New tools for tidal wetland restoration: Development of a reference conditions database and a temperature sensor method for detecting tidal inundation in least-disturbed tidal wetlands of Oregon, USA

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- December 10, 2015: added URLs for online access; corrected tidal datum for elevation of low marsh on page 24; added footers on pages 168-194.

Expanded Executive Summary

Issues: Estuarine habitat restoration is a top priority for U.S. coastal regions. However, many projects fail or cannot be evaluated, in part because of a lack of reference conditions datasets from least-disturbed sites to guide restoration design, evaluation, and adaptive management (National Research Council 2001). In the Pacific Northwest, region-wide reference datasets on physical and biological attributes are lacking for the tidal wetland habitats that are the most likely target of restoration (e.g., emergent, scrub-shrub and forested intertidal wetlands). This data gap is caused in part by the high costs and limited accuracy of available methods for monitoring key habitat drivers.

Approaches and solutions: This project addressed the constraints described above by developing and evaluating the following tools:

1) A **restoration practitioner survey** which gathered input from active practitioners on data gaps, monitoring practices and restoration priorities. These results offer important guidance for research, outreach and education.

2) A **temperature sensor method** for generating spatially explicit data on tidal inundation regime, a major ecosystem driver in estuarine wetlands.

3) A **reference conditions database** developed from key physical and biological characteristics measured at six least-disturbed (unimpacted) estuarine wetlands in Oregon**.** Other sites are being added to the database, and practitioners are actively using the data to improve design, evaluation and management of tidal wetland restoration projects in Oregon and the Pacific Northwest.

4) A **web portal** (http://oregonexplorer.info), which provides restoration practitioners with easy access to reference conditions data and metadata.

A fifth project component, development of multichannel wireless sensor networks to monitor key physical attributes in tidal wetlands, was dropped due to our manufacturer advisor's repeated failure to deliver functional prototypes. Funds budgeted for this element were shifted to enhance our reference conditions database with a study of the carbon content in Oregon tidal wetland soils (see **Appendix 8**).

Applicability: These results represent substantial improvements over existing technologies, and have broad applicability. The **restoration practitioner survey** represented what we believe to be the first concerted effort to identify estuarine wetland restoration practitioners' data needs and restoration priorities in the Pacific Northwest. The **temperature sensor method** is an efficient, inexpensive method for gathering information on exactly where and when tides are flooding across a site. The dime-sized iButton temperature sensors we tested are easy to deploy and cost only $15 to $25 each. Existing methods are less accurate or more costly. A single tide gauge costing hundreds of dollars cannot provide detailed, spatially-explicit inundation data for large, complex sites. Other methods, like computer modeling, are much more expensive and require considerable expertise – and accuracy of results is limited by quality of model inputs. The use of affordable iButtons, however, generates direct evidence of inundation from multiple locations over a large geographic area simultaneously, with no need for elevation survey. In a separately funded project, our team successfully demonstrated the iButton method in mangrove swamps in China (Doumbia 2011), showing its potential for applicability in distant habitat types. The

reference conditions database offers a “one-stop” resource to support restoration design and evaluation of restoration results. Previously, data were found in scattered reports and scientific literature – often poorly accessible to the public. The database is regionally applicable, and the database structure provides a broadly-applicable template for development of similar databases in other regions. The **web portal** is easily accessible, and because it is a permanent part of the Oregon State University Library system, it will be maintained and updated into the future.

Potential enhancements: Although all of these products are fully developed and delivered to end users, we see potential for future enhancements. 1) The temperature sensor method would benefit from development of application-specific software to automate detection of tidal inundation events. 2) Additional sites should be added to the reference conditions database. We are currently compiling and analyzing data for this purpose in our other projects. 3) A follow-up restoration practitioner survey within the next few years could provide useful updates to this study’s 2007 survey, revealing changes in priorities, data availability and monitoring activities.

End users: Feedback from our end user advisors improved our results. Those advisors were Stan Van de Wetering, Biologist, Confederated Tribes of Siletz Indians; Jon Souder, Executive Director, Coos Watershed Association; David Pitkin, USFWS Biologist (now deceased); and Nina Garfield, NOAA ERD. Representatives from NOAA NCCOS and the NOAA Restoration Research Program also agreed to be end user advisors for this project, but did not respond to our requests for feedback. A broad group of tidal wetland practitioners and coastal resource managers are now using our project results throughout the Pacific Northwest, and nationally and internationally (in the case of the temperature sensor method).

Key Findings

Temperature Sensor Method

- **Applicability to a priority coastal issue:** The temperature sensor method is broadly applicable to studies of coastal inundation in a variety of habitat classes in different geographical zones.
- **Cost:** The temperature sensor method is very inexpensive. Individual iButtons cost less than $20, software to launch and download iButtons is free, and required hardware (probes and connectors) currently costs $37US. Data can be analyzed using spreadsheet software such as Microsoft Excel or Open Office. By comparison, water level loggers generally cost over $400 per location, with additional costs for software.
- **Maintenance requirements:** iButtons require no maintenance. Most commercially available water level loggers are also maintenance-free.
- **Accuracy:** iButtons can detect time and duration of tidal inundation with temporal accuracy equal to the half the datalogging interval (adjustable from 1min to 255min). Accuracy of inundation frequency and duration measurements using commercially available water level loggers depends on the accuracy of the device’s internal clock, typically +/- 1min/mo to 1min/yr. iButtons do not measure depth of inundation. However, inundation depth can be estimated using a vertical array of iButtons; accuracy depends on vertical spacing of sensors. Accuracy of depth measurements using commercially available water level loggers varies with the cost and measurement range of the device; typical devices have an accuracy of around 0.5-1cm.

- **Speed:** The thermal response time for the iButton model we used (DS-1921G) is approximately 2min. The thermal response time for a typical commercial water level logger (Onset U20-001-01) is 10min.
- **Ease of use:** Ease of use for iButtons is comparable to commercially-available water level loggers. Application-specific software would make the method more user-friendly.
- **User capacity requirements (supplies, skills, hardware):** Hardware and supplies for using iButtons are inexpensive and easy to obtain (see **Cost** above).

Pilot Reference Conditions Database and Web Portal

- **Applicability to a priority coastal issue:** The pilot reference conditions database, disseminated via the web portal, offers a powerful tool for design, evaluation and management of tidal wetland restoration sites.
- **Cost:** The pilot reference conditions database is available online at no cost to end users at http://oregonexplorer.info/wetlands/DataCollections/ReferenceSiteData.
- **Maintenance requirements:** The reference conditions database requires no maintenance by end users. Web portal maintenance will be performed by the OSU Library system.
- **Accuracy:** Accuracy of data in the reference conditions database depends on the methods used for each parameter. See **Methods** below for details.
- **Speed:** End user access to the reference conditions database is instantaneous, a major advantage over previous methods of locating such data (literature searches, library visits, or correspondence with multiple practitioners and researchers).
- **Ease of use:** The reference conditions database is user-friendly compared to previous methods. Information is presented in broad categories, but users can drill down to specifics.
- **User capacity requirements (supplies, skills, hardware):** No skill is required to access the reference conditions database; a computer and internet connection are required.

Restoration Practitioner Survey

- **Applicability to a priority coastal issue:** The restoration practitioner survey determined data gaps, monitoring practices and restoration priorities as perceived by active restoration practitioners. These results offer important guidance for research, outreach and education.
- **Cost:** End users have free access to the results of the restoration practitioner survey at the Oregon Explorer website (http://oregonexplorer.info).
- **Maintenance requirements:** The restoration practitioner survey requires no maintenance by end users. As mentioned above, a follow-up survey in a few years would be useful.
- **Accuracy:** Not assessed.
- **Speed:** End user access to the restoration practitioner survey is immediate via the web portal described above, a major advantage over previous methods for locating information on restoration practices (literature searches and personal communication).
- **Ease of use:** The restoration practitioner survey is user-friendly; nontechnical language was used, and information is presented both graphically and in narrative format.
- **User capacity requirements (supplies, skills, hardware):** No skill is required to access the restoration practitioner survey; a computer and internet connection are required.

Project Development

Abstract

Coastal wetland loss is a worldwide concern, and predicted climate change and sea level rise further threaten these valued ecosystems. In the Pacific Northwest, there have been substantial losses of tidal wetlands, particularly scrub-shrub and forested wetlands ("tidal swamps"). Tidal swamps were once prominent in Pacific Northwest estuaries, but are now very rare; they have been little studied or characterized. In this study, we developed an innovative monitoring technology and piloted an online, multi-site reference conditions database for estuarine wetlands in Oregon, USA, with the ultimate goal of improving conservation and restoration effectiveness. An initial restoration practitioner survey queried regional estuarine restoration practitioners for restoration priorities and data gaps. The survey results guided selection of field sites and monitoring parameters for this study. Study sites were least-disturbed estuarine wetlands spanning the salinity range from euhaline to freshwater tidal and including examples of all major habitat classes: low marsh, high marsh, shrub and forested tidal wetlands. We collaborated with representatives from NOAA/NGS to obtain accurate land surface elevation surveys at our study sites. In collaboration with NOAA COOPS and other scientists, we then modeled tidal datums and river flow regimes to develop an integrated tidal/fluvial inundation regime ("total water level") model for 5 of our 6 study sites. Our team developed, tested and validated an innovative application of inexpensive iButton temperature loggers to detect tidal inundation (the "temperature sensor method"). We monitored additional controlling factors (channel water salinity, soil physicochemical characteristics, and groundwater level) and structural and biotic characteristics (vegetation and benthic invertebrate assemblages) to improve our understanding of ecosystem responses to the physical environment. To enhance the soils database, we analyzed carbon content from 75 soil samples across 10 additional least-disturbed tidal wetland reference sites, two diked and drained former tidal wetlands, and five tidal wetland restoration sites on the Oregon coast. Distinct differences in results by habitat class and land use history shed light on little-understood and highly impacted estuarine resources. Results were summarized in a pilot reference conditions database, which serves as a new resource for restoration design, resource management, and evaluation of restoration effectiveness. Study products – the reference conditions database, a User Guide to the iButton temperature sensor method, and the practitioner survey results – were disseminated via a pre-existing web portal -- the Oregon Explorer website (http://oregonexplorer.info/).

Introduction

Need for Reference Conditions Datasets

Estuarine habitat restoration is a top priority for U.S. coastal regions. However, many projects fail or cannot be evaluated, in part because of a lack of reference conditions datasets for restoration design, evaluation, and adaptive management (National Research Council 2001). Locating appropriate individual reference sites for restoration projects can be challenging in highly altered coastal landscapes (Schreffler and Thom 1993). A more robust approach is development of reference conditions datasets based on multiple reference sites (Merkey 2005, Thayer *et al.* 2003, Diefenderfer *et al.* 2003, Brinson 1993). Reference datasets should quantify controlling factors ("ecosystem drivers") such as tidal hydrology, groundwater regime, and salinity, as well as prioritized physical and biological attributes such as soil organic matter content, plant community composition and invertebrate assemblage composition and abundance (Thayer *et al.* 2005, Zedler 2001, Simenstad *et al*. 1991).

In Oregon, reference datasets based on multiple sites are lacking for the tidal wetland habitats that are the most likely targets of restoration -- emergent, scrub-shrub and forested intertidal wetlands (see **Appendix 12**). Data are particularly sparse for scrub-shrub and forested intertidal wetlands -- a significant challenge for restoration practitioners, since these habitat classes have been disproportionately altered by coastal development (Brophy 2005a, 2007a; Graves *et al*. 1995, Thomas 1983). Monitoring programs to establish reference conditions datasets should address these priority habitats and should be deliberately responsive to the needs of restoration practitioners. To be most useful to restoration practitioners, reference conditions datasets should be available through a central, accessible source.

Need for Cost-effective Monitoring Technologies

The expense and technical challenges of project site monitoring contribute to the reference dataset gap. To fill this gap and improve restoration efficacy, scientists and practitioners need cost-efficient and accurate monitoring methods and technologies. This need is particularly acute for three key habitat drivers: Tidal inundation regime (TIR), groundwater fluctuation, and salinity regime.

Among other goals, our project focused on developing an innovative method for measuring TIR that is inexpensive, and spatially and temporally precise. Current methods used to measure TIR are either imprecise or too costly for many practitioners. Continuous water level loggers to monitor tidal inundation or tidally-influenced groundwater levels generally cost $400-$1,000 per logger, including barometric pressure compensation (Onset Corporation 2011, Global Water Instrumentation Inc. 2011). Equipment installation can be time-consuming, and elevations of the instrumentation and study area must be acquired using costly geodetic survey methods to convert water level data to inundation regime. Because of these costs and logistics, many tidal wetland restoration and mitigation projects fail to monitor TIR onsite, instead estimating TIR by comparing wetland surface elevation to area tide chart predictions, or to data from nearby (or distant) tide gauges. Results can be inaccurate, particularly in middle and upper estuarine zones, which are generally distant from the NOAA tide stations used to create tide chart predictions. When distant (or onsite) tide gauges are used to predict inundation, accuracy may be low if factors such as variable river flow, dense vegetation, beaver activity, and tidal channel roughness and sinuosity create substantial deviations from predicted tide height. Lack of accurate data on inundation can have serious consequences, such as risks to infrastructure, liability exposure, and failure of restoration projects to meet performance criteria (Jon Souder, Coos Watershed Association, and James W. Good, Oregon State University, personal communication; Simenstad and Thom 1996).

Goals and Objectives

Goals

Goal 1: Test and develop innovative, cost-effective methods for gathering high spatial and temporal resolution data on three primary drivers of tidal wetland structure and function (tidal inundation regime, groundwater fluctuation, and salinity regime), thereby contributing to NOAA/NCCOS and other national monitoring guidance efforts.

Goal 2: Pilot an Oregon contribution to the NERRS/NOAA regional restoration reference site program by collecting data from a network of representative Oregon tidal wetland habitats, using NOAA/NCCOS restoration monitoring guidance.

Goal 3: Contribute to both NCCOS and NERRS efforts by populating a new reference conditions page on the Oregon Explorer web site which has been designed to provide easy access to reference site data and metadata and other relevant monitoring information to restoration practitioners.

Objectives

Objective 1: "iButton" temperature sensor method for monitoring TIR. Develop and test an innovative method using "iButton" temperature loggers to detect tidal inundation and generate spatially explicit data on tidal inundation regime.

Objective 2: Reference conditions database. Establish statistically rigorous baseline datasets for key habitat attributes in a network of high priority least-disturbed tidal wetlands in coastal Oregon, to help restoration practitioners improve restoration design, effectiveness monitoring, and adaptive management.

Objective 3: Internet-based interactive web portal. Test and demonstrate a reference conditions page on the Oregon Explorer web page providing restoration practitioners with easy access to reference conditions data and metadata.

