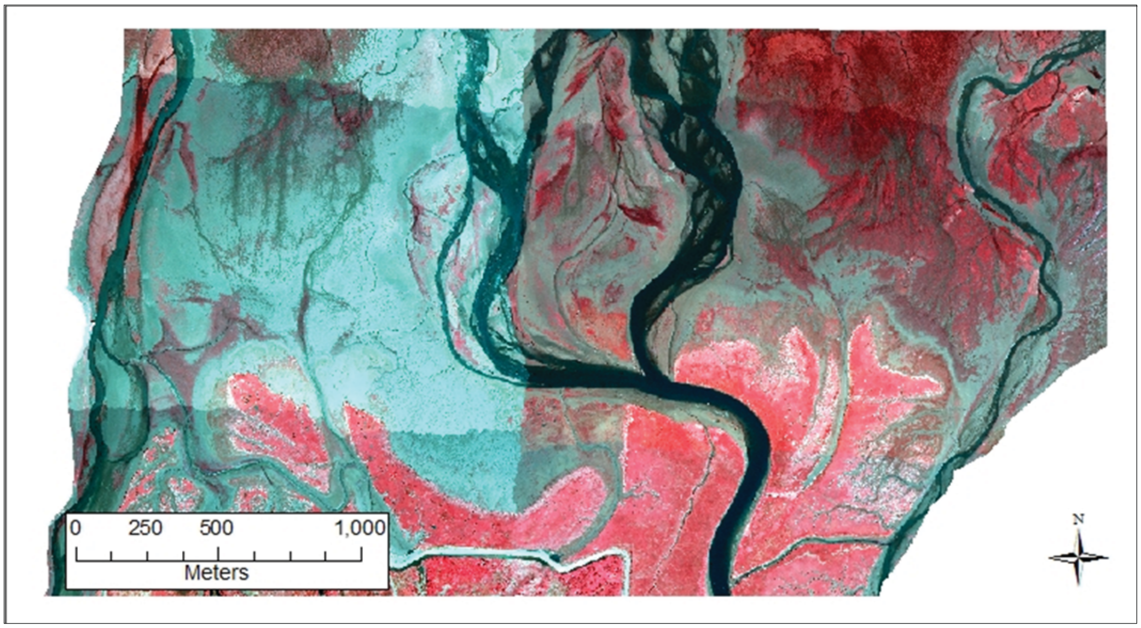

Figure 5. Mosaicked and subset original July 2009 aerial imagery. Source: USGS WERC

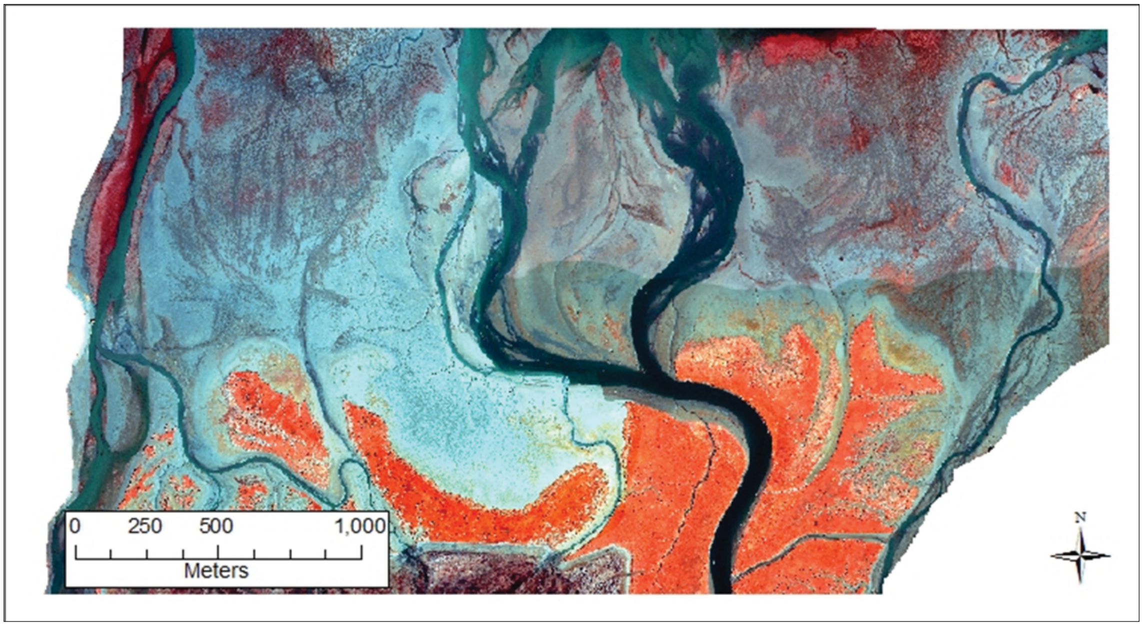

Figure 6. Mosaicked and subset original July 2010 aerial image. Source: USGS WERC

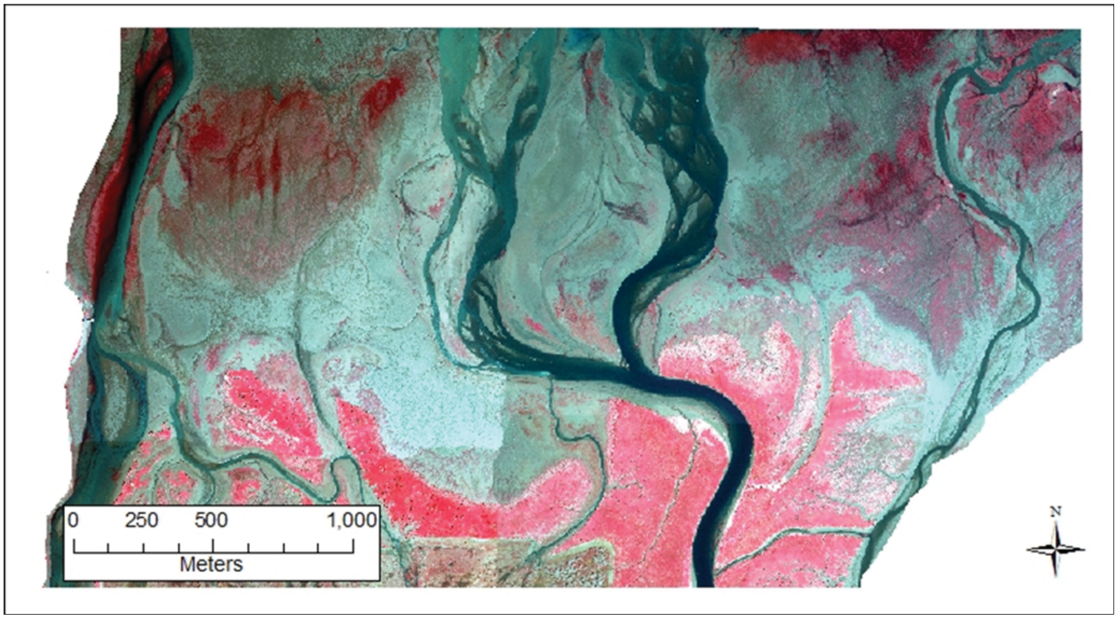

Figure 7. Mosaicked and subset original July 2011 aerial image. Source: USGS WERC

METHODS

This research compared two methods for mapping eelgrass distribution and determined their advantages and disadvantages for tracking change through time. In situ substrate type data was used as an indicator for change over time and ground reference fieldwork and accuracy assessment were both used to verify accuracy of detected changes.

Remotely sensed imagery is a common and effective method for distinguishing vegetation types and performing change detection (Baily 2007,Gullstrom 2006, Ackleson 1987, Baden 2003, Valta-Hulkkonen 2003) as well as modeling impacts of disturbance on a vegetation population (Flower 2009, Van Proosdijk 2004). Eelgrass spatial distribution in particular has been studied through aerial photography and satellite imagery for temporal change detection and monitoring continuing decline (Ward et al. 2003, Bulthuis 1995, Fredericksen et al. 2004, Ferguson et al. 1993, Young et al. 2010, Su et al. 2006). These methods are widely used because of the relatively inexpensive cost of obtaining the data and their efficiency at mapping extensive eelgrass distributions (Krause-Jensen 2004). Researchers have also focused on limiting factors to growth; including amount of light as a result of turbidity from suspended sediment, substrate type, wave energy, velocity, dissolved oxygen, and nutrient abundance (Koch 2001, Fonseca et al. 2003, Mumford, 2007, Dean 2000). While many studies investigate one or more of these limiting growth factors through in situ monitoring and fieldwork, combining these with image classifications and digitized polygons from the imagery are useful ways to add explanations of change through time. Specifically incorporating data which could show geomorphic effects can lend a clearer view as to why eelgrass distribution has changed with regard to substrate type.

Hood (2004) used tidal channel reconstructions and hydraulic geometry information for two restored areas of the Skagit River in north Puget Sound, Washington to investigate impacts from a dike removal on plant and animal communities located outside of the dike. Hood demonstrated the validity of not only focusing on the direct dike removal effects but also on indirect effects. Direct effects are those on the land restored to tidal flow as a result of dike removal, while indirect effects include how eelgrass and other plant growth is influenced by increased tidal flow and sediment flux from the river. He implemented a Geographic Information Systems (GIS) analysis of current true color orthophotos overlaid with historic aerial photography and digitized tidal channels and islands created from the historic aerial photos.