Objective 4: Restoration practitioner survey. Test and demonstrate methods to solicit practitioner input on data gaps, monitoring practices and restoration priorities. Use results to guide site selection for the current study, and to guide future research, outreach and education.

Our proposal contained one additional objective, **multichannel wireless sensor networks.** This objective was dropped because the manufacturer ultimately withdrew from the project after repeatedly failing to deliver functional prototypes; therefore, no further information about this objective will be presented in this report. The sensor networks were intended to generate high-resolution, reliable and accurate data on water level (including TIR and groundwater fluctuation), salinity (channel and porewater), and water temperature (channel and porewater). After the manufacturer withdrew from the project, the funds dedicated to this objective were re-allocated to the expansion of our reference conditions soils database (see **Results: Soils** and **Appendix 8** below).

Technical Methods

In the sections below, we describe the technical methods for each of our project objectives.

Methods: Temperature Sensor Method

The temperature sensor method for detecting tidal inundation, developed during this study, is based on the likelihood that the temperature of tidal waters inundating a wetland will differ from ambient air temperature. Oregon researchers had previously used temperature sensors (iButtons) to detect inundation in the rocky intertidal zone (Helmuth 2002; S. Hacker, Oregon State University, personal communication), and efforts had been made to use temperature sensors to document inundation in other intertidal environments (Helen Berry, Washington Department of Natural Resources, personal communication). However, a temperature sensor method for determining tidal inundation regime in emergent to forested estuarine wetlands had not previously been developed.

Selection of Datalogger Technology

Since the temperature sensor method is based on temperature differentials, any temperature logging device could, in theory, be used. Given our project goals, our first requirement was low cost, so we compared available temperature logging devices in the low price range (<$50US each). Only two temperature loggers were available in this price range at the beginning of our project in 2007: Onset HOBO Pendant loggers (http://www.onsetcomp.com/products/data-loggers/ua-001-08) at $42US each, and iButtons (http://www.maxim-ic.com/products/ibutton/products/ibuttons.cfm) at $12US each. Between these two devices, iButtons were superior for our purposes because of their very small size and low cost. iButtons are dime-sized, only 0.17cm diameter by 0.06cm thick, comparing favorably to the much larger Onset Pendant loggers (5.8 x 3.3 x 2.3cm). This small size and low cost allows easy deployment of multiple iButton arrays, enabling collection of data at very high spatial and temporal resolution. For example, a restoration practitioner could monitor TIR at 10 locations on a site, providing greatly superior spatial resolution for about half the cost of a single tide gauge; or they can simply deploy three iButtons (one “unknown,” one air reference and one water reference) at low cost to verify tidal inundation at a particular point of interest.

How the Temperature Sensor Method Works

The temperature sensor method relies on the difference between air and water temperature to detect tidal inundation. In our study, duration and timing of tidal inundation were determined by comparing the temperature at a particular “unknown” iButton to reference water and air temperatures (obtained with other iButtons). Time of tidal inundation at a “variable” iButton was marked by an “inundation signal” – a rapid convergence between the temperature of the variable iButton and the reference water temperature, and rapid divergence between the variable iButton’s temperature and the reference air temperature. Conversely, time of re-exposure of the variable iButton was marked by divergence between the variable iButton temperature and the reference water temperature, and convergence between the variable iButton’s temperature and the reference air temperature (the “re-exposure signal”).

iButton Sourcing

We purchased 168 iButtons for this project, and 10 more were donated to our project by Dr. Sally Hacker of Oregon State University. This total of 178 iButtons enabled us to test the method at all of our study sites simultaneously, improving our ability to interpret results during different weather and tidal conditions and in different seasons.

iButton Waterproofing

Instrumentation for measuring tidal inundation should be waterproof, but iButtons are only rated as water-resistant (http://www.maxim-ic.com/datasheet/index.mvp/id/4023). Waterproof enclosures were therefore needed, and these enclosures needed to be inexpensive and easy to construct. The enclosures also needed to allow close contact between the iButtons and the surrounding air or water in order to achieve rapid temperature response. After testing several methods, we found the easiest and most effective method for waterproofing iButtons was to vacuum-seal the buttons in plastic using an inexpensive consumer-grade vacuum sealer (Tully 2007).

iButton Bench Tests and Field Deployments

We conducted numerous bench tests and two pilot field tests of iButtons. Details on bench and pilot tests are found in Tully (2007). The pilot tests led us to develop two alternative iButton deployment methods: 1) wetland surface deployments, and 2) vertical post deployments.

In the ***wetland surface deployment method*** (Photograph 8, **Appendix 4**), individual iButtons were mounted in protective white PVC tube housings attached to the wetland surface in a horizontal orientation; other iButtons were attached in the deepest portions of channels to provide reference data on channel water temperature, and in locations above the highest tides (in both sun and shade) to provide reference air temperature data. Our initial pilot test used this method; results suggested that the main challenges in data interpretation would relate to differing sun/shade environments between wetland surface buttons and those logging reference air and water temperatures.

The ***vertical post deployment method*** (Photographs 7 and 9, **Appendix 4**), was developed as one possible response to these challenges. Vertical post deployments used a series of 3 or 4 iButtons mounted vertically on rods inside perforated, well-vented PVC tube housings. These stake assemblies provide a more consistent, shaded environment within which temperature change due to water inundation might provide a clearer signal. In our second pilot test at the Yaquina Swamp (see **Study sites** below), both deployment methods were successful. Vertical post deployments require elevation survey to wetland surfaces of interest (see **Results: Temperature Sensor Method** below).

We deployed 4 vertical posts, 8 wetland surface iButtons, and water and air reference iButtons at our 5 study sites in summer 2007 and winter 2008 (**Appendix 1**, Maps 2-6). Wetland surface iButtons were deployed in a rectangular array at the outer perimeter of each study plot (see **Methods: Sample design** below). Reference iButtons were deployed in deep channels and in air (both sun and shade locations) nearby. The 4 vertical post deployments were placed in deep tidal channels, one near each study plot and two in other locations nearby. The July 2007 deployment lasted 21 days and included all of our study sites. Full details on this deployment are found in Tully (2007).

Our test sites on the Oregon coast have considerable seasonal variability, with cool rainy winters and warm dry summers. To test applicability of the method under these varying seasonal conditions, we conducted a second deployment in January 2008. Duration, logging interval, and deployment methods were the same as in July 2007.

Methods: Reference Conditions Database

Methods: Study Sites

Field work was conducted at six sites on the Oregon coast: five study sites and one pilot test site. Site selection was based on the following criteria:

- Range of sites covering all major vegetation classes (emergent, shrub and forested) for PNW tidal wetlands

- Geographic spread from north to south Oregon coast
- Habitat classes identified as an information gap in the Restoration Practitioner Survey
- Tidal influence apparent, with well-defined tidal channels
- Availability of large, internally homogeneous blocks of wetland vegetation within a given Cowardin class
- Tidal energy regimes typical of each habitat class
- Least-disturbed, and protected from future disturbance
- Easily accessible, for efficient sampling during brief visits

The six sites selected were the pilot test site (Yaquina Swamp), and five study sites (Blind Slough, Coal Creek, Siletz Keys, Millport Slough, and Hidden Creek Marsh) (Map 1, **Appendix 1**; Photographs 1-6, **Appendix 4**). Site characteristics are shown in Table 1 (**Appendix 2**). Since one of the goals of this project was to determine how the temperature sensor method functioned in different habitat classes, sites were selected to represent the full range of emergent to forested tidal wetland vegetation classes present in the Pacific Northwest. We did not attempt to evaluate the method in intertidal aquatic bed classes.

Methods: Monitoring Parameters and General Approach

To establish our pilot reference conditions database, we needed to gather information on key controlling factors, structural characteristics, and biological outcomes, in order to determine relationships among these factors. We gathered data on key components of a conceptual model of Pacific Northwest estuarine wetlands (Roegner *et al*. 2008, Thom *et al*. 2004), which are also recommended monitoring parameters for assessing effectiveness of tidal wetland restoration projects in the Pacific Northwest and nationally(Roegner *et al*. 2008, Thayer *et al*. 2005, Rice *et al*. 2005). The parameters we measured are listed in Table 2 (**Appendix 2**). Our methods for measuring these parameters are described below; these methods were based on regional and national guidance (Roegner *et al*. 2008, Thayer *et al*. 2005, Rice *et al*. 2005, Simenstad *et al*. 1991, Zedler 2001), as well as our team's experience monitoring Oregon tidal wetlands (e.g. Brophy 2001, 2002a, b, 2004a, 2007b) and the recommendations provided by Brophy (2007a).

Methods: General Sample Design

Our general sample design was based on our team's field experience monitoring Oregon tidal wetlands (as listed above) and assessing estuarine wetland resources (Brophy 1999, 2001, 2003, 2005a, 2007a; Brophy and So 2005a, b, c). Permanent study plots were used to structure all sampling for physical and biotic characteristics at each site. Plots were placed within strata characterized by internally consistent elevation, vegetation type, and mapped soil type. (Since accurate elevation data were not available at the time of study plot layout, we used vegetation patterns visible in aerial photographs as a guide to likely elevation zones.)

Two sites (Blind Slough and Hidden Creek Marsh) contained more than one Cowardin class; these classes were sampled separately (1 plot per class at Blind Slough, 2 plots per class at Hidden Creek Marsh). Plot characteristics are shown in Table 3 (**Appendix 2**). Plot size was 60 by 150ft (18.3 by 45.7m), except for Hidden Creek Marsh Plots 3 and 4, where slightly smaller plots were used to avoid crossing visible elevation strata. Sampling methods within study plots varied by parameter; see sections below for details.

Methods: Vegetation

Vegetation was sampled in 2007 and 2008 at randomly-located sample units within each study plot. Sample unit size varied by stratum (herbaceous, shrub or tree). For shrub and forested plots, the different-sized sample units were nested within the study plots following methods described in Peet *et al*. (1998). Vegetation was not sampled at the Yaquina Swamp pilot test site because it had previously been characterized by Brophy (2007b, 2009a) using the same methods.

Herbaceous vegetation at low and high marsh sites (Hidden Creek Marsh, Siletz Keys and Millport Slough) was sampled in both 2007 and 2008, but woody vegetation was sampled only once in 2007 due to the high time requirements for sampling these sites, the fragile nature of the understory vegetation at Blind Slough – easily damaged by the act of sampling (Photograph 19, **Appendix 4**) -- and inaccessibility of plots at Coal Creek due to extensive wind-throw during the record-breaking December 2007 windstorm (Photograph 18, **Appendix 4**).

For emergent wetlands (Hidden Creek Marsh, Siletz Keys and Millport Slough), percent cover of herbaceous vegetation was visually estimated within ten 1sq m quadrats located along the central axis of each study plot (Photograph 20, **Appendix 4**). Locations for these 10 quadrats were randomized in 2007 at all sites, and at the Hidden Creek Marsh site in 2008. At the Millport Slough and Siletz Keys sites in 2008, we used a partial replacement method: 5 of the 2007 quadrats were re-sampled, and the other 5 quadrats were re-randomized.

For shrub and forested wetlands (Blind Slough and Coal Creek), shrub measurements were made within ten subplots, each 60cm by 5m, extending at a right angle to the plot’s central axis from a random starting point. All shrub stems were counted and identified to species within each of these subplots. For multiple-stemmed shrubs, stems were counted using the methods described in Peet *et al*. (1998): Branches (stems) that emerged below 50 cm (about knee height) and reached breast height (137cm = 4.5ft) were counted separately. For multiple branches (stems) that emerged above knee height, only the dominant branch was counted. Stem counts were “binned” – that is, placed into diameter classes: 0-1cm, 1-2.5cm, 2.5-5cm, 5-10cm, and 10-15cm. However, analyses were conducted for the total stem count, not by diameter class.

For forested wetland plots (Blind Slough P1, Coal Creek), trees were counted and measured within the entire study plot (60 by 150ft). Each tree was identified to species and its diameter was measured at breast height (dbh). Average percent cover, woody stem density and basal area were calculated for each species within the entire plot.

Methods: Soils

Soil samples from the surface rooting zone (0-30cm) were collected using a Dutch auger at 10 to 20 random subsample locations within each study plot. Where an obvious horizon boundary occurred within the surface 30cm, the lower horizon was sampled separately (at Siletz Keys), or excluded (at Hidden Creek Marsh). Subsamples were bulked in the field; in the lab, large roots were removed and samples were mixed and dried. Laboratory analysis was conducted by the Oregon State University Central Analytical Laboratory, where pH and electrical conductivity of the soil solution were measured, percent organic matter was determined by loss on ignition, and particle size analysis was conducted by the quick hydrometer method (after initial treatment with hydrogen peroxide to remove organic material).

In addition to the soil samples collected at our six study sites, we conducted a separate study to enhance our reference conditions database and address a soils data gap in the Pacific Northwest.

We measured soil carbon content from 75 locations at 13 tidal wetland reference sites and 7 tidal wetland restoration sites to address this data gap and expand this project's reference conditions database. Soils were sampled and analyzed using the methods described above; see **Appendix 8** for details.

Methods: Groundwater

We monitored groundwater levels in both plots at each of our shrub and forested wetland sites (Blind Slough and Coal Creek), and at two of our four high marsh study plots (Millport Slough Plot 2 and Hidden Creek Marsh Plot 4). We did not monitor groundwater at the low marsh sites, since informal observations suggested that groundwater in these habitats probably remains at or near the soil surface year-round regardless of tide cycle (since these habitats are inundated daily by the tides). Groundwater was monitored using standard shallow groundwater observation wells (U.S. Army Corps of Engineers 2005) but well design was modified as follows: tall risers were installed to prevent overtopping of the wells by surface tidal flows (Photographs 21 and 22, **Appendix 4**). In addition, the dense vegetation and challenges of foot travel made transport of sand to the well sites difficult, so we wrapped the perforated section of the well ("well screen") with three layers of heavy-duty commercial landscape cloth to exclude sediment instead of using a sand filter. Automated water level loggers (Onset HOBO Model U20-001-01) were deployed in each well from January 2009 through January 2010 at Blind Slough, Coal Creek, and Millport Slough P2; from January 2009 through November 2009 at the Yaquina Swamp pilot test site; and from March through December 2010 at Hidden Creek Marsh P4. Data were collected at 12 to 15min intervals. This extensive groundwater data collection was well beyond the project's original scope of work; therefore, due to time limitations, we were not able to adjust results for barometric pressure. As a result, our results may vary a few centimeters from actual groundwater levels depths during storm events.

Methods: Channel Water Salinity

Four YSI sondes (models 6000 and 6600) were available for salinity logging at our study sites. Sondes were installed in major tidal channels near study plots within the Blind Slough, Coal Creek, Millport Slough, and Siletz Keys study sites (Maps 2-5, **Appendix 1**). Salinity was logged at 12min intervals from late February through early June 2008. The measured salinities can be considered representative of surface water salinities at our study plots, since study plots at these sites were not located near any channelized freshwater inputs or major hillslope seepages. Channel water salinities for Hidden Creek Marsh were obtained from the Winchester Creek station of South Slough NERR's System Wide Monitoring Program (Rumrill 2006). The Winchester Creek station is about 1,300 m from the Hidden Creek Marsh site, so salinities should be representative of surface water salinities at Hidden Creek Marsh Plots 1, 2, and 3, which lack freshwater inputs. However, surface water salinities at HM P4 could be somewhat lower (particularly in winter), since HM P4 is located near a small freshwater drainage.

Methods: Elevation Survey

NOAA/National Geodetic Service (NGS) collaborated with our project team to conduct accurate elevation surveys at our study sites (Photographs 11-18, **Appendix 4**). NGS established permanent vertical control (elevation benchmarks) at each project site, and tested high precision RTK GPS equipment for mapping wetland surface elevations. The test was successful, producing accurate results even under challenging field conditions at Blind Slough and Coal Creek (tall, dense shrub and tree canopy cover). NGS survey crews acquired elevations of iButton deployments, tide gauges, and study plot wetland surfaces (plot axis endpoints, plot corners, and surrounding wetland surfaces). In addition, at our tidal marsh sites (Millport Slough, Siletz Keys and Hidden Creek Marsh), NGS surveyed the overall project site (marsh plain and/or channels). At the Siletz Keys and Hidden Creek Marsh sites, we demonstrated the use of the marsh plain survey data to create a visual map of elevations using the “create TIN from features” tool in ArcGIS 9.3 (Maps 12 and 13, **Appendix 1**). The tide gauge elevations were used (along with water level data) to calculate tidal datums for each site; study plot elevations were used to calculate tidal inundation regimes for each plot.

Methods: Water Levels, Tidal Datums and Inundation Regime Modeling

To determine local tide range, tidal datums, and inundation regime at each site, we monitored water levels using Onset HOBO (model U20-001-01) and Global Water (WL-16) water level loggers. Loggers were factory-calibrated and bench-tested for accuracy prior to deployment. We deployed the loggers in standard stilling wells in the deepest available tidal channel near study plots at each site. Logging interval was 12 to 15 minutes depending on deployment period; duration is shown in Table 1, **Appendix 9**. Data from the non-vented Onset HOBO water level loggers were adjusted for ambient barometric pressure using the manufacturer-provided software (HOBOWare Pro). Continuous barometric pressure records for the water level monitoring period were obtained from nearby National Weather Service stations (online data) for all sites except Hidden Creek Marsh (where South Slough NERR weather data were used).

Using the elevations of the water level sensors at our tide gauges (see **Methods: Elevation survey** above), we determined water levels relative to a geodetic datum (NAVD88). Tidal datums at the 6 sites were then calculated by simultaneous comparison with NOAA/CO-OPS tide stations. Astoria station (9439040) was used to determine datums for Blind Slough; Garibaldi (9437540) for Coal Creek; South Beach (9435380) for Millport Slough, Siletz Keys, and the Yaquina Swamp pilot test site; and Charleston (9432780) for Hidden Creek Marsh.

Through collaboration with the CO-OPS, we applied an innovative “total water level” (TWL) method for modeling combined tidal and fluvial inundation regimes. We applied the model at those sites most likely to experience a strong fluvial contribution to the inundation regime (Coal Creek, Millport Slough, Siletz Keys and Yaquina). Our model built upon a method first developed by Burgette *et al*. (2009) which assesses combined tidal and fluvial inundation in Oregon estuaries where river flow strongly influences inundation regime. This approach was subsequently modified for use in the Siuslaw River estuary of Oregon (Dr. Ray Weldon, personal communication), where it has been used to guide wetland restoration planning and evaluate restoration results (Brophy 2009a).

We used two slightly different versions of the total water level method. At Millport Slough, Siletz Keys and Yaquina Swamp, we used the method detailed in **Appendix 9**: local water levels were detided, and a regression was run on the detided water levels *versus* normalized river discharge; results were used to generate predicted water levels. At Coal Creek, we used the more refined model described in **Appendix 10**, including generation of tide predictions using harmonic constituents. See the appendices for details.

Working concurrently with Brophy’s monitoring work in the Siuslaw estuary (Brophy 2009a), we developed new, user-friendly inundation regime metrics to express the inundation regimes calculated above. Inundation regime is usually expressed as “percent of time inundated” or "hours inundated" per month or per year – metrics that aren't easy to relate to end users' field experience of spring and neap tide cycles. We added a new metric -- number of days with at least one inundation event during each month. This metric can be more easily related to spring and neap tide cycles – for example, if a site has 3 days with inundation events during July, that suggests it only floods on spring tides during the summer. If a site has 20 days with inundation events during January, it floods on both neap and spring tide cycles in winter. We developed graphics expressing these metrics by month, to illustrate the importance of the yearly precipitation cycle to inundation regimes in our region. We also developed graphics illustrating inundation regime at typical and high river flows, to show the variability and importance of the fluvial component. These metrics and graphs offer new visualization tools to help scientists and practitioners understand tidal inundation regimes.

Methods: Benthic Invertebrates

Oregon Institute of Marine Biology contracted with Ayesha Gray of Cramer Fish Sciences, Gresham, OR to design and implement the benthic invertebrate sampling at our study sites. Full details on this project component are provided in **Appendix 11**. Benthic invertebrate samples were collected in 2007 and 2008. Sampling methods followed the Estuarine Habitat Assessment Protocol (Simenstad *et al*. 1991). Fifteen replicated benthic core samples (90 total) were collected in 2007 and 12 replicated samples (72 total) in 2008. Samples were collected at our five primary study sites (Hidden Creek Marsh, Siletz Keys, Millport Slough, Coal Creek, and Blind Slough); benthic invertebrates were not sampled at our Yaquina Swamp pilot study site. The 2008 sampling omitted the shrub tidal wetland stratum at Blind Slough (Plot 2) due to the difficulty of locating an appropriate substrate for the benthic cores (substrate consisted of dense root fibers). Samples were taken near the study plots but not directly in the plots, since benthic invertebrates must be sampled from exposed substrates during low tide in tidal channels. Therefore, the sample locations are representative of habitat classes (low marsh, high marsh, shrub tidal wetland, and forested tidal wetland) rather than study plots.

In the lab, all benthic invertebrates in each core were counted and identified to the finest taxonomic resolution possible without dissection (generally to family or species). Invertebrate assemblage characteristics were explored using multivariate statistics, and indicator species were identified. Further details on sampling, processing and analytical methods are provided in **Appendix 11**.

Methods: Compilation of Reference Conditions Database

We summarized project data and initiated a reference conditions database. We organized the database in two ways: study plot average, and habitat class range. Since study plot layout was stratified (see **Methods: General sample design** above) and the study plots were carefully selected to be representative of their habitat class at the study site, they provide useful information at the highest possible resolution given our sample design. By contrast, the range of values for each habitat class is fairly broad and overlaps between habitat classes for most parameters. Because of the breadth of the range, we did not average data within habitat classes. One end user commented that the site-specific information (organized by study plot) was more useful than the habitat class range (Jon Sounder, personal communication).

One of the objectives of our study was to determine whether there were strong relationships between physical site characteristics (elevation, inundation regime, groundwater, soils, channel water salinity) and biological attributes (vegetation, benthic invertebrates). Since our study had a very limited number of samples per habitat class (4 permanent plots in low marsh, 4 in high marsh, 3 in forested, 1 in shrub) we did not attempt to determine statistical significance of differences. In this section, we describe the contrasting physical characteristics within the different habitat classes, and compare our results to other studies.

Evaluation Methods

Evaluation Methods: Validation of Temperature Sensor Method

To validate the iButton method and to calculate tidal inundation regimes, we used water level data collected with commercial water level loggers (see **Methods: Water levels, tidal datums and inundation regime modeling** above). We surveyed the elevations of iButtons and used the water level logger data to predict the time at which that elevation would have inundated. We then compared the predicted time of inundation to inundation and re-exposure "signals" described above. See **Results: Validation of Temperature Sensor Method** below. Validation was conducted for four tide cycles in summer 2007 and winter 2008, at two tidal swamp sites (Blind Slough, Coal Creek) and one tidal marsh site (Siletz Keys).

Collaboration Methods

Project Team

We collaborated with team members via face-to-face meetings, phone calls, and email throughout this study. Team members contributed consistently to every step of the project, from initial site selection and development of technology specifications to interpretation of study results. The end user advisors listed above also provided input throughout the study. Their input was most intensive during early phases of the project, when we were developing the format for the reference conditions database and specifications for technology.

Graduate Student Projects

This study formed the basis for Master's degree research projects completed by Rebecca Tully, Julie Doumbia, and Megan MacClellan within the Marine Resource Management Program, College of Oceanic and Atmospheric Sciences, Oregon State University. All three of these students have successfully defended their Master's projects; final reports are completed (Tully 2007) or in preparation (Doumbia 2011, MacClellan 2011).

Restoration Practitioner Survey

In March 2007, Cornu, with the assistance of Laura Brophy, John Bragg (South Slough NERR's CTP Coordinator), and Derek Sowers (former Oregon Department of State Lands Wetland Restoration Specialist), developed the Pacific Northwest Estuarine Wetland Restoration Information Gaps Survey using the on-line format provided by SurveyMonkey.com. Draft versions of the survey were circulated for comment to a regional restoration advisory team that included representatives from NOAA Fisheries and the NOAA Restoration Center. Comments were considered by the survey authors who determined the final structure and wording of the survey questions. The goals of the survey were to: 1) provide an end-user "reality check" with respect to the estuarine habitats selected for this CICEET project's reference conditions database; and 2) provide the basis for discussions about adaptive approaches to estuarine wetland restoration in the Pacific Northwest at an estuarine wetland restoration advisory group meeting convened at the South Slough NERR in July 2007.

The survey was distributed via e-mail on April 3, 2007 to 50 restoration scientists, planners, and practitioners from government agencies, and non-profit, consulting, and academic organizations including watershed associations. The message we sent with the survey link to potential respondents is included in **Appendix 12**.

Knowledge Dissemination Methods

User's Guide to the Temperature Sensor Method for Determining Tidal Inundation Regime

To help end users apply the temperature sensor method, we created a step-by-step **User's Guide to the Temperature Sensor Method** (**Appendix 5**). The guide focuses on lessons learned during development of the method, and provides practical hints to improve results. We disseminated the guide *via* the web portal described below.

Web Portal

One of the goals of this project was to explore the feasibility of providing easy access to long term datasets that describe the natural variability of key attributes in a variety of tidal wetland habitat classes. Posting the data to a stable location on the web offered the most logical and workable solution.

Several web portals and associated programs were considered as host for the data. After considering alternatives, we chose to work with Oregon State University's Institute for Natural Resources (INR), and disseminate our results via the INR web portal, Oregon Explorer (http://oregonexplorer.info). This portal provides an ideal host for the reference conditions data. The Program's goals ("…integrate and provide comprehensive information about Oregon's natural resources and environment to support effective decision-making at local, state and regional levels…") mesh well with the goals of our project (if not CICEET itself). Most importantly, because it is a permanent part of the Oregon State University Library system, the portal will be maintained and updated into the future.

Presentations

Presentations by our project team are listed in **Appendix 13**.

Results and Discussion

Results: Temperature Sensor Method

A user-friendly summary of our results is presented in the **User's Guide to the Temperature Sensor Method** (**Appendix 5**). We found that a consistent "signal" of inundation could be detected using the temperature sensor method, regardless of season, deployment method, or wetland habitat class. Summer 2007 results were published in Rebecca Tully's M.S. project report (Tully 2007). Winter 2008 results and comparison of the winter and summer results are provided in this report.

Tidal inundation was detected by observing convergence and divergence between the temperatures of "variable" iButtons (on wetland surfaces and vertical posts) and reference iButtons monitoring the ambient air and water temperatures (Figures i-1 through i-8, **Appendix 3**). Inundation events were signaled by sharp directional change of the "variable" iButton temperature curves -- towards the water reference temperature at inundation, and towards the air reference temperature when the tide receded. This "inundation signal" was best detected during night-time high tides, although daytime high tides could sometimes be detected in forested wetlands (Figure i-2). Sequential inundation according to iButton height was clearly visualized in the vertical post data (Figures i-1, i-2, i-4). The observed tidal inundation events were validated by local tide measurements (water level logger) and NOAA tide observations at nearby gauging stations (see **Evaluation Methods: Validation of temperature sensor method** below).

We observed the following general patterns during summer and winter observation periods, illustrated in Figures i-1 through i-8:

- At night, non-inundated iButtons showed a general cooling trend (matching the falling ambient air temperature). During high tide events, inundated iButtons showed a sharp increase in temperature corresponding to the warmer temperature of the incoming tide. Similarly, as the high tide subsided and the iButtons were again exposed, the iButton temperatures dropped sharply to match ambient air temperature. These sharp directional temperature changes were consistently observed during night-time high tide periods for nearly all of the iButtons regardless of season or habitat class.
- During the day (especially during summer months), tidal inundation was more difficult to detect using iButton temperature curves because of solar warming, which obscured temperature changes due to tidal inundation. There were temperature differences between the "variable" and "air" iButtons, but both temperature curves tended to follow the general heating and cooling trend that occurs during daytime hours. Figure i-2 provides an illustration of a post that was inundated during both day and night high tides, showing the difference in iButton "signals" between day and night.
- iButtons that followed the water temperature curves or air temperature curves (i.e., iButtons that do not show distinct temperature changes during high tides) were most likely continually inundated or not inundated at all, respectively. Many iButtons only inundated during the higher high tides (see Figure_i-1 versus Figure_i-3).
- The two deployment methods (wetland surface iButtons and vertical post assemblies) were each useful for different purposes. The wetland surface iButtons allowed precise determination of inundation at a specific location, while the vertical post assemblies were best for validation of the method at each location and for documenting water levels within a tidal channel (similar to a tide gauge, though limited by the spacing of the iButtons).

Validation of Temperature Sensor Method

Our results were validated for all sites and plots. We defined validation as follows: 1) the iButton inundation signal occurred at the same time as predicted by the HOBO water level logger (within the range of the 12min logging interval), unless the iButton was located far enough from the validating logger to cause a delay due to water movement across the site; and 2) groups of iButtons near each other should show a consistent relationship between their inundation signals and the predicted inundation times (because any time differences due to distance from the water level logger would be similar for these groups of iButtons). Figure 10 in the User's Guide (**Appendix 5**) illustrates successful validation of the temperature sensor method: The predicted inundation times matched the inundation signals for all the iButtons. Further validation examples are provided in Tully (2007).

One iButton at Blind Slough did not inundate at the time predicted by the validation process. However, it did inundate at the same absolute time as the others, so we suspect the surveyed elevation of the iButton was in error – not unlikely given the dense vegetation at the site. The aberrant outcome for this iButton does not affect our conclusions for the validation process.