Fieldwork

Field sampling and ground truthing were implemented for three specific reasons: (1) to collect ground reference points to be used in an accuracy assessment of image classifications; (2) to add eelgrass observation data to specific sites within the Nisqually delta used by USGS monitoring before and following dike removal and restoration; and (3) to collect substrate type field observations for each ground truth point to be used for later comparison with previously collected USGS 2009 substrate type data.

For accuracy assessment of the remote sensing classification results specific points throughout the Nisqually tide flat study site were ground truthed. The point locations corresponded to the USGS sites for the research mentioned above. In addition to these USGS points, additional point locations were chosen based on July 2011 imagery from visual observations of where change was predicted to occur based on dike removal changes. Points were also chosen based on high reflectance values i.e. where eelgrass presence and absence were distinguishable from the false color imagery. These included areas near reconnected tidal channels, where the McAllister Creek and Nisqually River flow into the delta, and bare seafloor and marsh vegetation areas to use for comparison with eelgrass beds. Both sets of point locations provided comprehensive coverage of the tide flat study site (Fig. 8). Twelve points were selected based on imagery and twenty three original USGS sites were located within the study site extent.

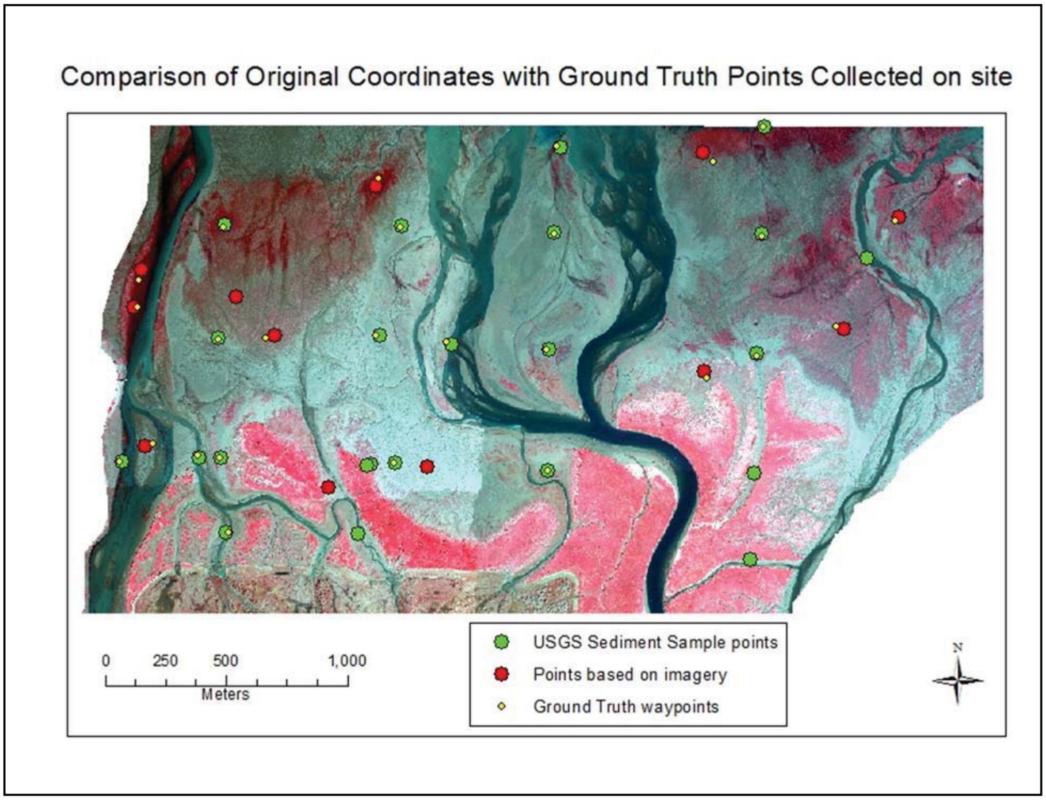

Figure 8. Map showing locations of ground-truth points, both USGS sediment sample points and points chosen based on the imagery, within the Nisqually Delta study site extent. Image: USGS WERC 2010. Cartography: A. Davenport

Of these thirty five potential points twenty six were accessible to fieldwork efforts. Although the sample size of points was small it provided a variety of coverage across the tidal flats (stratified USGS sites) and points that showed clear changes in land cover class from imagery and pixel spectral reflectance values (points based on imagery) adequate for accuracy assessment of imagery.

Fieldwork used underwater video for eelgrass observations and involved taking a small sample of substrate to record type at each point location. Using dropdown underwater video has been documented as an efficient and accurate way to observe eelgrass presence at higher tides when the plants are not exposed (Precision Identification 2002). Dropdown underwater video lowered to the seafloor provides information on presence and relative density of the eelgrass bed. Some advantages of using this method include low cost, easy deployment, time efficiency (many drops can be completed per day), and its ability to ground truth remote sensing results (Precision Identification 2002).

An angled underwater video camera was deployed by boat at each site. Navigating from a Garmin GPSMAP handheld GPS with 3-5 meter accuracy, the boat was centered on a point then the anchor was dropped until the boat was anchored to the seafloor. A video camera was lowered on a line down to the seafloor and what was visible was observed from a video screen onboard the boat. For each point the underwater video camera was deployed on both the right and left sides of the boat to ensure accuracy of eelgrass bed size, if present, and homogeneity of the site- either bare seafloor, eelgrass bed or otherwise. Presence, absence, and relative density- either 75-100% for dense or 25-50% for medium density- and substrate type were recorded for each site and marked with a waypoint. This fieldwork occurred August 19th 2011, three weeks after aerial imagery for July 2011 was taken on July 30th 2011. The 2009 and 2010 classifications could not be evaluated with the same confidence as no field sampling was undertaken at these times.

Image Classification

If collected at low tide, digital high resolution aerial photography works well with mapping intertidal aquatic vegetation (Young et al. 2010, Ferguson 1993, Lathrop 2001). As Young et al. (2010) discuss, it is ideal for mapping vegetation in the Pacific Northwest because the timing of the survey in summer can take advantage of daytime low tides, optimal sun angles and weather opportunities and provides adequate spatial resolution. In their study the authors used false-color aerial imagery to map eelgrass distribution in three coastal estuaries in Oregon, comparing the distributions between each area to test a hybrid method of pixel based classification and polygon delineation of vegetation within the estuaries, similar to the methods used in this research. They found that the large tidal range that exposes the eelgrass was ideal for mapping distribution across space and time. The EPA's guide to mapping intertidal eelgrass in the Pacific Northwest estuaries (2007) also advocate that using false-color infrared imagery is effective for mapping exposed submerged aquatic vegetation especially in Pacific Northwest estuaries with large tidal ranges. The timing of the aerial photography survey that yielded the data sources for this research was also effective for vegetation exposure at low tide and had decreased sun glint errors.

The method for image processing and classification was based on a Standard Operating Procedure for aerial imagery classification from Isa Woo of the USGS Western Ecological Research Center (Nisqually Delta Image Classification SOP and Thoughts 5/4/11, Isa Woo, Ben Gustafson) for similar objectives: to classify vegetation type within the formerly diked area of the

Nisqually Delta wetland to track vegetation changes from a freshwater to brackish wetland as a result of the dike removal and restoration.

The eelgrass distribution imagery analysis process began with re-mosaicking of original tiles to reduce mosaicking errors from the photogrammetry vendors. Errors occurred when tiles overlapped creating new false land cover classes. These errors were mitigated by prioritizing the most important tiles for the study area to ensure they were not overlapping. The shoreline areas on the east and west sides of the delta were masked out of each image to reduce confusion in classification. Because the area to the northwest of Hogum Bay is private tideland inaccessible to field work and managed for intensive shellfish aquaculture (Chris Ellings pers. comm. November 30th 2011) it was also masked from the study area.

Using a Normalized Difference Vegetation Index (NDVI) and performing unsupervised classifications on imagery to inform final supervised classification are useful ways to distinguish vegetation and provide a baseline classification for the imagery respectively (Ward et al. 2003, Valta-Hulkkonen 2003). Both of these methods were used on each image to direct the maximum likelihood supervised classification. By grouping pixels based on their digital number the isodata clustering method used in the unsupervised classification allows land cover classes to be defined quickly. Although this method is faster, accuracy is reduced and confusion between classes and misclassification are unavoidable; however applying a supervised maximum likelihood classification which uses training areas defined by the user for each class to determine the classification, increases accuracy. The NDVI for each image showed the difference between eelgrass and river channel in the delta front and distinguished marsh vegetation and restored wetland vegetation. Unsupervised classifications were applied, with two and three classes to separate water from other land covers and then twelve classes to determine specific differences in vegetation spectral reflectance pixel values. These showed that water was well separated from other classes but marsh vegetation and eelgrass were easily confused, which informed where to focus training areas.