For test plots located further from the water level logger (Blind Slough P2, Siletz Keys P2), there was a delay between predicted inundation and the iButton inundation signal. The delay is related to the distance between the water level logger (located in a main tidal channel) and the iButton sensor. For example, Plot 1 at Blind Slough was much closer to the HOBO water level logger than Plot 2 (Map 2, **Appendix 1**), so we could expect a longer delay at Plot 2 than Plot 1. As expected, Plot 1 showed a mean delay of 3 minutes after predicted inundation times, while Plot 2 showed a 22-minute delay. This delay provides a good illustration of how iButtons can be used for spatially explicit tracking of inundation lag time across a large site.

Results: Vegetation

Vegetation cover, woody stem densities and basal area for our study sites are provided in **Appendix 2**. Table 4 (**Appendix 2**) shows stem densities and basal area for woody species at the tidal swamp sites. Herbaceous vegetation measurements (percent cover by species) are summarized in Tables 5 through 7 (**Appendix 2**). Plant community composition and percent cover by species corresponds well to measurements conducted by our team at other Oregon sites in the same habitat classes (Brophy 2002a, 2004a, 2007b, 2009a, Brophy and Christy 2008, 2009a, b, 2011, Christy and Brophy 1975) and by others in seminal literature on Oregon tidal wetlands (Akins and Jefferson 1973, Eilers 1975, Jefferson 1975). This correspondence suggests these sites are appropriate for use as references for restoration planning and monitoring.

Table 1 (**Appendix 2**) shows woody vegetation measurements (densities for shrubs, saplings and trees; basal area for trees). Tree densities and basal areas corresponded well to other studies in Pacific Northwest coniferous forests. Shrub/sapling densities at the Blind Slough and Coal Creek sites were high in comparison to other studies, as was expected based on the exceptionally dense understory.

Although upland shrubs were prominent at Coal Creek, these were found only on nurse logs, never rooted directly in the generally saturated soil.

Results: Soils

Soil characteristics for our study plots are shown in tabular form in Table 8, **Appendix 2**. Soils were generally high in organic matter (20-30%). Organic carbon levels in 6 of the 13 study plots were high enough for these soils to be classified as histosols (Soil Survey Staff 2010), although soil taxonomy was not fully characterized. An exception was the Siletz Keys low marsh, which is located in a relatively high-energy landscape setting (lower estuary, bay fringe, subject to strong wind and wave action). Most likely, the wind and wave action at this site carry organic material off the site, unlike the lower-energy settings of our other sites where organic matter produced *in situ* may be more likely to accumulate.

Results from our extended study of soils at 17 tidal wetlands in Oregon (**Appendix 8**) corroborated the high carbon content of least-disturbed high marsh and forested tidal wetland reference sites, and showed that soil carbon content was lower in disturbed (diked and drained) tidal wetlands. The average concentration of soil organic carbon in reference sites was 15.7% -- significantly higher than at disturbed sites, which averaged 12.1% C ($p<0.01$). When disturbed sites were divided into those that had undergone hydrologic restoration (dike breaching or dike removal), pairwise comparisons showed that the restored sites did not differ significantly from the reference or unrestored sites, but unrestored sites had significantly lower soil carbon compared to the reference sites (9.4% versus 15.7% for the reference sites; $p=0.03$). The lower carbon content at unrestored sites compared to reference sites strongly suggests that drainage and agricultural use of these former tidal wetlands caused loss of stored soil carbon. Worldwide, wetland drainage is associated with large releases of carbon to the atmosphere, a phenomenon of global importance in the face of rising atmospheric carbon and resultant climate change (Armentano 1980).

Soil salinities, texture, and pH corresponded closely to habitat class, with salinities highest in the low marsh sites and lowest in the shrub and forested tidal wetlands. However, we found strongly brackish salinities (mesohaline) in the shrub and forested tidal wetlands at the Coal Creek and Yaquina Swamp sites. This finding corroborates our team’s other studies, which found forested and shrub tidal wetlands had brackish soil salinities in the Siuslaw estuary of Oregon (Brophy 2009a). These results contrast with surveys of vegetation in the Columbia River estuary, which stated that Sitka spruce tidal swamps occur in the freshwater tidal zone (MacDonald 1984, Fox *et al.* 1984). Brophy (2009a) and the current study constitute the first comprehensive data on the controlling factors, site structure, and biology of least-disturbed brackish tidal swamps of Oregon’s outer coast.

Results: Groundwater

Groundwater levels at our high marsh and tidal swamp study sites were highly responsive to tidal cycles (Figures G1-G11, **Appendix 3**). During extreme tide cycles (spring tides) – when the soil surface was inundated -- groundwater became contiguous with surface water. However, groundwater also fluctuated strongly in response to neap tidal cycles, when the wetland surface was not inundated. Wetlands with strong, regular fluctuation in water level are among the most productive and the most likely to export biota, nutrients and energy to other nearby ecosystems (Mitsch and Gosselink 1993). Groundwater fluctuation is also a likely controlling factor for wetland functions like carbon sequestration, since organic matter breakdown is slow in saturated, anaerobic soils. Organic matter levels in soils at our study sites were very high, ranging from to 30% organic matter (by loss on ignition). Groundwater fluctuation affects organic matter accumulation, and in a typical example of a “feedback loop,” soil organic matter content affects hydraulic conductivity – thus in turn affecting groundwater levels. Soils that are high in organic matter are often hydraulically conductive (Mitsch and Gosselink 1993) and have high porosity.

The dynamic groundwater regime we observed suggests that groundwater may indeed be a controlling factor for many tidal wetland functions at these sites.

At Blind Slough, groundwater dynamics in the Sitka spruce habitat differed sharply from those in the willow zone (Figures G1-G3, **Appendix 3**). In the Sitka spruce swamp (Plot 1), groundwater levels between high tide events were generally around 30cm below the soil surface. By contrast, groundwater in the willow swamp (Plot 2) remained at or near the soil surface year-round. The soil surface elevation was the same at both plots (2.64m NAVD88). Therefore, the contrasting hydrology is probably due to two factors: 1) The proximity of a major tidal channel (about 4m wide and about 1m deep) within about 5m of the groundwater well in the Sitka spruce plot; and 2) intense beaver activity in the willow community. We observed abundant beaver sign in the willow community, and it seems likely that the high water tables are caused by impoundment by beaver dams. Diefenderfer and Montgomery (2008) and Diefenderfer *et al*. (2008) found that beaver had a strong influence on channel morphology and step-pool structure in tidal swamps of the Columbia River estuary. Brophy (2009a) observed similar plant community and groundwater hydrology linkages in the Siuslaw River estuary. These highly visible plant community patterns -- Sitka spruce communities near the tidal channels, willow wetlands in the interior – provide an interesting example of the links between channel development, plant community distribution, and wildlife activity. These patterns also confirm the role of beaver as system engineers in Oregon's outer coast tidal wetlands, as described by Brophy (2009a).

Groundwater levels at the Coal Creek Sitka spruce swamp were more dynamic than in the spruce plot (Plot 1) at Blind Slough. Groundwater generally dropped to 20-30cm below the soil surface between high tide events during the dry summer months (Figure G5, **Appendix 3**); groundwater in fall, winter and spring at this site appeared to be very responsive to precipitation and river flows (Figures G4 and G6). Although more detailed analysis was beyond the scope of this study, these results illustrate the strong fluvial contribution to this site's hydrology (**Appendices 9** and **10**).

Groundwater at the Hidden Creek high marsh (Plot 4; Figures G10-G11, Appendix 3) remained at the soil surface during fall, winter and spring. During the driest months of summer and early fall, groundwater dropped to 20cm below the soil surface during neap tide cycles, but rose to the surface during spring tide cycles, dropping gradually after those events. This pattern was referred to as a spring tide "reset" by Brophy (2009a). Millport Slough high marsh (Figures G7-G9) showed a similar summer groundwater pattern, but groundwater levels at Plot 2 at Millport Slough dropped much lower than at Plot 4 at Hidden Creek – about 30cm lower, relative to the soil surface. A likely explanation was the small freshwater stream entering the Hidden Creek Marsh site near Plot 4 (visible in the LiDAR imagery, Map 12, Appendix 1). This freshwater inflow probably maintained higher summer water tables in the vicinity of the groundwater well.

The consistent patterns of groundwater fluctuation we observed within habitat classes (high marsh, shrub swamp, forested swamp) across sites strongly suggest that tidally-influenced groundwater fluctuation is a controlling factor in the ecology of Pacific Northwest tidal wetlands.

Results: Channel Water Salinity

Channel water salinity results are shown in Figures S1-S4, **Appendix 3**. Graphs are shown only for sites and monitoring periods where salinity exceeded 0.5ppt. Salinity was fresh (<0.1ppt) at the Blind Slough study site during the entire monitoring period (February 27 - August 28, 2008). At Coal Creek, salinities were fresh (<0.5ppt) during the first YSI deployment (February through April 10, 2008) but brackish (up to 12ppt) during the latter part of the summer deployment (May 19 – August 29, 2008). At the Millport Slough high marsh, we monitored salinity only during spring, but it climbed to 25 ppt by June, suggesting that summer salinities at this site are probably near marine levels. At Siletz Keys, salinities during the late winter through spring were in the marine salinity range (>30ppt), as would be expected given this site's estuary position (lower estuary bay fringe) and vegetation (primarily succulent halophytes).

The mesohaline salinities at Coal Creek provide further evidence to support Brophy's (2009a) observation that tidal swamps (including Sitka spruce swamps) can thrive in brackish conditions. This contrasts sharply with the few publications describing tidal swamp in Oregon, which suggested that tidal swamps are found only in freshwater tidal zone (MacDonald 1984, Fox *et al.* 1984). Elliot (2008) found oligohaline salinities in surface water and soil porewater of Russian Island (Columbia River) tidal swamps, averaging 1.6 ppt in summer. However, her study area did not include higher (mesohaline) salinities, and she found no relationship between salinity and plant community composition. It seems likely that spruce tidal swamps were once also found in the mesohaline zone in the Columbia system, but they are now almost completely missing from the landscape. Thomas (1983) documented 96% loss of spruce tidal swamp from Youngs Bay, which is located in the mixing zone of the Columbia River estuary.

Results: Elevation Survey

Data on NGS benchmarks established at our study sites are provided in Table 1 (**Appendix 2**). Survey points are shown in Maps 7 through 11 (**Appendix 1**). Wetland surface geodetic elevations determined by NGS survey are shown in Table 9 (**Appendix 2**). We used the NGS survey data to relate geodetic elevations of wetlands and instrumentation to tidal datums and to model inundation regimes (next section).

Results: Water Levels, Tidal Datums and Inundation Regime Modeling

Detailed results from this component of our study can be found in **Appendices 9** and **10**.

The tidal datums we calculated for each site with the help of NOAA/CO-OPS (Figures T1-T2, **Appendix 3**) enabled us to relate the elevations of our study plots to the local tide range – a critical analysis, since tidal inundation regime is a key controlling factor in tidal wetland ecology (Thom *et al*. 2004, Johnson *et al*. 2008). We discuss those relationships in **Results: Reference conditions database** below.

By incorporating our field monitoring data into tidal elevation modeling, we characterized combined inundation from both tidal and fluvial forces at our study sites. This work represents the first attempt to explicitly model how river flows modify tidal inundation regime on Oregon's outer coast. Models in the Columbia River estuary (Jay and Kukulka 2003) have characterized fluvial contributions to water level fluctuation in tidal areas. Our comparatively simple modeling approach provides an accessible method for analyzing tidal wetland ecosystems and addressing flood risks in coastal lowlands.

The effects of combined tidal and fluvial forces on inundation regime are illustrated by the modeled inundation frequency at Coal Creek. We compared our Coal Creek results with the observed inundation frequency at the NOAA tide station at South Beach, OR, which represents typical tides along the Oregon Coast (Figure 9, **Appendix 10**). There were approximately 20,598 observed hourly heights above MHHW over 44 years (1967 –2010) at South Beach, and 38,275 hourly heights above MHHW during the same time period at Coal Creek. Not only were there many more high water events at Coal Creek, but the water level elevations were also much higher. Over 40% of the inundation elevations at Coal Creek were higher than 0.45 m above MHHW, compared to South Beach where only 10% of the inundation elevations were higher than 0.45 m above MHHW.

The fluvial component was also a strong system driver at the Millport Slough, Siletz Keys and Yaquina Swamp (Y28) study sites. At Millport Slough, compared to inundation from tides alone, median river flows increased percent inundation by about 500% (Figure 21, **Appendix 9**), and doubled or tripled the days each month with inundation events (Figure 20, **Appendix 9**). Patterns were similar at the Yaquina site (Figures 22 and 23, **Appendix 9**). As expected, the fluvial component was weakest in summer when precipitation and resulting river flows are low. The Siletz Keys study plots were low marsh which flood almost daily year-round, so river flows did not strongly increase the number of days with inundation events (Figure 24, **Appendix 9**). However, but median river flows did strongly increase percent inundation at Siletz Keys (Figure 25, **Appendix 9**).

The strength of the fluvial component at Millport Slough and Siletz Keys is particularly interesting, because these sites are located in the lower estuary. Siletz Keys in in the broad bay about 3km from the river mouth; Millport Slough is 2km further upstream, where the floodplain has just begun to broaden as the river enters the lower estuary. As reported in Brophy (2009a), we initially developed the fluvial analysis to allow more accurate inundation modeling in middle and upper estuarine sites, where we reasoned that local geomorphology (i.e., greater valley confinement) would result in higher peak river flows compared to sites in the less-constrained lower river valleys and open bays. The importance of the fluvial component at this lower estuary site suggests the usefulness of this method for a variety of applications that would benefit from accurate inundation predictions (e.g., restoration site selection, restoration design, adaptive management, coastal zone planning, climate change adaptation).

Results: Benthic Invertebrates

Detailed results for this project component can be found in **Appendix 11**.

An invasive gastropod, New Zealand mudsnail (*Potamopyrgus antipodarum*), was found in three sites: Coal Creek forested marsh, Blind Slough scrub-shrub marsh and Millport Slough High Marsh. The average abundance in Coal Creek was 18.25 snails per sample, compared to 2.3 snails per sample in Millport Slough and 0.78 snails per sample in Blind Slough. The Siletz (Millport Slough) and lower Columbia (Blind Slough) estuaries were already known to be colonized by *Potamopyrgus*, but the presence of the mudsnail in the Nehalem estuary (Coal Creek) may not have been documented prior to this monitoring effort. The project team disinfected gear between sites to limit the spread of this species, using one of the protocols (Formula 409 disinfectant) recommended in Hosea and Finlayson (2005).