Based on what was visible in the imagery, background knowledge from site visits, and these classifications, seven land cover classes were determined to be appropriate for distinguishing various densities of eelgrass from other marsh vegetation and river channels within the delta front for the July 2011 and July 2010 imagery. Eight classes were appropriate for the July 2009 imagery because of the intent to include the former dike as its own class before it was removed to show the clear separation between freshwater wetland and tide flat. The common classes chosen for each image were: Bare Seafloor, Dense Eelgrass, Medium Eelgrass, Restored Wetland, Marsh Vegetation, River Channel, and Unclassified. Non-eelgrass vegetation types were not important to the analysis and thus classification did not go to species level. Multiple signatures for each class were reclassified into the seven or eight classes for each image and given uniform symbology in ArcMap 10. An accuracy assessment (Congalton and Green 2009) was done using ERDAS Imagine 2010 for the July 2011 imagery classification using August 2011 ground reference points for validation. Overall accuracy, producer (omission error) and user (commission error) accuracy, and a Kappa score were calculated for each ground reference class. Producer accuracy is error of commission or inclusion and refers to pixels that were classified as belonging to a class but actually represent other land covers, while user accuracy is error of omission or exclusion and refers to pixels that were omitted from being assigned to the actual land cover class they represent.

Creating Eelgrass Polygons from the Imagery

In addition to image classification as a method for mapping eelgrass distribution over time, on-screen or “heads-up” digitizing of dense eelgrass beds from the image itself was used as a comparison for eelgrass distribution change over time. Advantages of this method include its attention to texture as well as spectral reflectance which allows a clearer delineation of cover density- dense versus medium. It is commonly used in conjunction with pixel based classification to give a more accurate measure of eelgrass (Young et al. 2010). Although there is more risk of human error with this method because the polygons are drawn based on visual discrimination of eelgrass, establishing a minimum mapping unit (MMU) helped to minimize these errors. The MMU is used to distinguish a particular distance between eelgrass beds that separates beds from one another and identifies between eelgrass bed and bare seafloor. The MMU was established as thirty meters based on the large extent of eelgrass within the imagery, which meant only the large dense eelgrass beds were digitized as polygons. By creating eelgrass polygons for each image date the shapefiles allowed for comparison between years as well as comparison to dense eelgrass coverage from the classification method for each year. Three main areas of eelgrass beds were evident from the imagery- the dense narrow strip along where McAllister Creek flows into the delta on the western side of the delta, the circular dense patch towards the center of the delta, and the large patch in the northeastern delta north of Red Salmon Slough.

RESULTS AND DISCUSSION

Accuracy Assessment of July 2011 Imagery Classification

The standard way to assess accuracy of remotely sensed imagery is to create an error matrix which compares reference data to classified map data for each ground reference point (Congalton and Green 2009). Creating a confusion table or error matrix helps account for error in classes and assesses the overall accuracy of the classification. Accuracy assessment involved comparing known ground reference point class values with the class values for each point in the July 2011 classification. From the assessment a table was created and accuracy values for producer and user accuracy were calculated for each class with ground reference data (Table 1).

Lyons et al. (2011) similarly used accuracy assessment to validate change detection analyses of seagrass coverage between 2004 and 2007 using Quickbird satellite imagery in the Eastern Banks, Australia. Their sources did not include comprehensive data showing average annual growth per year to compare to change incurred between the two years. As these data were not available for their study the authors determined patterns in change and reasons for these through error matrices and analysis of confusion tables for each image. Similarly in this study there was a lack of comprehensive average annual growth figures for eelgrass prior to the dike removal to compare to changes incurred after the restoration. This meant that finding the statistical significance of change over time was not appropriate to determine reasons for these changes and what may have caused the change. Instead of this the confusion index was used to determine significant class changes in eelgrass distribution and bare seafloor through investigation of each class' accuracy.

The overall classification accuracy for the supervised classification of the July 2011 imagery with eight classes was 73.08% with a Kappa statistic of .5777 (Table 1). This is an adequate percentage accuracy, but analyzing the accuracy for the eelgrass and bare seafloor classes through their producer and user accuracy gives a more thorough explanation for this percentage of total accuracy. Producer accuracy and user accuracy were calculated for each of these classes and for River Channel in comparison.

ERROR MATRIX

Classified Data	Dense Eg	Medium Eg	Bare Seafloor	Marsh Veg	Restored Wetland	River Ch.
	Reference Data					
Dense Eelgrass	3	1	0	0	0	0
Medium Eelgrass	1	3	1	0	0	0
Bare Seafloor	0	1	12	1	0	0
Marsh Vegetation	0	0	0	0	0	0
Restored Wetland	0	0	0	0	0	0
River Channel	0	1	1	0	0	1
Column Total	4	6	14	1	0	1

ACCURACY TOTALS

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Dense Eelgrass	4	4	3	75.00%	75.00%
Medium Eelgrass	6	5	3	50.00%	60.00%
Bare Seafloor	14	14	12	85.71%	85.71%
Marsh Vegetation	1	0	0	---	---
Restored Wetland	0	0	0	---	---
River Channel	1	3	1	100.00%	33.33%
Totals	26	26	19		

Overall Classification Accuracy = 73.08%

KAPPA (K^) STATISTICS

Overall Kappa Statistics = 0.5777

Conditional Kappa for each Category.

Class Name	Kappa
Dense Eelgrass	0.7045
Medium Eelgrass	0.4800
Bare Seafloor	0.6905
Marsh Vegetation	0.0000
Restored Wetland	0.0000
River Channel	0.3067

Table 1. Accuracy Report for July 2011 Imagery Supervised Maximum Likelihood Classification. Source: ERDAS Imagine 2010

As seen in Table 1 above, dense eelgrass had the same producer and user accuracy percentage (75%) while medium eelgrass had higher user accuracy than producer. The table shows the confusion of medium eelgrass with dense eelgrass and bare seafloor. Figure 9 below, showing lower producer and user accuracy for medium eelgrass than dense eelgrass and bare seafloor, supports the error table's conclusions. This is likely because medium and dense eelgrass classes were easily confused as the difference between them is density for the same class. They have similar spectral reflectance, although because of density differences one is darker red in the image than the other. The same issues were encountered with the seagrass confusion tables of Lyon et al. (2011); they concluded that it was best to combine percent densities into one class. To mitigate these errors, dense and medium eelgrass were combined into one eelgrass class to calculate change in area over time compared with bare seafloor area. In addition dense eelgrass area was calculated individually for each year to compare with the digitization mapping method (Fig. 11). For the percent accuracy for bare seafloor both producer and user accuracy were 85.71%, although river channel had different percentages for each type of accuracy. The confusion table shows that this is a result of bare seafloor being the majority of classified pixels in the image, and this class is easily distinguishable from other classes based on its spectral reflectance values. Confusion between river channel and medium eelgrass probably accounted for the lower accuracy of user accuracy for that class. The classifications may have underestimated the amount of dense eelgrass in each image especially for the 2010 image where differences in tides meant fewer dense eelgrass beds were exposed. This accounts for the large increase in dense eelgrass area between 2010 and 2011. Bare seafloor area steadily increased over time between

2009 and 2011 (Fig. 11). Issues such as these stemming from misclassification and underestimation of eelgrass have led to the discrepancies in change of eelgrass distribution over time. Looking at each class area for each year (Fig. 10) overall eelgrass area (combined dense and medium) appears to decrease between 2009 and 2010, and increase slightly between 2010 and 2011.

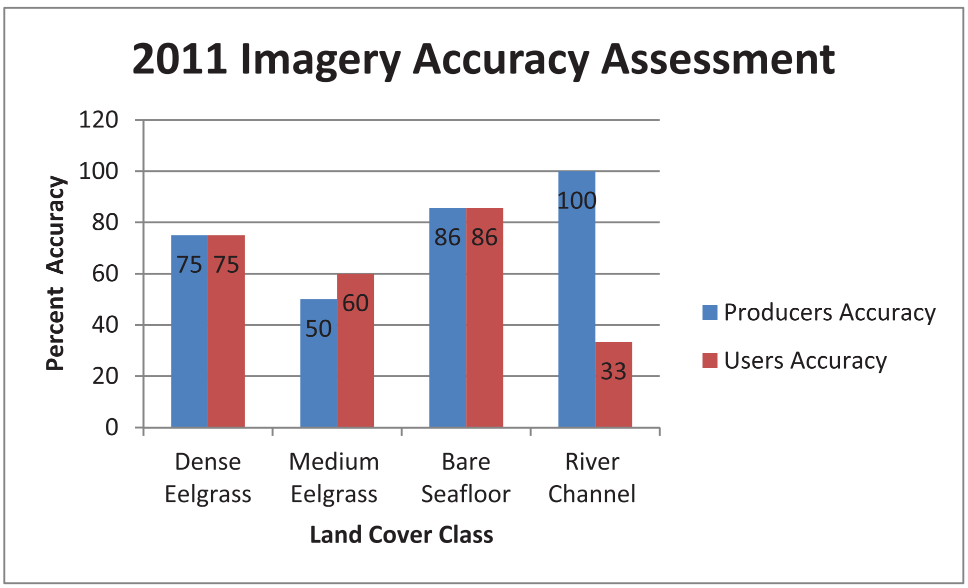

Figure 9. Producer (omission error) and user (commission error) accuracy percentage values for 2011 imagery classification calculated from confusion table using ERDAS Imagine 2010.

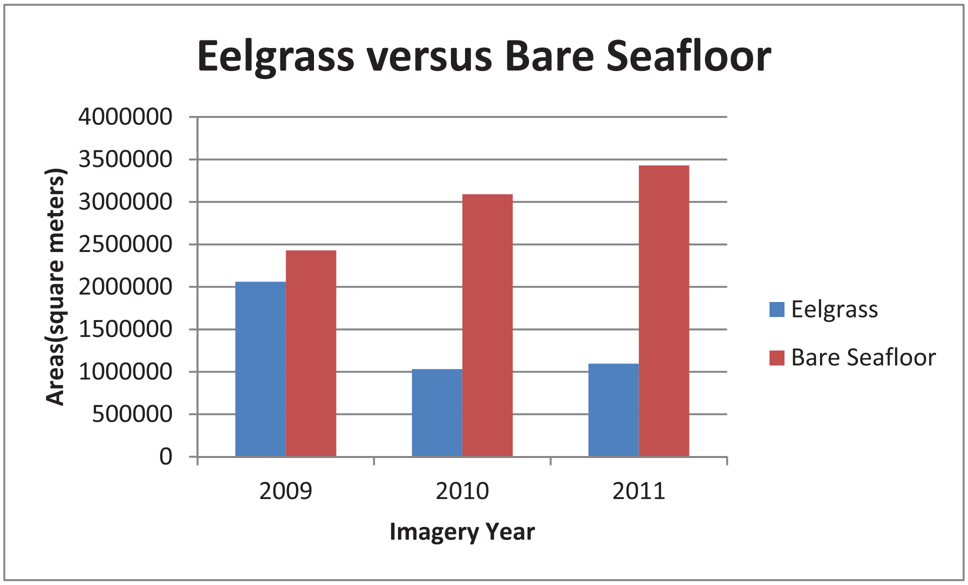

Figure 10. Comparison of combined Medium and Dense Eelgrass classes and Bare Seafloor class area for 2009, 2010 and 2011 classified images.

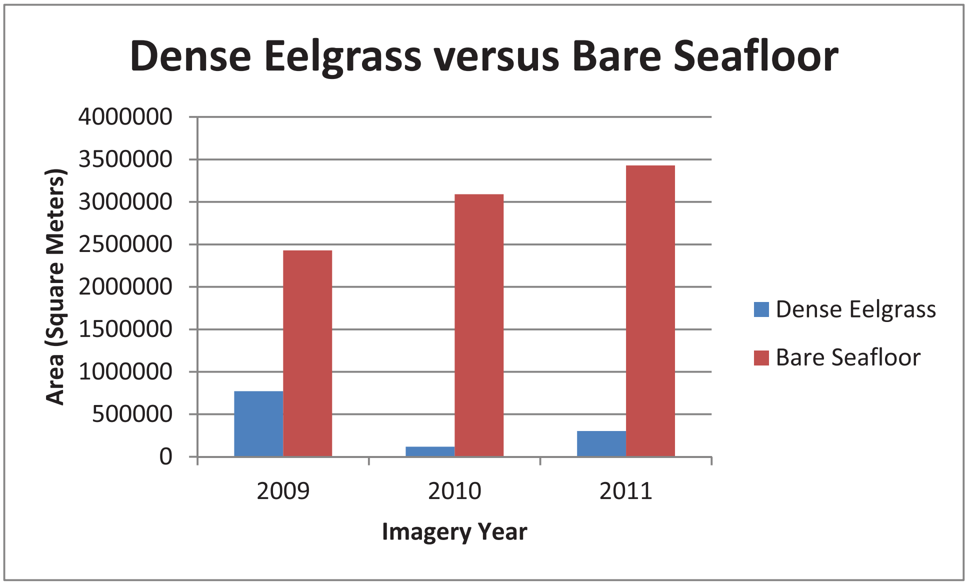

Figure 11. Comparison of Dense Eelgrass class with bare seafloor class area for 2009, 2010 and 2011 classified images.

Analysis

The greatest land cover class changes calculated between each classification for the July 2009, 2010 and 2011 were in eelgrass distribution compared with bare seafloor (Figs. 12, 13). Visible, significant change occurred in the large bed in the center of the delta and in the dense beds located on the northeastern edge of the image in Red Salmon Slough. These are the locations of some of the largest eelgrass beds in the tidal flat. They could be impacted differently from increased sediment outflow of the restored area through reconnected tidal channels into the delta from the dike removal, as an indirect effect. The large central bed is located near reconnected tidal channels that likely concentrate sediment flow moving offshore toward the delta front. These have experienced the most change in area when medium and dense eelgrass classes are combined between 2009 and 2011. This could be as a result of the increased sediment flow out to the tide flat and could also be from sediment inflow to the marsh increasing because of the expanded tidal prism (Jesse Barham pers. comm. November 30th 2011).

Although the amount of pixels classified as eelgrass in the large bed near Red Salmon Slough in the eastern side of the delta front has changed between 2009, 2010 and 2011, the general extent of the eelgrass bed has remained the same. This fluctuation in eelgrass cover over the years could be due to misclassification between more sparse patches of eelgrass within the larger bed and bare seafloor in addition to large differences in tide when the imagery was taken. Because Red Salmon Slough is located outside of the sphere of the direct influence of reconnected tidal channels increasing sediment flow to the tide flats, the changes may have been caused by fluvial sediments coming from the nearby Nisqually River and the earlier restoration on the eastern side of the river. There is also a chance that sediments transported to the tidal flats from the newly restored mashes affect the Red Salmon Slough eelgrass since that movement would preferably occur during ebb tides which would transport materials in a northeast direction.

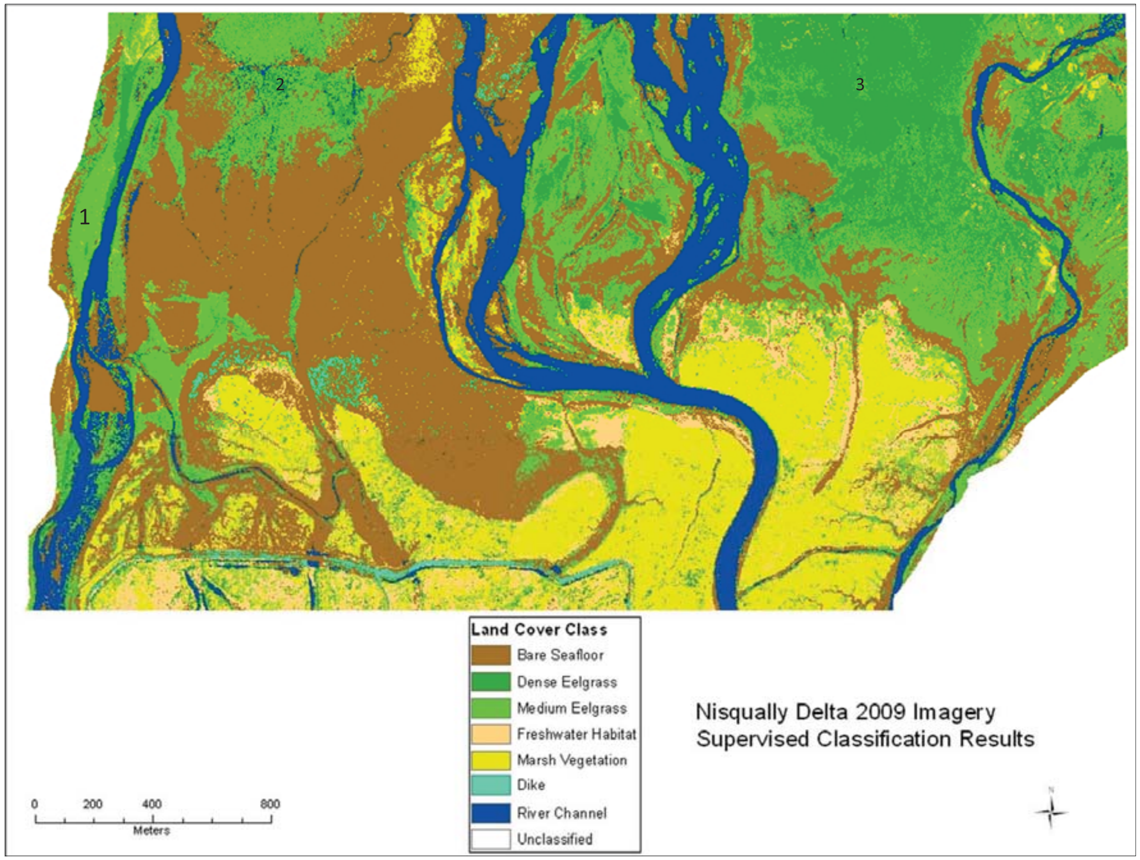

Figure 12.Supervised classification results for July 2009 imagery with maximum likelihood classification. Labeled eelgrass beds: 1) dense beds along McAllister Creek 2) large central bed 3) Red Salmon Slough bed Source: ERDAS Imagine 2010, cartography and symbology in ArcMap 10 by A. Davenport, Imagery: USGS WERC