Total benthic invertebrate abundance was highest at Hidden Creek Low Marsh, and lowest in the shrub and forested wetlands. Taxonomic richness was also highest in the Hidden Creek Low Marsh, but comparable with all other sites except Coal Creek Forested Wetland, where taxonomic richness was lower. Taxonomic richness at the Coal Creek site was low due to the predominance of New Zealand mudsnails (*Potamopyrgus antipodarum;* non-native, invasive). New Zealand mudsnails made up over 50% of the sample in 2007, and over 90% in 2008.

Multivariate analysis using NMDS showed that assemblage structure was similar for high and low marshes, while the shrub and forested wetlands were significantly different from each other and from the high and low marshes. Based on ANOSIM, most pair-wise site comparisons showed significant differences in invertebrate assemblages.

The INDVAL analysis provided repeatable indicators across the two sample years at all sites, except for Siletz Keys Low Marsh. New Zealand mudsnails were identified as the only indicator at the Coal Creek site in both years. Indicators at Blind Slough Plot 1 (forested wetland) included the common bivalve, *Macoma* spp., and the brackish-water isopod, *Caecidotea* spp. Indicators at the two high marsh sites were different, with Hidden Creek having isopods and the non-native amphipod *Grandidierella japonica*, and Millport Slough having flatworms and polychaetes. Indicators were also different at the two low marsh sites, with Hidden Creek Low Marsh having nematodes, the free-living estuarine anemone, and diptera larvae, whereas Siletz Keys had no repeatable indicators and only one indicator in 2008 (an ostracod). No indicators were found in 2007 at the scrub-shrub Blind Slough Plot 2 (scrub-shrub wetland), and this wetland was not sampled in 2008.

The lack of repeatable indicators for Siletz Keys low marsh suggests a need for further study to characterize macroinvertebrate communities in low marsh. However, the detection of different repeatable indicators in low versus high marsh at Hidden Creek suggests the INDVAL analysis is capable of detecting small differences in biological structure between neighboring sites.

Results: Reference Conditions Database

We summarized project data in a reference conditions database (**Appendix 2**, Tables 9 and 10). Table 9 provides data for each study plot individually; Table 10 summarizes the data by habitat class (averaged across sites).

Clear relationships were apparent between controlling factors (elevation, salinity, inundation regime, groundwater levels), structural site characteristics (soils), and biological response variables (vegetation and benthic invertebrates). These relationships are discussed in the sections above. In this section, we discuss relationships between multiple controlling factors, such as geodetic elevation, tidal elevation, salinity, and beaver.

Tidal elevations (elevations relative to tidal datums) in Tables 9 and 10 are expressed relative to MHHW, since the onsite water level loggers were out of water at low tide. As expected, tidal elevations were lower for low marsh (.05-0.20m below MHHW) compared to other habitat classes. However, tidal elevations were similar for outer coast high marsh, shrub swamp, and forested swamp (0.11-0.19m above MHHW). Brophy (2009a) saw similar results in the Siuslaw River estuary. The fact that all habitat classes occurred within a narrow tidal elevation range (0.4m) illustrates the vulnerability of our coastal wetlands to sea level rise (Ruggiero *et al*. 2010).

Tidal elevations of the Sitka spruce forested tidal wetlands at the Blind Slough study site were low (0.16m below MHHW) compared to outer coast spruce tidal swamps. At the Coal Creek site, Sitka spruce swamp occurred at 0.1 to 0.2m above MHHW. In the Siuslaw River estuary, Brophy (2009a) found that Sitka spruce swamp occurred at 0.16m above MHHW, and willow swamp occurred at 0.08m below MHHW. The relatively low tidal elevation of the shrub and forested wetlands at the Blind Slough site may relate to several factors, including the distinct geomorphology of the Columbia River estuary and the fact that river flows are highly regulated in the CRE (Jay *et al.* 2011).

Johnson and Simenstad (2011) used LiDAR data to estimate elevations of shrub and forested tidal wetlands at the Big Creek swamp, about 1.6km downstream from the Blind Slough site. She found an elevation range from 1.62m (5.31ft) to 2.60m (8.53ft) NAVD88. The upper end of that range is similar to the elevations we measured at the Blind Slough swamp (2.64m NAVD88). Elliot (2008) used RTK-GPS to measure the elevation of a willow-dominated tidal swamp on Russian Island and obtained a value of 0.08m above MHHW (2.55m above MLLW); no geodetic elevation was provided. This tidal elevation was high compared to our willow swamp study site at Blind Slough, which was 0.16m below MHHW. As might be expected based on that tidal elevation, the Russian Island site had vegetation that is less tolerant of flooding, with the upland species Himalayan blackberry (*Rubus discolor*, now *R. armeniacus*) and the transitional species tall fescue (*Festuca arundinacea*, now *Schedonorus phoenix*) prominent in the understory along with the more typical tidal swamp species Pacific lady fern (*Athyrium filix-femina*).

Our results showed broad relationships between tidal elevation and habitat class, but also showed that salinity, landscape setting, land use history, and “system engineers” (beaver in particular) were likely controlling factors. For example, Plot 2 at Millport Slough is a diverse, forb-rich high marsh, and its tidal elevation (0.15m above MHHW) was similar to the forested wetlands at Coal Creek (0.10 to 0.20m above MHHW). Channel water salinity was much higher at Millport Slough (27ppt, vs. about 12ppt at Coal Creek), though soil salinity was similar (10-13ppt at Millport, vs. 9ppt at Coal Creek). Development of woody vegetation may be limited by surface water salinity at Millport Slough, and land use history (particularly grazing history) may play a role. Another example is found at Blind Slough Plots 1 and 2. Here, scrub-shrub tidal wetlands (willow swamp, Plot 2) occur at the same elevation as forested tidal wetlands (Sitka spruce swamp), and groundwater hydrology is very different between the two plots. Beaver may be a key factor controlling development of willow *versus* spruce communities here. Diefenderfer and Montgomery (2008) discussed the role of beaver in structuring tidal swamp ecosystems in the Columbia River estuary, and Brophy (2009a) noted the likely role of beaver as system engineers in tidal swamps of the Siuslaw River estuary.

Results: Web Portal

Products from this study are available on the Oregon Explorer website (http://oregonexplorer.info/wetlands/DataCollections/ReferenceSiteData). The data include maps of study sites; tables, graphs, and figures from this report; the User’s Guide to the temperature sensor method; and links to download detailed reports and appendices.

Results: Practitioner Survey

The response rate for the survey was 62% (31 respondents). Detailed results are compiled in **Appendix 12** and are available online at http://www.oregon.gov/DSL/SSNERR/docs/EstuarineWetlandRestorationInfoGaps_Survey.pdf.

In general, the survey respondents confirmed that their priority habitats for restoration are those we chose for this CICEET project: high and low emergent marshes and scrub shrub and forested swamps. Other survey highlights included:

- Scrub-shrub and forested tidal wetlands and tidally-influenced freshwater floodplains were the habitats most often mentioned (35% of respondents) when asked which habitat classes are not being restored but should be. Unvegetated tidal flats were the second most commonly mentioned habitat class (10% of respondents).
- Most respondents undertake effectiveness monitoring as a part of their restoration projects (80%). When asked why they do not conduct effectiveness monitoring (or do not collect as much information as they would like), the overwhelming response was lack of funding. 80% indicated general lack of funding for monitoring, and 52% responded that funders require monitoring but do not provide adequate funding. No respondents (0%) chose administrative constraints or lack of monitoring guidance as obstacles to effectiveness monitoring.
- Most respondents (70%) report that they conduct monitoring for additional reasons besides evaluation of project effectiveness. The reason given by most respondents (55%) was to contribute to the science of habitat restoration (e.g., evaluate various restoration treatments; answer specific ecological or physical process-based questions). Specific research questions and hypotheses being addressed by respondents are listed in the survey report.
- When asked whether they use reference sites as part of project monitoring, most respondents (76%) answered that they did. When asked if they were able to find reference sites from which they could collect useful data, most said they could (70%), but the comments indicated some concern over the appropriateness of the reference sites being used, as well as the need for high quality reference condition datasets.
- When asked whether and how they would use long term reference condition data sets if such data were made available, an overwhelming number of respondents indicated that they would use them for evaluating restoration projects (93%), designing restoration projects (80%), and evaluating adaptive management options (80%).
- Finally, the survey asked respondents in four separate questions to articulate their top “burning questions,” which, if answered, would help them improve coastal habitat restoration prioritization, design, implementation, and evaluation. Their responses are listed in the survey results (**Appendix 12**) and became the basis for discussion at the 2007 estuarine wetland restoration advisory group workshop at South Slough NERR.

State of the Technology

The technologies we developed have been fully tested, validated, and applied in the field by end users (see **Application** below). We achieved our four primary objectives: 1) Testing and developing innovative, cost-effective methods for monitoring key drivers of ecosystem processes in tidal wetlands; 2) Piloting a new Oregon tidal wetland reference condition database for a proposed National Estuarine Research Reserve System/NOAA regional restoration reference site program; 3) Contributing to restoration monitoring guidance such as NOAA/National Center for Coastal Ocean Science's "Science-Based Restoration Monitoring of Coastal Habitats;" and 4) Developing and testing a new internet web portal to disseminate reference conditions datasets generated by the project team as well as other researchers and restoration practitioners.

For Objective 4, we decided to use an existing web portal to maximize data visibility and availability (http://oregonexplorer.info). In addition, we have moved far beyond posting our results to the web: we have directly applied our CICEET results to a wide variety of projects ranging from strategic planning efforts to on-the-ground restoration actions (see **Application** below).

Demonstration

As described above and in **Application** below, the technologies we developed are already being applied by end users, so they have moved beyond the demonstration phase.

Application

During the course of this project, our results have been applied in several settings. The temperature sensor method was applied to measure inundation regimes in mangrove swamps in China (**Appendix 6**), and we fielded inquiries and provided the User's Guide to other researchers planning to use the method elsewhere in the U.S.

The reference conditions database is now being used in tidal wetland restoration planning, design and evaluation throughout coastal Oregon and the Pacific Northwest. Most of these applications involve multi-disciplinary and multi-stakeholder teams for which our CICEET research team provides technical leadership. These team settings are ideal for disseminating our project results: communication is frequent and technically-oriented, and project partners subsequently have many opportunities to further distribute results in their own workplaces. Partners include staff of federal, state, tribal, and local governmental agencies, private nonprofits, and restoration contractors that are "key players" in tidal wetland restoration in Oregon. Examples of on-the-ground projects that used this project's reference conditions data include Brainerd 2010; Brophy 2009b, c; 2010a, b, c, d; and 2011; Brophy and Christy 2008, 2009a and b, 2010, 2011; and Brophy and van de Wetering 2011. In addition to on-the-ground project applications, we have applied our results in guiding strategic planning for tidal wetland restoration in Oregon, the Pacific Northwest, and on the West Coast. Presentations by our project team (**Appendix 13**) provide illustrations of the many venues in which we have provided leadership for restoration planning.

The restoration practitioner survey results were presented by Cornu at the SSNERR tidal wetland restoration advisory group meeting in 2007, and were the basis of a discussion on pressing restoration science questions in the Pacific Northwest. The results were also used by Washington Department of Fish and Wildlife (WDFW) staff to develop adaptive management objectives for applicants for WDFW Estuary and Salmon Restoration Program funds.

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Next Steps

Although all of these products are fully developed and being applied by end users, we see potential for future enhancements as described below.

The temperature sensor method would benefit from testing in additional climate zones. Our team successfully tested and validated the method in mangrove swamps in China (**Appendix 6**); testing in other habitats and climates would help advance the method. The temperature sensor method would also be enhanced by development of application-specific software. Data analysis is possible with commonly used spreadsheet software, but some skill is needed to create and interpret graphs of the temperature curves. Software which automates detection of the inundation signal would make the process more user-friendly.

The reference conditions database will be enhanced by adding data from more sites. This process is currently underway; for example, **Appendix 8** describes data on soil carbon content from 13 additional tidal wetlands in Oregon. Our team is currently monitoring 27 tidal wetland restoration and reference sites in Oregon (e.g., Brophy 2004a, 2007b, 2009a, b, c; 2010a, b, d; Brophy and Christy 2008, 2009a, 2009b, 2010, 2011; and Brophy and van de Wetering 2011). These projects use methods that are consistent with our CICEET study, so the monitoring results can be used to build our reference conditions database and provide data on restoration trajectories.

A follow-up restoration practitioner survey within the next few years could provide useful updates to this study’s 2007 survey, revealing changes in priorities, data availability and monitoring activities.