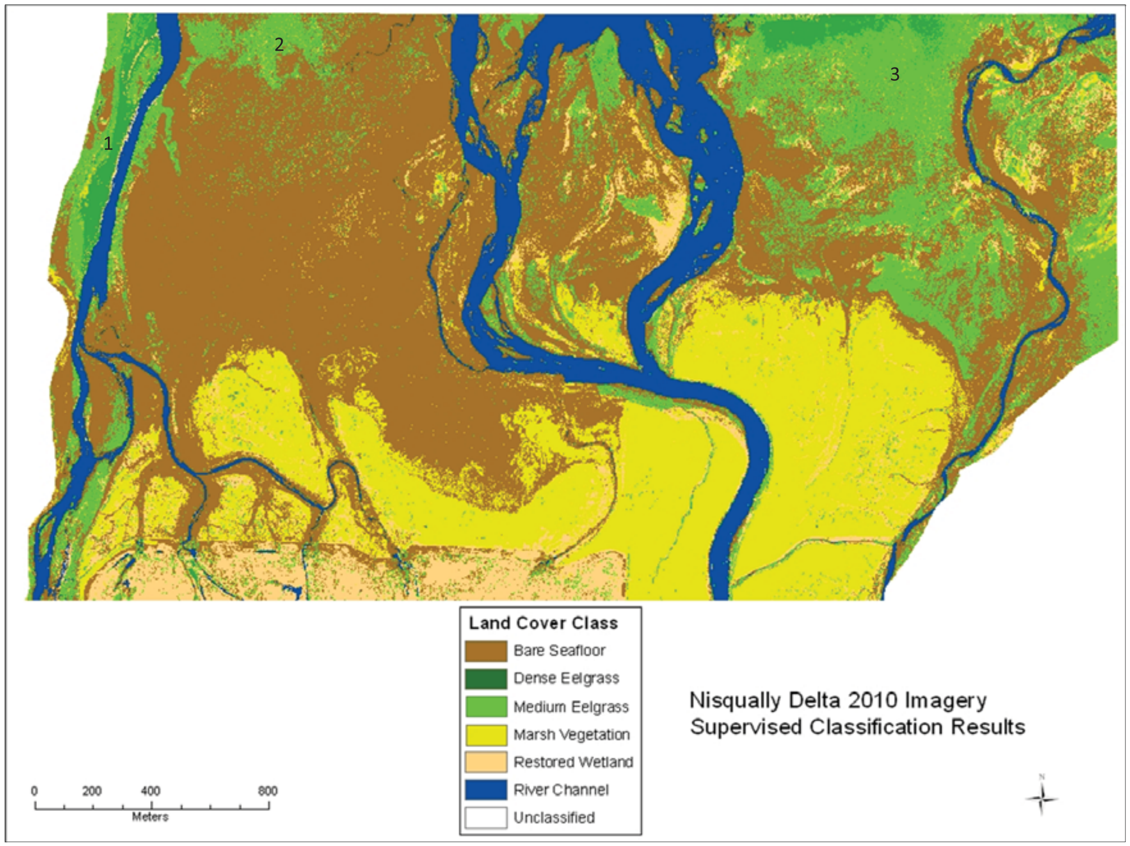

Figure 12. Supervised classification results for July 2010 imagery, maximum likelihood classification, with eelgrass beds as labeled above.

Source: ERDAS Imagine 2010, cartography and symbology in ArcMap 10 by A. Davenport. Imagery: USGS WERC

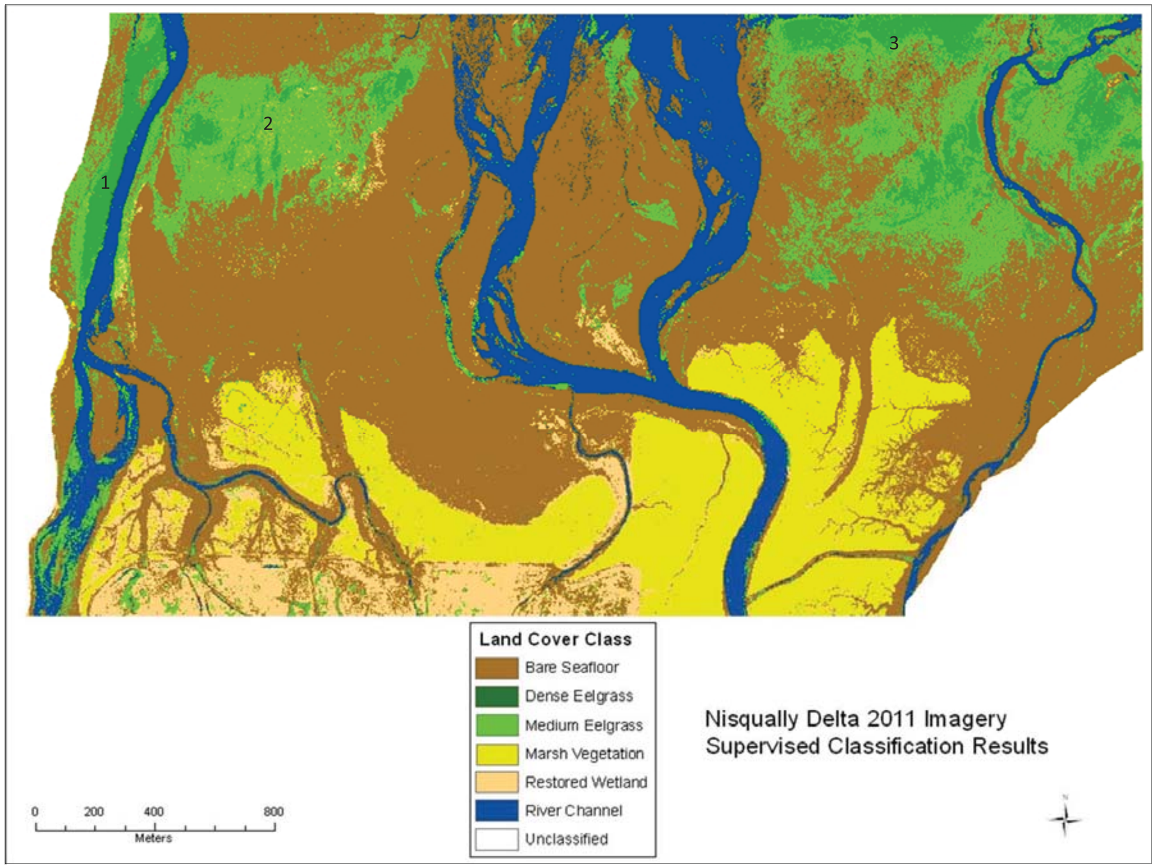

Figure 13. Supervised classification results for July 2011 imagery, maximum likelihood classification, with eelgrass beds as labeled above.

Source: ERDAS Imagine 2010, cartography and symbology in ArcMap 10 by A. Davenport. Imagery: USGS WERC

For consistency between the mapping methods only locations of dense eelgrass beds were digitized from the imagery to compare with dense eelgrass classes from the image classifications for each year. While combining medium and dense classes for eelgrass area comparison between classifications made sense because each used the same method to classify, to mitigate error from inconsistent tides between images exposing different amount of eelgrass only visibly dense eelgrass beds were digitized from the imagery. Digitization has inherently more human error and focusing only on dense eelgrass helped to reduce this. Comparing the dense eelgrass class from the classifications with the digitized dense eelgrass polygons from the imagery, the classifications consistently underestimate the area of dense eelgrass for each year. For 2009 the classification estimated the dense eelgrass class area to be 772, 856 square meters while the digitized polygons totaled 826,925 square meters of dense eelgrass. Similarly for 2010 the classification estimated 118, 102 square meters versus 169, 775 for the digitized polygons. The 2011 classification estimated 303, 375 square meters versus 404,975 square meters for the digitized polygons.The difference between both 2009 and 2010 mapping methods was about 50,000 square meters while the difference between the 2011 classification and digitization was more dramatic at about 100,000 square meters (Fig. 14).The differences in these amounts could be due to the range of low tides when each image was taken and as a result of misclassification between dense eelgrass and land cover classes with similar spectral reflectance.

The dense eelgrass digitized polygons also vary in area between each year, 2009, 2010, and 2011 because of visibility of eelgrass based on the tides when the image was collected and change in eelgrass distribution as a result of the dike removal (Fig. 15). Although not enough data is available to make conclusive statements as to what degree the change in eelgrass area over time was a result of the dike removal and estuary restoration, these two methods of mapping, classification and imagery analysis, help show change within the tide flats.