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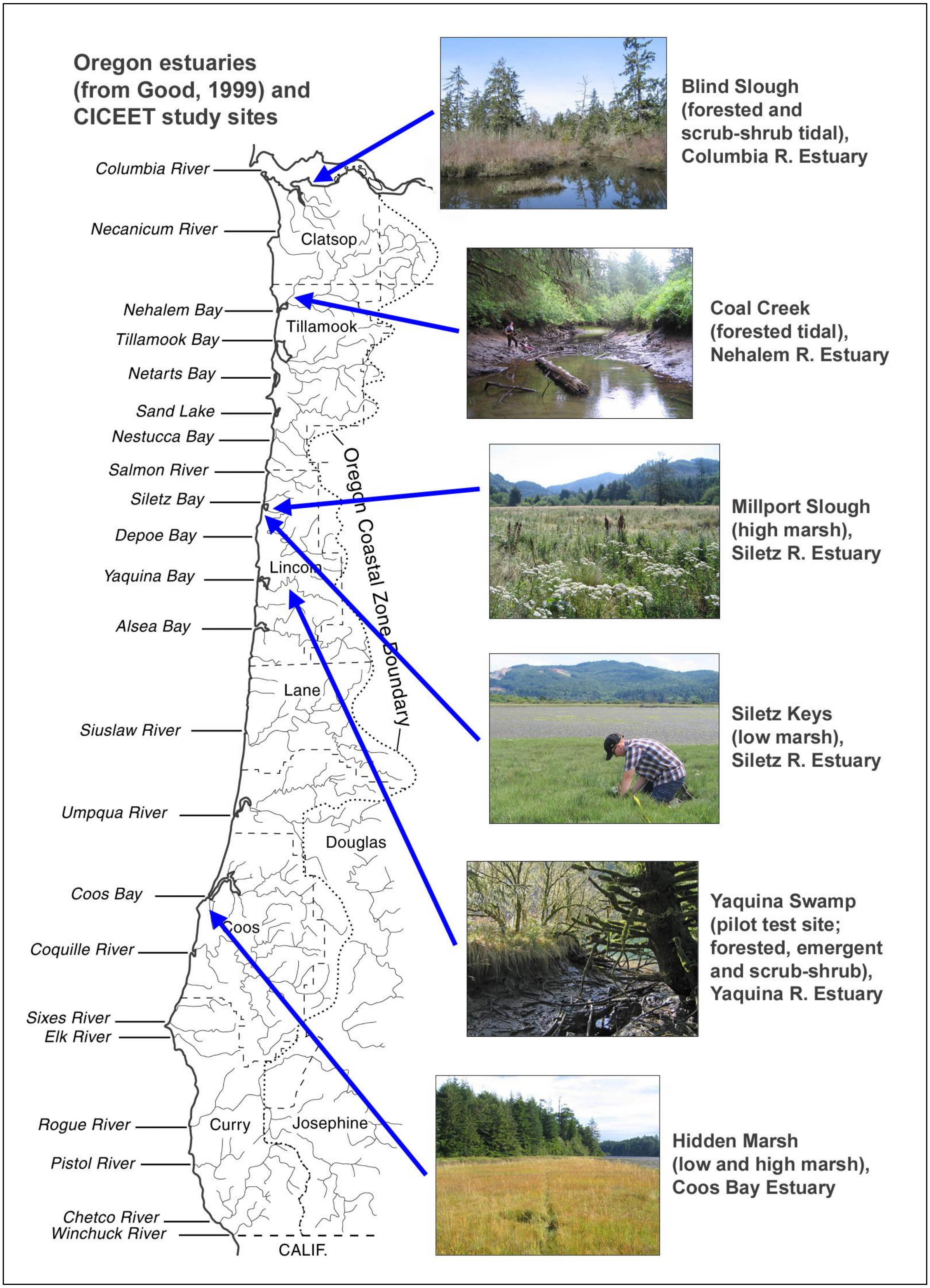
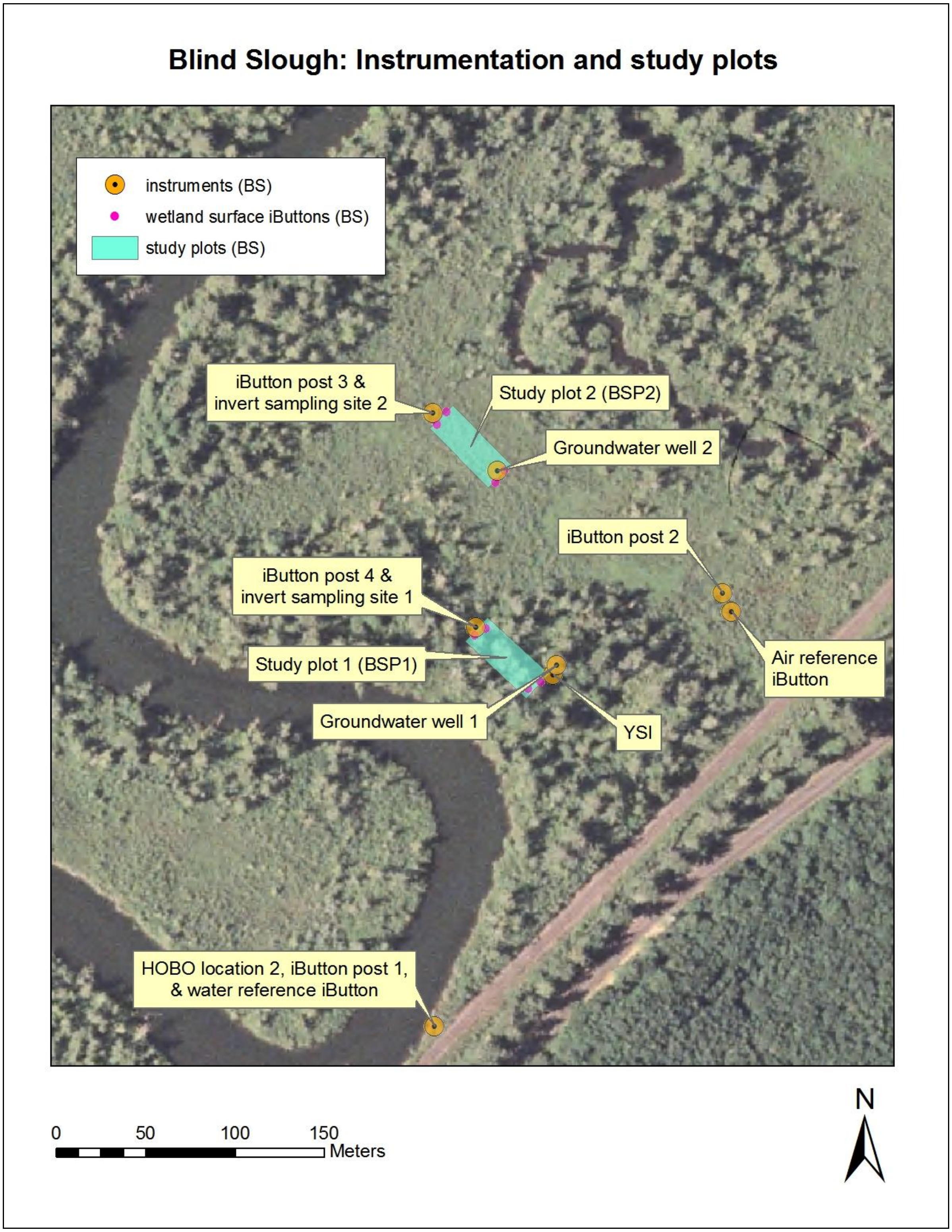
Appendices

1. **Maps**
2. **Tables**
3. **Figures**
4. **Photographs**
5. **User's Guide to the Temperature Sensor Method for Determining Tidal Inundation Regime**
6. **Tully: M.S. Research Report (Abstract)**
7. **Doumbia: M.S. Research Report (Abstract)**
8. **MacClellan: M.S. Research Report**
9. **Huang: CICEET Water Level Data Analysis**
10. **Huang, Brophy and Lindley 2011: Proceedings of Solutions to Coastal Disasters**
11. **Gray: Benthic Invertebrates at CICEET Study Sites**
12. **South Slough NERR Restoration Practitioner Survey**
13. **Presentations by CICEET Project Team**
14. **Acknowledgments**

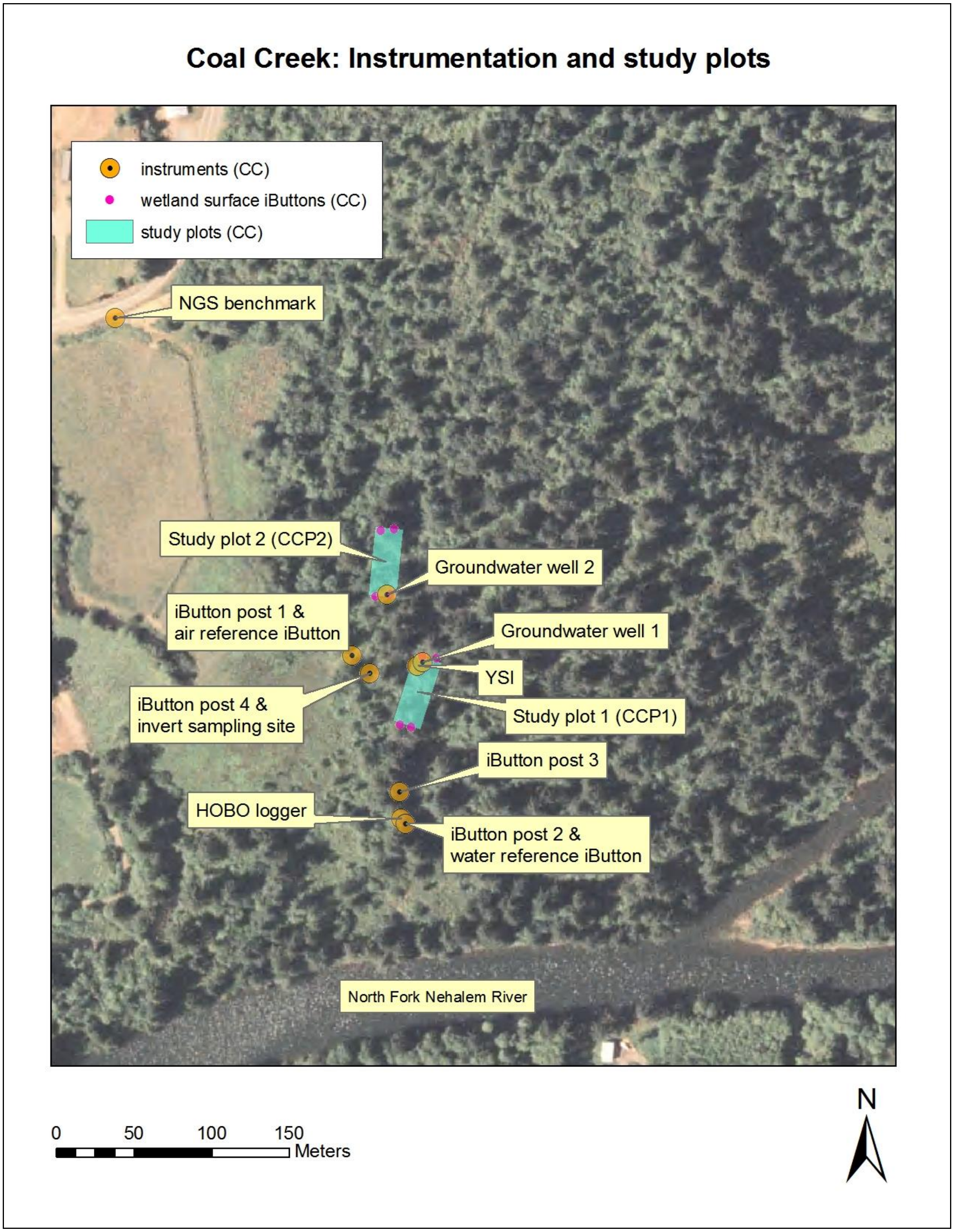
Appendix 1. Maps



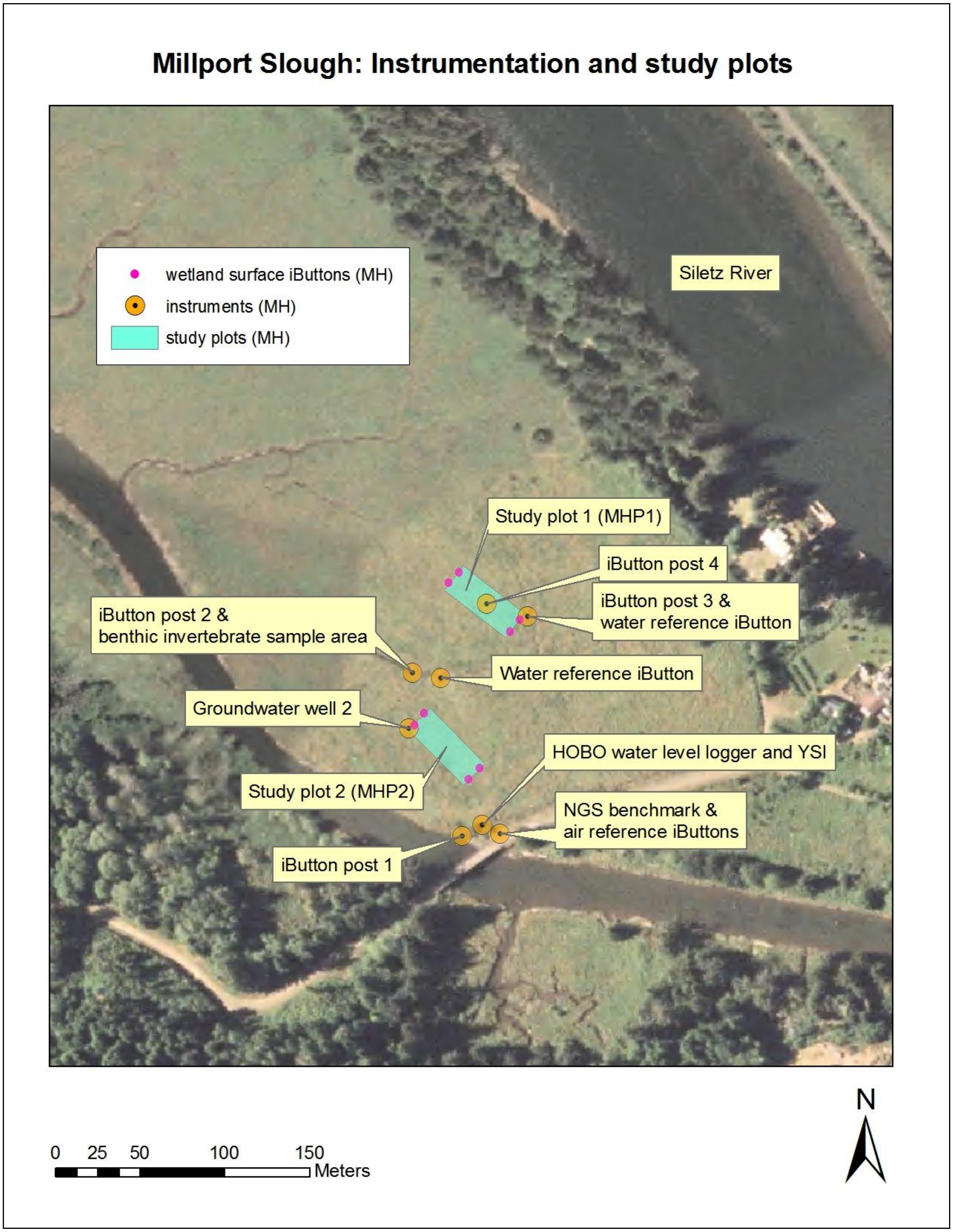
Map 1. Study sites, pilot test site, and Oregon estuaries