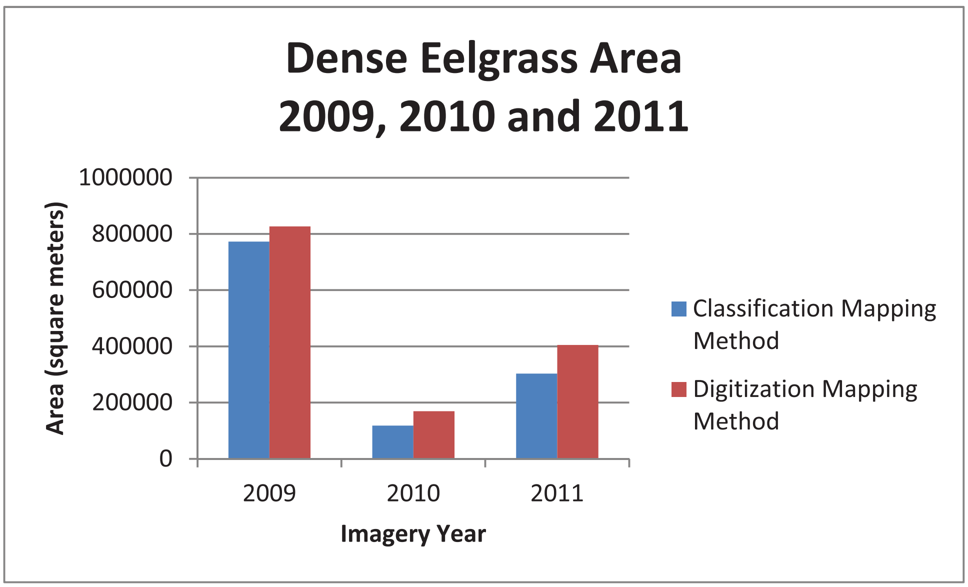

Figure 14. Graph comparing eelgrass area for 2009, 2010 and 2011 for classification and imagery mapping methods.

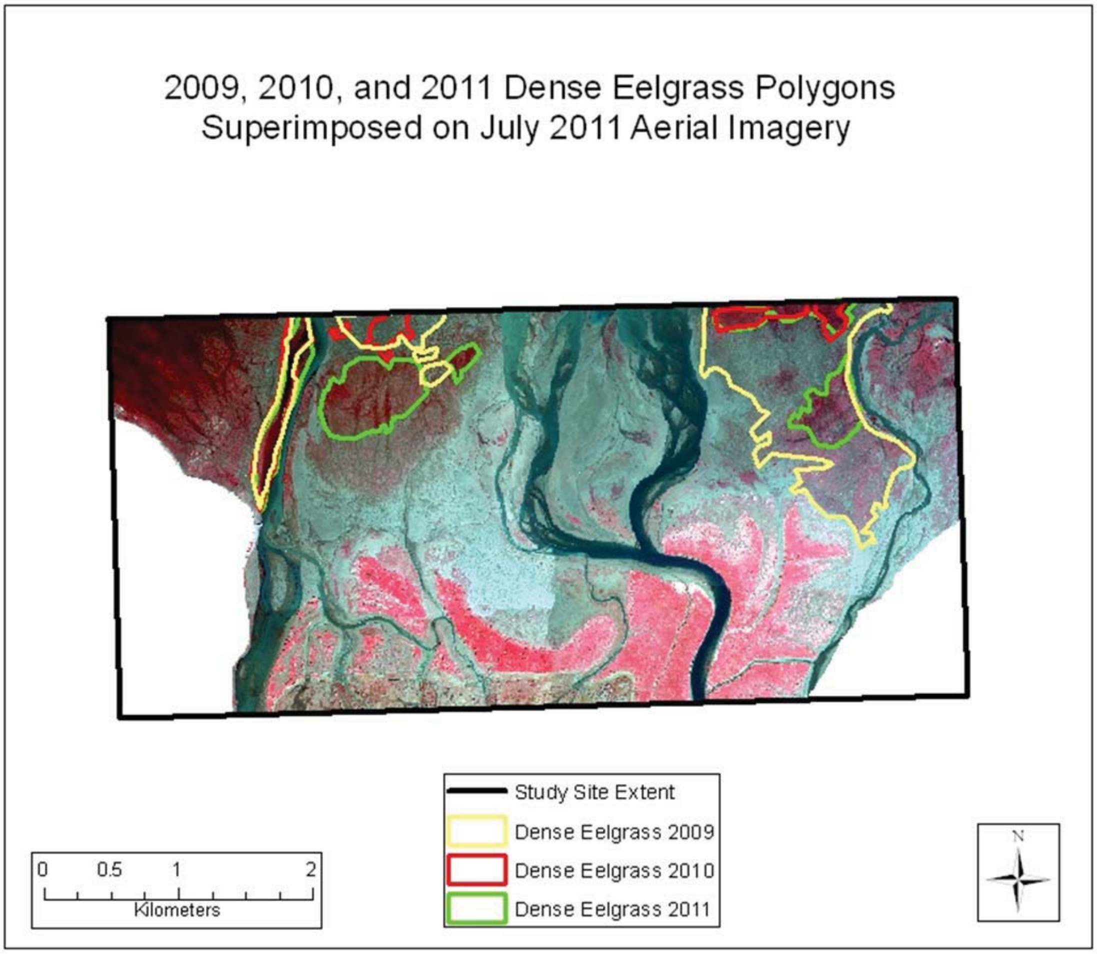

Figure 15. Map of Nisqually Delta study site with 2009, 2010, and 2011 dense eelgrass polygons digitized from each year's imagery superimposed on July 2011 aerial imagery. Source: ESRI Base Maps. Maps and graphics added by A. Davenport

Investigating change in substrate type helps illustrate the changing geomorphology of the Nisqually Delta as a result of the dike removal and estuary restoration. From initial breaching of the Brown Farm dike and the first tidal inundation of the former freshwater habitat, change has been recorded by substrate type point observations before and after the dike removal. With potential increasing sediment flow through reconnected tidal channels, the hypothesis is that finer substrate may be increasing in the tidal flat. McAllister Creek and Red Salmon Slough west and east of the Nisqually River empty into the delta and deposit silty mud onto the tidal flat, similarly reconnected tidal channels could also be increasingly depositing muddy sediments onto the tidal flat as the restoration progresses. This increase of sediment flow through tidal channels could be impacting eelgrass distribution by covering over existing beds and meandering channels may be cutting into beds as well. Large sand lobes have also been surveyed as extending into the delta front, incised by meandering tidal channels (Barnhardt and Sherrod, 2006.

The sediment deposits within the Nisqually delta are clearly in a constant state of change as a result of the dike removal and restoration, however the literature has shown that eelgrass can grow on substrates from sand to mud (Short et al 1996, Neinhuis and De Bree 1977). Eelgrass has been observed growing on both sand and mud substrates in the Nisqually Delta tide flats, (Figs. 16, 17) with any range of sediment grain size sufficient for its growth. These initial comparisons of change in substrate type before and after the dike removal create a baseline for further research into the causes of change in eelgrass.

Comparison of 2009 substrate type point samples with samples collected in 2011 attempt to test this hypothesis and demonstrate change through time. These data came from USGS sediment cores taken at designated points throughout the delta before dike removal (2009) and observations of substrate type at the same points two years later during ground reference fieldwork (2011). The substrate type data was collected with different methods so the changes observed cannot be quantitatively assessed but they are helpful in showing general trends over time in change from sand to mud and vice versa. The USGS 2009 sediment data was classified after particle analyses into gravel, sand, and mud classes. To increase consistency between substrate type comparisons with the 2011 substrate type observations, the 2009 substrate type data were designated as sand, mud, or mud/sand depending on the largest particle size percentage. For the 2011 data, a sample of the substrate at each ground-truth point was examined in the field and general substrate type was recorded as mud, sand, sand/mud or mud/organic matter.

As distance increased away from the dike and towards the tide flat, ground-truth records at these points were recorded as sand for the 2009 data (Fig. 16). When these same sites were sampled in 2011 they were observed to be mud (Fig. 17). This shows possible effects from dike removal with sand changing to mud over time. One possible explanation is increased sediment transport through reconnected tidal channels from the dike removal but it remains uncertain how long any mud reaching the tidal flats will remain there. In 2009 eelgrass beds were located in the tidal flat on sandier substrate and may be able to expand farther south towards the former dike with increased time after restoration, although either substrate is sufficient for eelgrass growth. Changes seen on the eastern side of the delta where the large eelgrass bed north of Red Salmon Slough is located could be as a result of the earlier 56 hectares restored by the Nisqually Tribe on the eastern side of the Nisqually River, although this has not been quantified, rather than as a result of the 2009 dike removal and restoration (pers. comm. Jean Takekawa, November 28th 2011).

Although the Nisqually Delta tidal flat geomorphology is changing as a result of the 2009 dike removal and estuary restoration, lack of conclusive data on tidal channel morphology and sediment transport does not allow for quantification of geomorphic effects. However using a small sample of substrate type points and comparing their results over time helps to clearly show changes are occurring in the tide flats. Eelgrass distribution reflects these changes and further studies incorporating sediment transport and tidal channel data will help to strengthen these initial findings of substrate type changes from sand to mud.