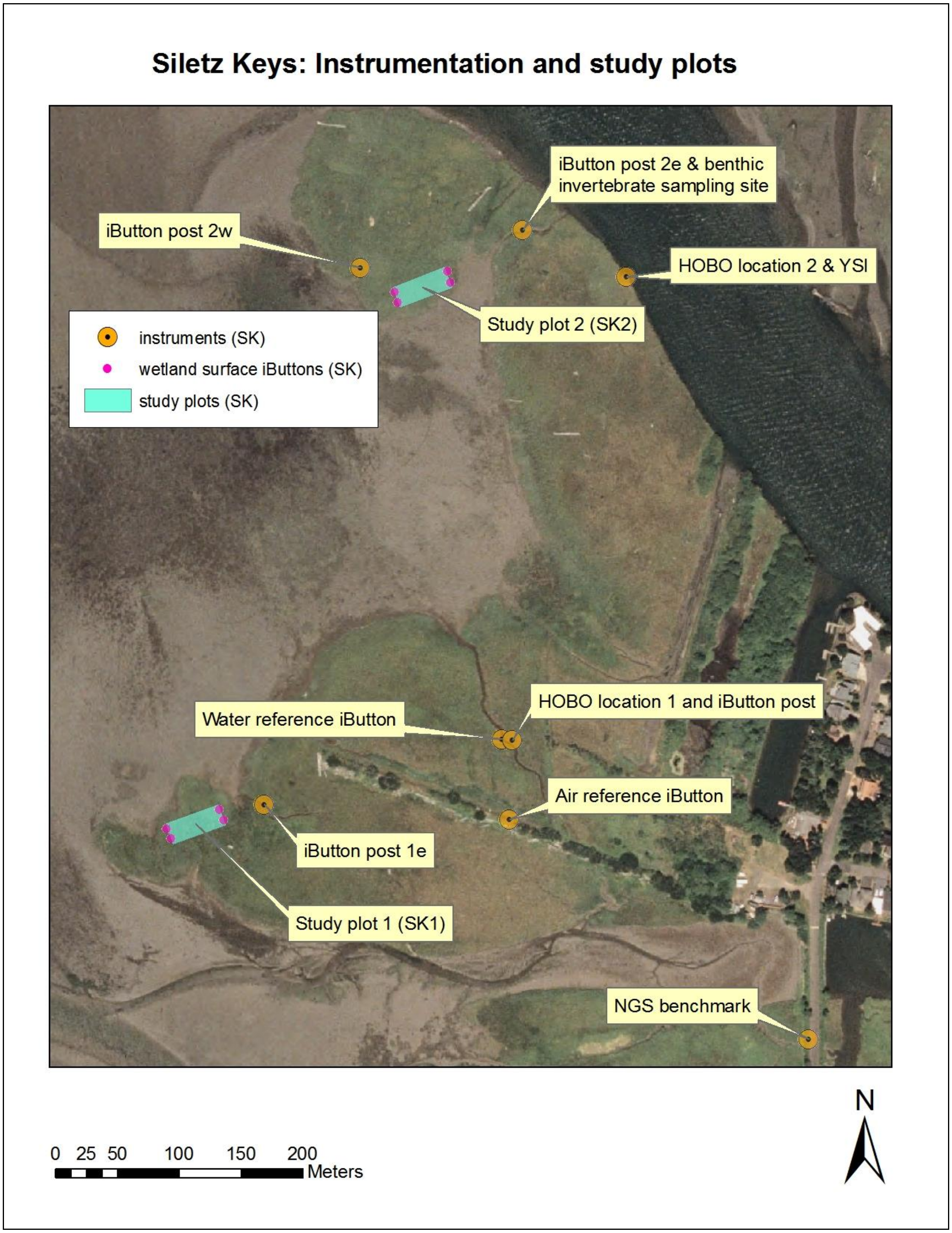
Map 2. Blind Slough study site: Instrumentation and study plots



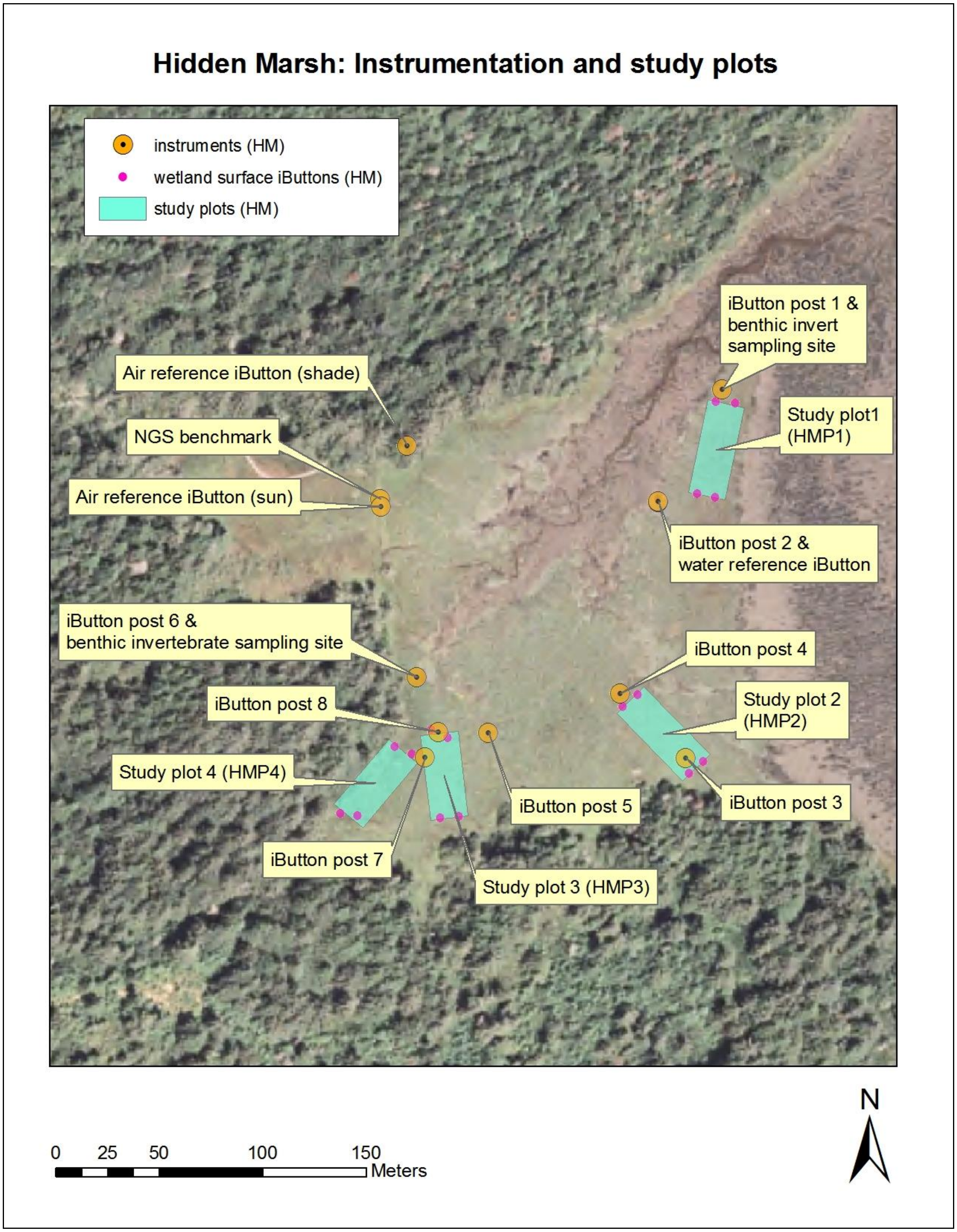
Map 3. Coal Creek study site: Instrumentation and study plots



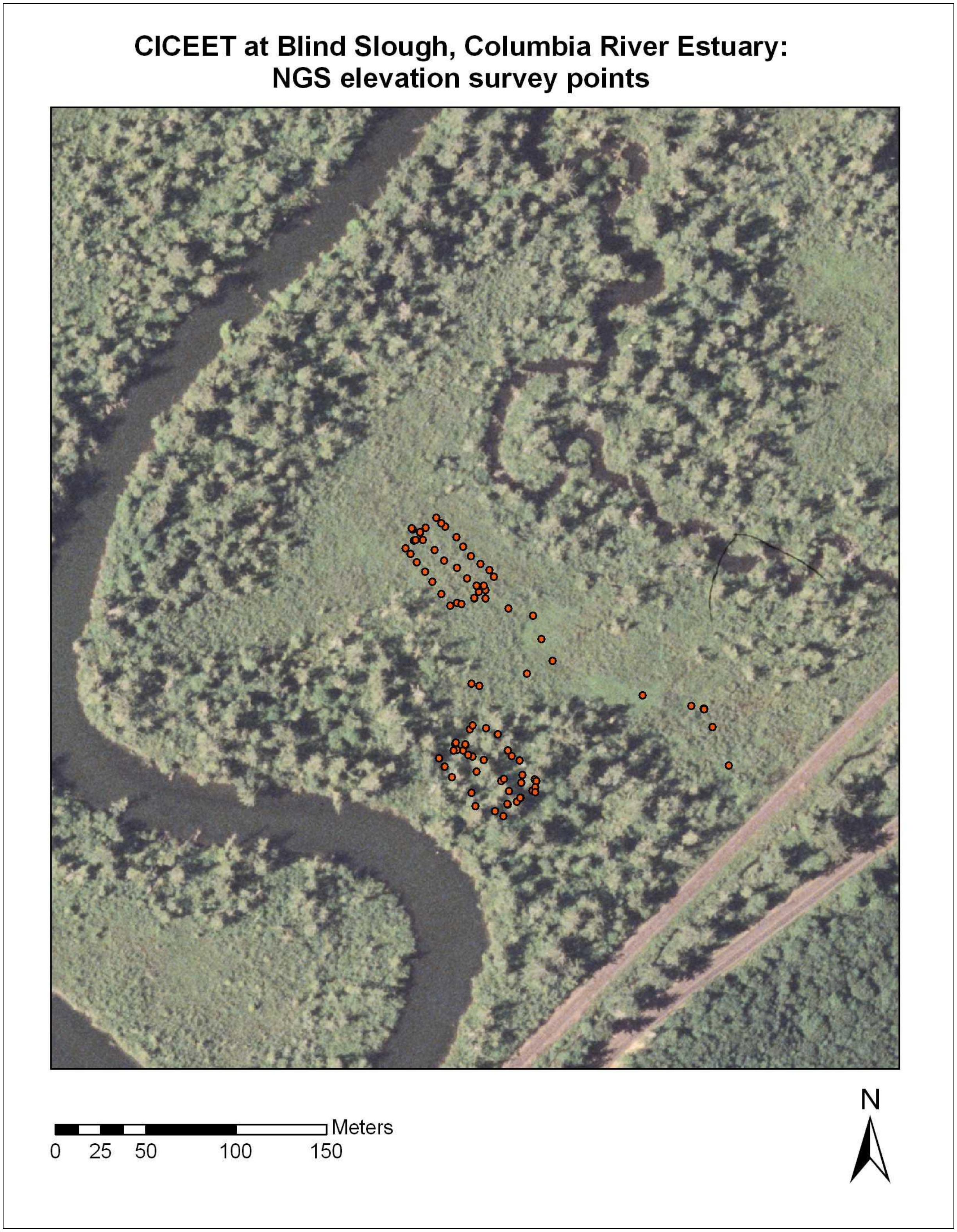
Map 4. Millport Slough study site: Instrumentation and study plots



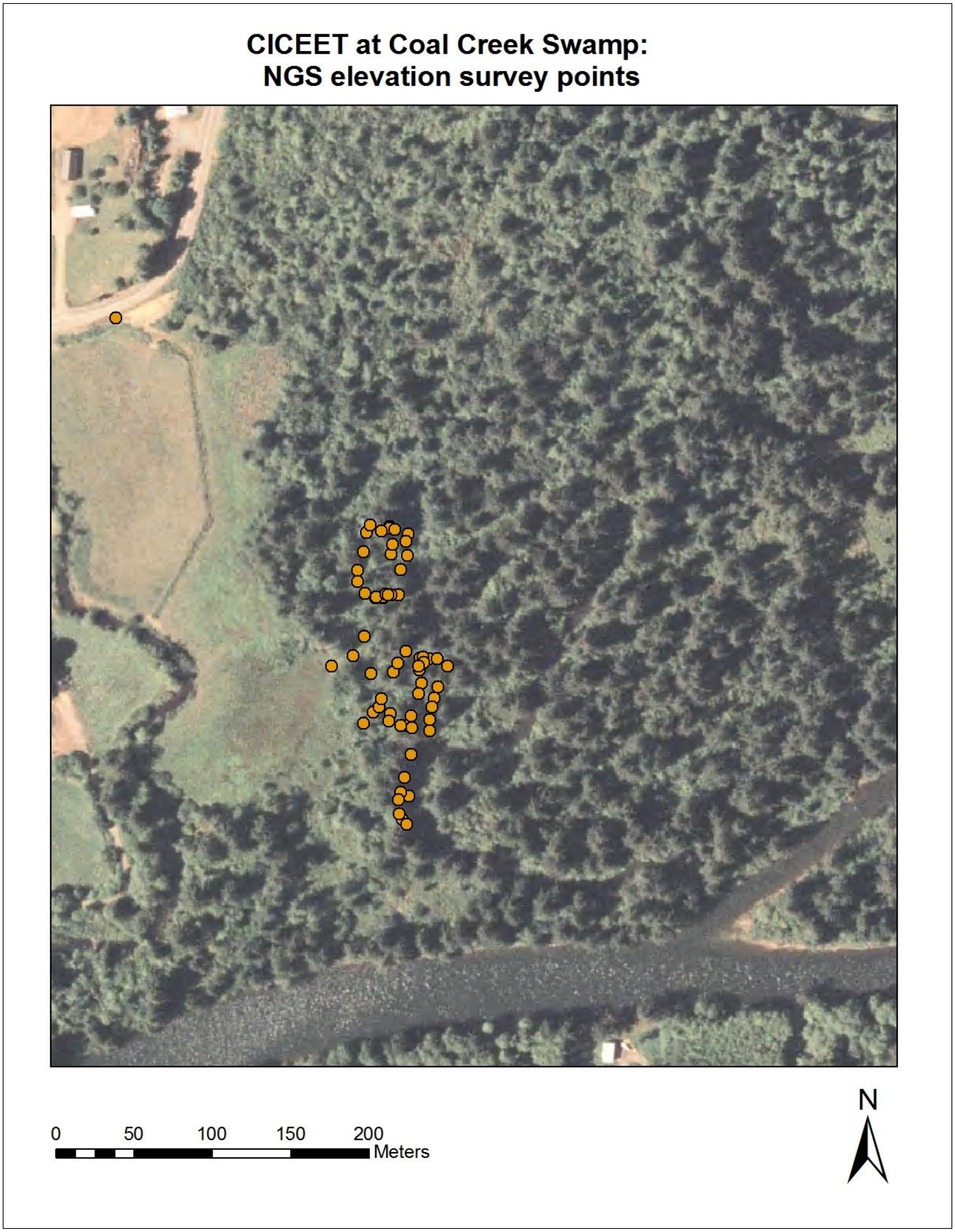
Map 5. Siletz Keys study site: Instrumentation and study plots