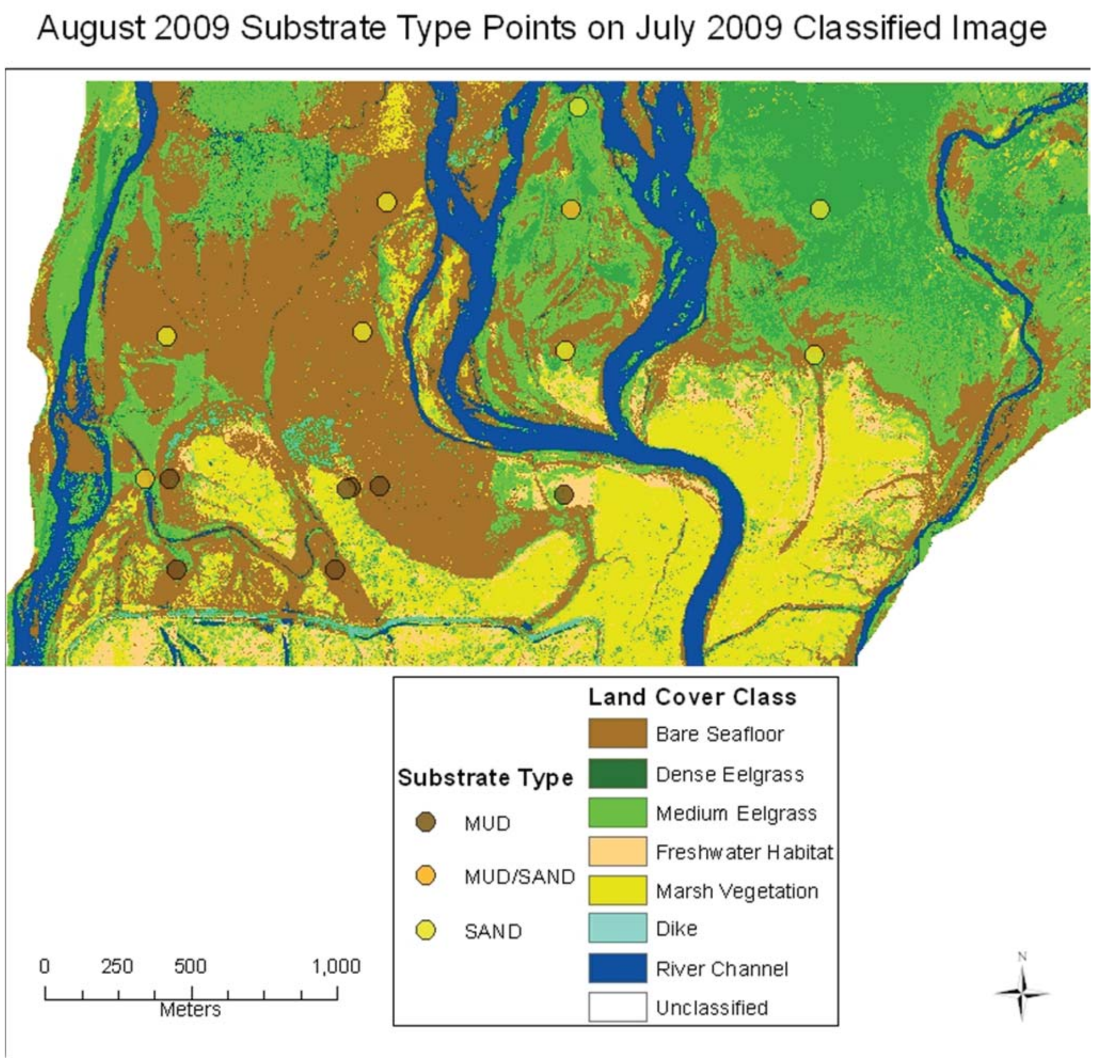

Figure 16. Substrate type point data comparison for August 2009 points with July 2009 classification using maximum likelihood classification in ERDAS Imagine 2010, cartography and symbology in ArcMap 10 by A. Davenport

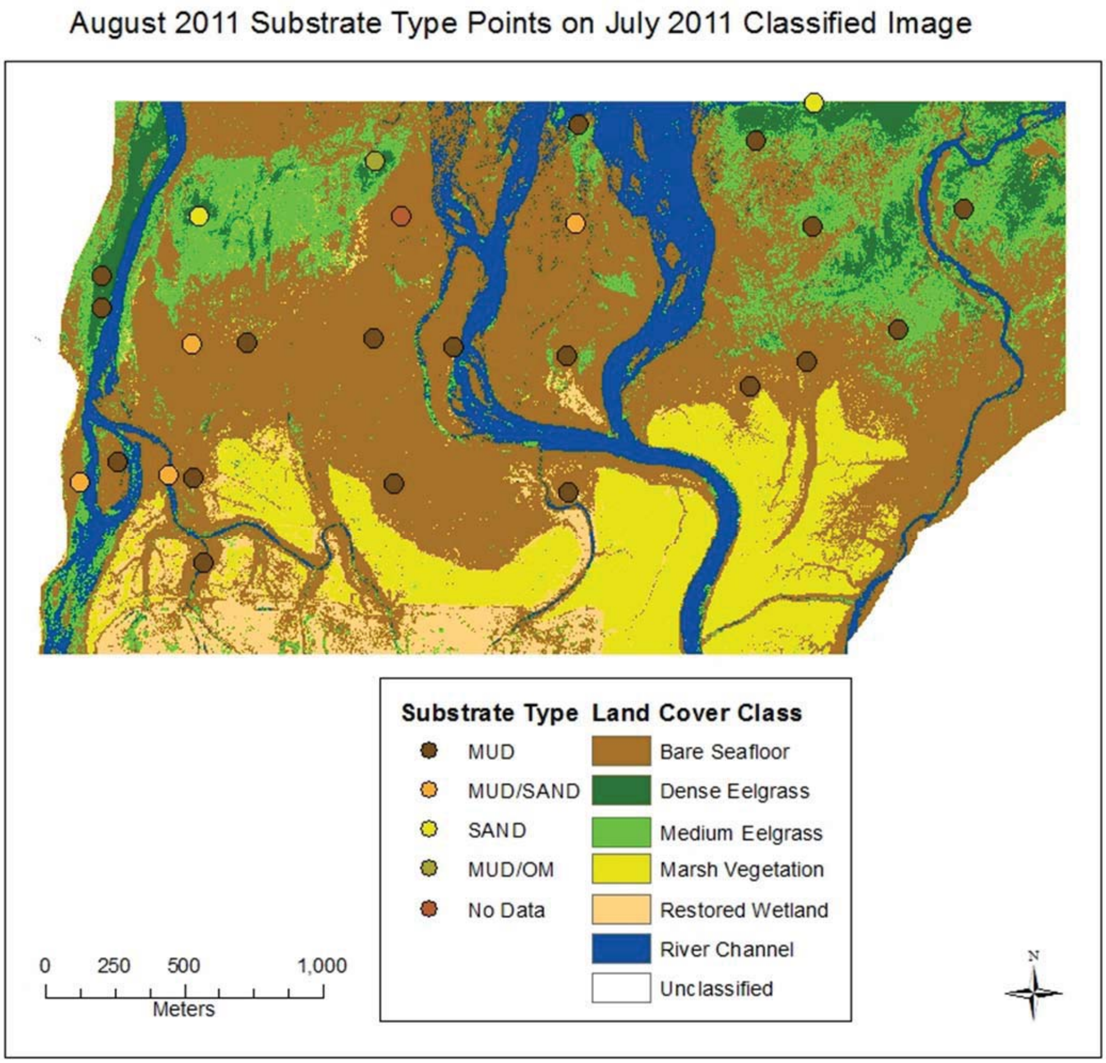

Figure 17. Substrate type point data comparison for August 2011 points with July 2011 classification using maximum likelihood classification in ERDAS Imagine 2010, cartography and symbology in ArcMap 10 by A. Davenport

Sources of Error

Uncertainty was inherent throughout the fieldwork, classification, digitization, and analysis process. Both human-caused error and systematic error from instruments contributed to the overall decrease in accuracy of the final results. Efforts to mitigate these errors helped to increase accuracy but results could be impacted by uncertainty, thus a discussion of these is important to determine where error occurred and why.

Inaccuracies during fieldwork included GPS device capability and navigation ability and inconsistent tides and depths between when the imagery was flown in July 2011 and when ground truth points were collected in August 2011. Differences in GPS accuracy may also account for issues with inconsistent field sampling records for ground-truth points compared with what is visible in the imagery. With several of the points the recorded observation was inconsistent with what was predicted visually as the land cover class in the aerial imagery before fieldwork. This could be as a result of the 3-5 meter GPS error in the field compounded with slight georeferencing errors in the original processing of the imagery from the vendor, causing coordinates to be off from the imagery and the imagery to be off from what is truly on the ground. With these situations not only was the pixel that corresponded to the point a different land cover class than was expected, the surrounding pixels and dominant land cover surrounding the pixel were also not as expected. In these cases for the accuracy assessment the observation of substrate type and eelgrass presence or absence from fieldwork records were used as ground truth rather than the 2011 imagery. In addition to errors in the field, the process of supervised classification using maximum likelihood reasoning was also error prone. Through the process of choosing training areas based on spectral reflectance of each pixel, pixels with similar reflectance colors may have been confused into the same class although they should be separated into two separate classes. This occurred with pixels belonging to marsh vegetation and those belonging to restored wetland for the July 2010 and July 2011 imagery. The distinction between these classes are that the restored wetland class reflects the change from freshwater habitat to tidally inundated wetland for vegetation within the former dike such as salt tolerant vascular plants while marsh vegetation refers to the vegetation that grows in the brackish tidal flats outside of the dike including high marsh plants. Because these land cover classes have similar pixel values in the imagery they show up as similar colors and they were confused when the signatures were combined to create the seven distinct classes.

More importantly, the same issues occurred with the distinction between dense eelgrass and medium eelgrass, because they could not be spectrally separated as they are the same land cover class but have different densities. Misclassifying ulva, a green algae very prevalent in the tidal flats, as eelgrass could have also been an issue. Ulva floats on the surface which could be detected in the imagery as exposed eelgrass. Ground truthing helped to inform classification but error exists in distinguishing eelgrass from other tidal flat vegetation. Prior maps and data indicated areas of usual eelgrass presence and were another way in addition to fieldwork to determine where eelgrass was actually located in the tidal flat. Classes were chosen based on both spectral reflectance in the imagery for each date and by what was recorded in the field during field sampling. Splitting eelgrass into medium and dense classes was helpful for visual determination of eelgrass beds although it was advantageous to combine the two for area calculations compared with bare seafloor.

Other errors in misclassification were accounted for through testing each class individually to see which pixels belonged to which class, although confusion between classes and issues with sun glint and different reflectance spectra between years was also an issue. Each image was georectifed and projected to the same coordinate system by Bergman Photographic to North American Datum (NAD) 83 State Plane Washington South 4602 using feet as the linear unit. Although the images were georeferenced there were slight differences between each image. When looking at a fixed feature such as the Nisqually Reach Nature Center fishing pier, the pier is offset about 20 meters in the July 2011 image compared to the July 2009 and 2010 imagery. This offset could explain some of the error in groundtruthing, as the imagery was slightly off from the ground, eelgrass may have been recorded as present although it was not visible in the imagery because of the offset. Although every image had the same extent and all were displayed in false color infrared to distinguish vegetation, the reflectance spectra between images were not exactly alike, and for each image there may have been classes that were compromised by mosaicking effects.

Each image had approximately the same number of classes present within it and classes were checked individually through the raster attribute table. This table shows the signatures combined into individual classes with their class name, number, and spectral reflectance information. Following the methodology in the Standard Operating Procedure outlined above (Isa Woo and Ben Gustafson 2011), classes were examined one at a time to see all the pixels with values belonging to particular class, and initial accuracy could thus be determined by seeing which pixels belong to which classes. The image was then reclassified until classes were the least confused as possible meaning one class was made up of only those with the same or similar pixel values. This was an iterative process and required constant adjusting until a classification that represented the land cover classes in the image based on ground reference fieldwork and training areas was reached.

Another consideration is that eelgrass annual growth could be the reason for the changes observed in eelgrass distribution before and after the dike removal and restoration and the changes were not directly as a result of the disturbance. This possibility was accounted for through sampling at the same phenological stage of the plant and through an examination of annual growth rates. Multiple studies have shown that annual growth rates vary widely from those as a result of a disturbance (Olesen and Sand-Jensen 1994, Zharova et al. 2001, Giesen et al. 1990). Colonization is through both reproductive seed dispersal and vegetative growth of lateral shoots through rhizome cloning, although growth through seed dispersal has been shown to be more efficient and faster for average annual growth (Olesen and Sand-Jensen 1994). Eelgrass in the subtidal colonizes mostly through vegetative shoot growth not reproductive seed dispersal (Phillips and Watson 1984) and seed germination peaks in late fall and early spring, with dieback occurring in summer. It has been estimated that eelgrass in the Pacific Northwest on average adds 8-15 blades per year through vegetative growth (Phillips and Watson 1984); these however do not correspond to the large changes in distribution observed as a result of the dike removal and restoration.

Another major consideration for the integrity of the results is how much eelgrass was actually exposed, detectable by the camera, and identified as eelgrass between years. Although all images were taken at approximately the same conditions- low tide at mid to late morning in July of each year- the tides were dramatically different at the time each image was taken. The July

2009 and July 2011 imagery were both taken at approximately 11:00 am at tides of -.96 m. and -.54 m respectively, while the July 2010 was taken at approximately 9:45 am with a tide of -.33m. As noted in the Clinton et al. (2007) guide to mapping intertidal eelgrass in Pacific Northwest estuaries for aerial imagery the IR band cannot penetrate through water and thus cannot detect subtidal eelgrass unless it is exposed at a very low tide, there was high absorption even at shallow depths. This means that differences in eelgrass area between years stems from difference in tides when each image was taken, as the eelgrass growing in the Nisqually Delta is subtidal it will not be exposed unless there are low enough tides. Consequences of these tidal differences can be seen in the 2009 imagery versus the other two years. Eelgrass shows up as very bright red and very dense and expansive both on the eastern side of the delta (near Red Salmon Slough) and in the central and western (along McAllister Creek outfall) portions in the 2009 image compared with 2010 and 2011.

Although some of this is true change from the dike removal as evidenced with substrate type changes, other reasons for these changes are because the other imagery dates were taken at not as low tides meaning varying amounts of water covered eelgrass beds between each imagery year. In these cases subtidal eelgrass would not be exposed and therefore not identified as dense in the classification or the digitized polygons from the imagery. Medium dense eelgrass is likely even more affected. This could account for the large differences in area extent between years and comparisons between eelgrass and bare seafloor area. Both the classification and the imagery were sensitive to eelgrass exposure at low tide when the imagery was taken, leading to inconsistency in determining eelgrass areal extent over time. Further research could use imagery taken at consistent tides or apply other calibration measures such as known targets with specific spectral characteristics at varying depths to control for light attenuation with increasing water depth.

CONCLUSIONS

To determine if changes in eelgrass spatial distribution over time are related to the extensive dike removal and restoration of the Nisqually Delta, two mapping methods were implemented to determine accuracy of eelgrass change detection relative to changes in substrate-image classification and digitizing polygons from the imagery. In addition to these, substrate analyses between 2009 and 2011 illustrated changes from sandy to muddier substrates in the tidal flats as a possible result of geomorphic effects from dike removal.

Image classification of each image before the dike removal and one and two years after enabled a relatively fast and efficient method for determining land cover classes present within the image. Although error in classification was an issue, the overall percentage accuracy of 73% for the 2011 imagery was adequate for comparison of eelgrass classes over time. Classification excelled in identifying River Channel from other land cover classes but had issues with more easily confused vegetation classes such as those between marsh vegetation and restored wetland. This method of supervised classification can be used as a tool in which to see what is present within the imagery but cannot be used solely for explanations of change. The original imagery itself should be the main reference because it has fine resolution so the human eye can detect features that help delineate eelgrass beds. For this reason the research incorporated digitized dense eelgrass polygons from the imagery as another comparison of distribution change through time. Inherent issues with digitization also occur with human error becoming an issue. However using the texture of dense eelgrass in addition to what is visible in the image help to improve estimations. Consistently the classification underestimated the area of dense eelgrass as compared with the imagery digitization. These two methods in concert help to show change over time both with general area of eelgrass beds and with specific beds changing in area from dike removal and other external impacts.

Difference in tides was a major factor that contributed to the eelgrass area measures for both the classification and the imagery analysis. The imagery used for this research was not flown for the express purpose of eelgrass identification and thus not all subtidal eelgrass was exposed consistently between the imagery dates. Although the imagery was all flown at low tides it was collected to identify change in vegetation growing inside the former dike and to track the change from freshwater wetland to salt marsh vegetation. The change in elevation within the former dike and that in the tide flats also meant that vegetation in and outside the dike may not have been both exposed the same amounts during each date of imagery collection. Further studies could mitigate this by ensuring that imagery used was collected at dates where eelgrass would be exposed consistently by similarly low tides. This may also eliminate mosaicking issues which create false classes between tiles by prioritizing the eelgrass beds for collecting imagery.

Substrate type recorded both in 2009 and 2011 showed change that may have been caused as a result of the dike removal and could begin to explain where eelgrass distribution may be with increasing time after the restoration. Substrate changes help to illustrate the state of flux of sediment deposits in the Nisqually Delta as a result of the dike removal and restoration. Incorporating sediment core particle analysis of substrate for each year- including 2010- and an examination of tidal channel expansion into eelgrass beds could begin to quantify the causes for these changes.

Mapping eelgrass within the Nisqually Delta before and after an extensive dike removal and estuary restoration enabled eelgrass distribution to be observed at a time when the substrate and presumably geomorphology was changing rapidly. Eelgrass area extent was determined by comparing two mapping methods- classifications and digitization of dense eelgrass beds. This research showed clear change over time in eelgrass distribution and examined possible reasons for these changes with a comparison of substrate type over time and the possible implications on eelgrass beds as a result. Similar dike removal efforts are ongoing or planned throughout Puget Sound with little understanding of how valued eelgrass nearby will respond. With this research as a model, environmental managers focusing on eelgrass conservation may be able to use the maps and findings to improve conservation management. The results establish eelgrass presence currently and could enable monitoring trends of change with increasing time after dike removal. Although no one method is ideal for determining change in eelgrass distribution over time, remote sensing techniques combined with field data succeeded in creating a baseline explanation of change in eelgrass distribution within the Nisqually Delta as a result of the dike removal and estuary restoration in October 2009.

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