Map 6. Hidden Creek Marsh study site: Instrumentation and study plots

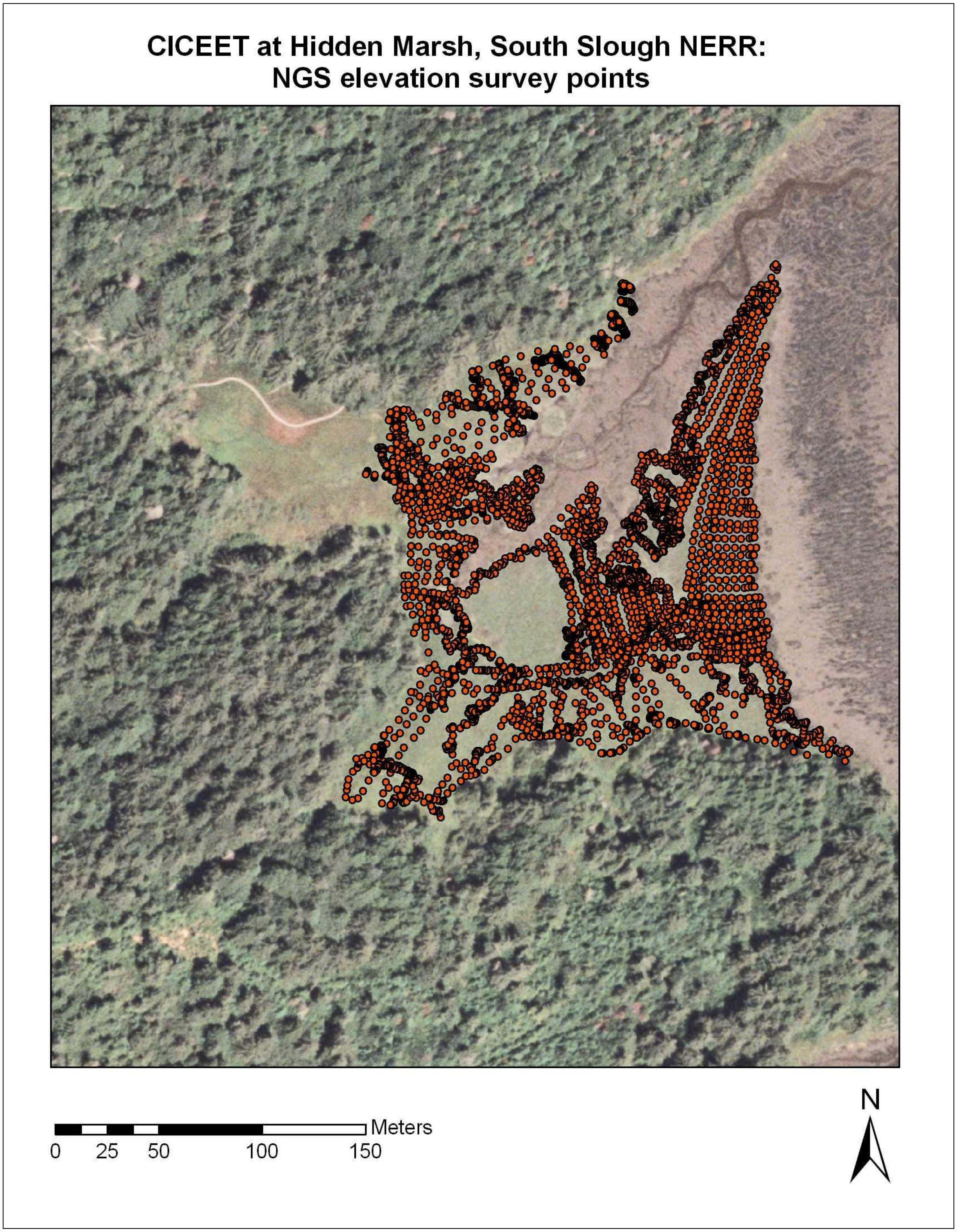


Map 7. Blind Slough study site: National Geodetic Survey elevation points



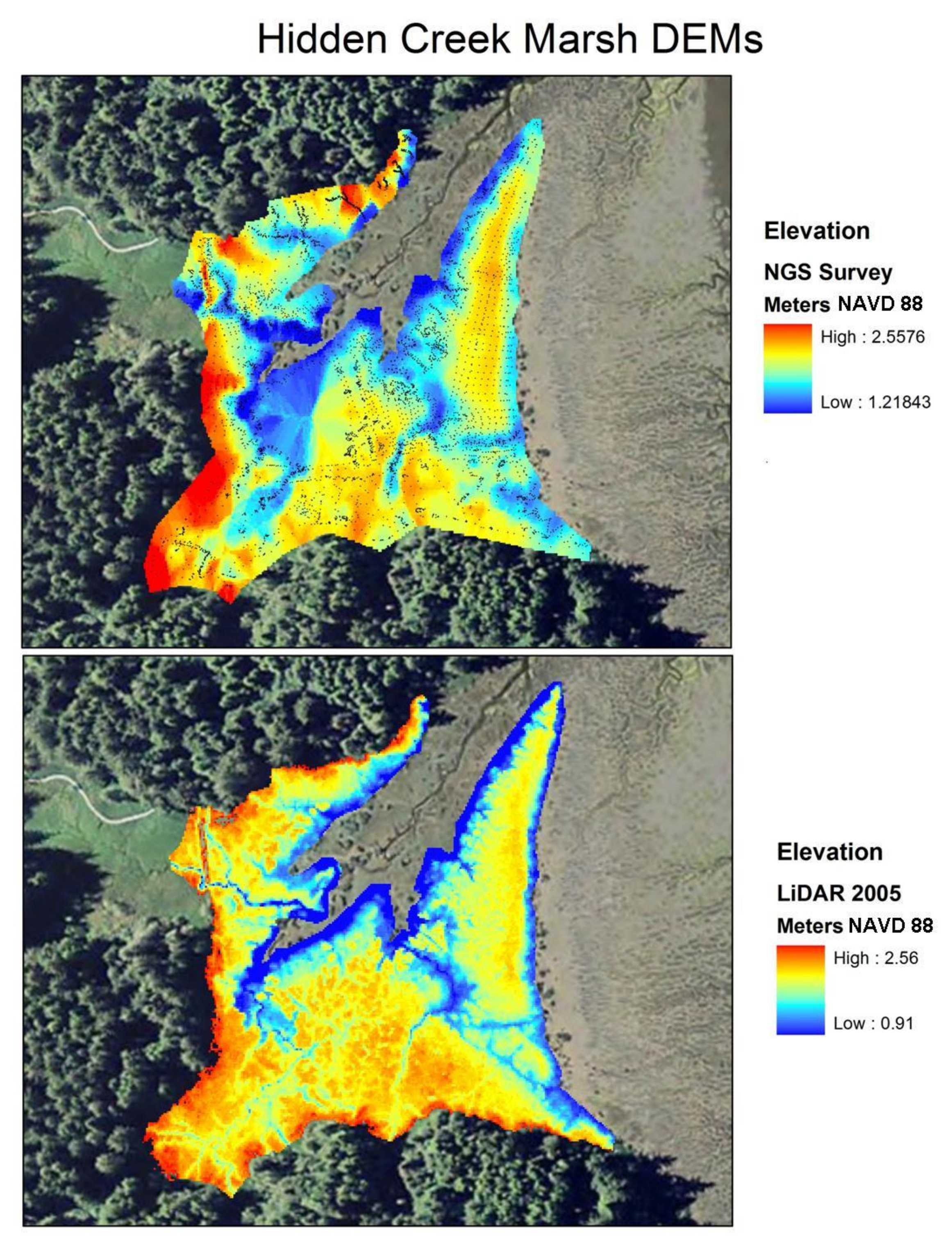
Map 8. Coal Creek study site: National Geodetic Survey elevation points

Map 9. Millport Slough study site: National Geodetic Survey elevation points

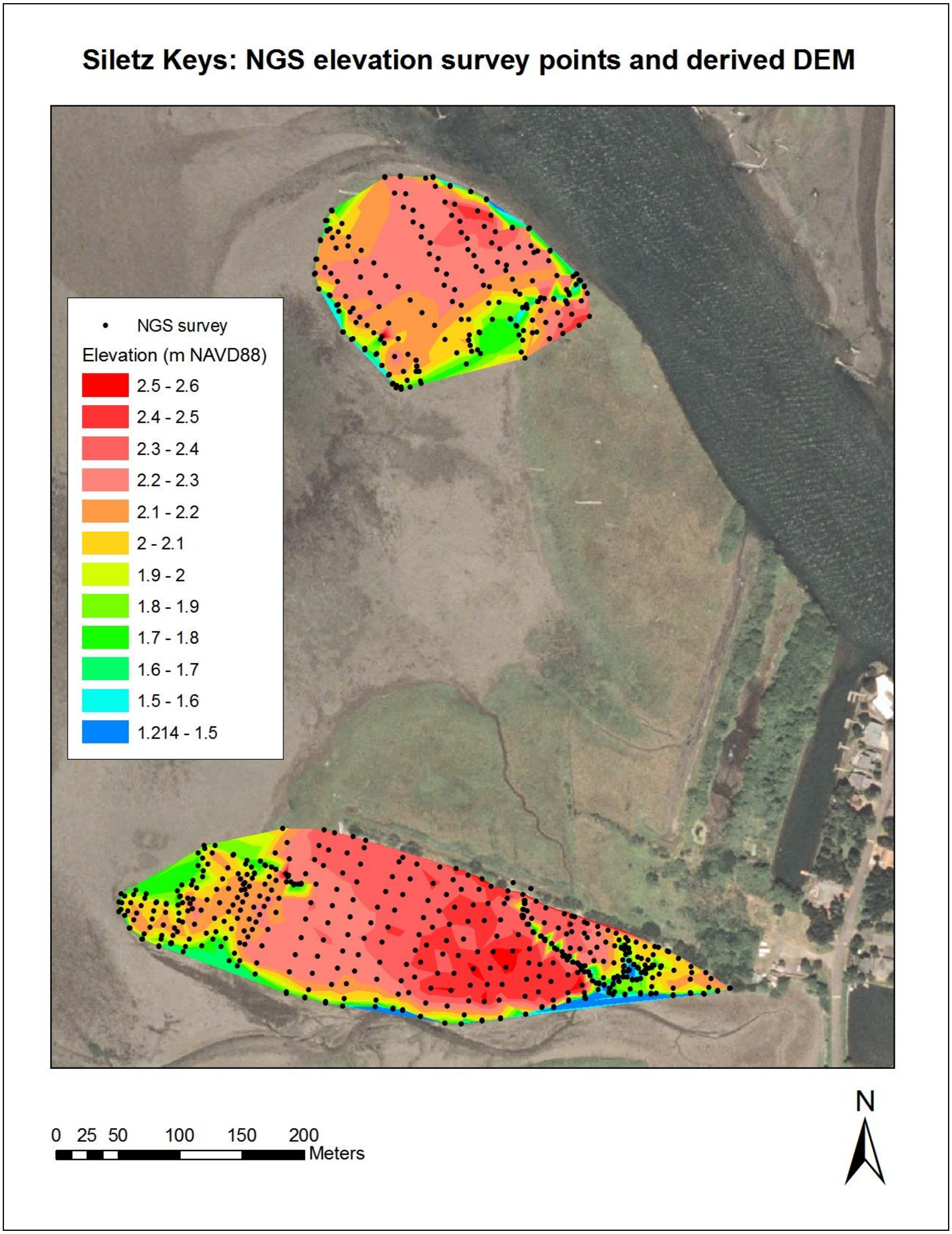


Map 10. Hidden Creek Marsh study site: National Geodetic Survey elevation points

Map 11. Siletz Keys study site: National Geodetic Survey elevation points



Map 12. Hidden Creek Creek Marsh study site: Comparison of digital elevation models derived from National Geodetic Survey RTK-GPS survey (top) and airborne LiDAR (bottom).



Map 13. Siletz Keys study site: National Geodetic Survey elevation survey points and derived digital elevation model (DEM)

Appendix 2. Tables

Table 1. Study site characteristics

Site	Blind Slough	Coal Creek	Millport Slough	Siletz Keys	Hidden Creek Marsh	Yaquina Swamp
Site type	study site	study site	study site	study site	study site	pilot test site
Estuary	Columbia	Nehalem	Siletz	Siletz	Coos	Yaquina
Approx. lat/long	46°11'34"N 123°34'45"W	45°44'30"N 123°51'15"W	44°53'18"N 123°59'46"W	44°54'00"N 124°00'50"W	43°17'31"N 124°19'29"W	44°36'45"N 123°54'08"W
Site size (ha)	152.0	50.8	48.0	15.7	4.6	7.3
Salinity zone	freshwater tidal	brackish	brackish	marine	brackish	brackish
Cowardin class code*	PFOR, PSSR	E2FOP	E2EMP	E2EMN	E2EMN, E2EMP	E2EM/SS
Cowardin class description	tidally-influenced palustrine shrub and forested	estuarine forested	estuarine emergent (high marsh)	estuarine emergent (low marsh)	estuarine emergent (low and high marsh)	estuarine emergent and scrub-shrub
NGS benchmark name, coordinates, elevation**	ROY_ADJUSTED 455845.42m 5115787.30m elev=5.564m	SWMP_ADJUSTED 433178.10m 5066126.33m elev=5.914m	STZ2 421327.37m 4970947.63m elev=4.73m	STZ1 420182.73m 4972031.69m elev=4.33m	HC_BENCHMARK 392667.36m 4794198.78m elev=2.30m	none

* Cowardin classification in Table 1 is based on field measurements, including surface water salinity and vegetation. Classification may therefore differ from the National Wetland Inventory, which is based on remote data.

** NGS benchmark coordinates: Units = meters; coordinate system = UTM Zone 10N, horizontal datum = NAD83, vertical datum = NAVD88.

Table 2. Monitoring parameters

Indicator category	Metric(s)
CONTROLLING FACTORS	
Tidal hydrology	• Tidal inundation regime (frequency and duration of inundation) • Tidal datums (MHW, MHHW)
Groundwater hydrology	• Water table depth (monitored only at high marsh, shrub and forested sites)
Topography	• Wetland surface elevation
Water quality	• Surface water salinity
Soils	• Soil salinity (electrical conductivity) • Organic matter content • pH • Soil texture
ECOSYSTEM STRUCTURE AND FUNCTION	
Vegetation	• Plant community composition • Woody plant density • Tree basal area
Benthic macroinvertebrates	• Density • Taxonomic composition

Table 3. Study plot characteristics

Site	Plot	Width (m)	Length (m)
Blind Slough	P1	18.3	45.7
	P2	18.3	45.7
Coal Creek	P1	18.3	45.7
	P2	18.3	45.7
Millport Slough	P1	18.3	45.7
	P2	18.3	45.7
Siletz Keys	P1	18.3	45.7
	P2	18.3	45.7
Hidden Creek Marsh	P1	18.3	45.7
	P2	18.3	45.7
	P3	18.3	41.1
	P4	18.3	41.1
Yaquina Swamp	P5	18.3	45.7

Table 4. Woody vegetation summary: Stem density and basal area. Shrub/sapling densities include all stems; tree densities include trees over 5cm dbh.

	Tree basal area (sq m/ha)			
	Blind Slough	**Blind Slough**	**Coal Creek**	**Coal Creek**
Species	**BS P1**	**BS P2**	**CC P1**	**CC P2**
Alnus rubra	2			2.5
Malus fusca			0.7	
Picea sitchensis	27		42.3	36.2
Thuja plicata	10			
Total	39		43	39

	Tree density (trees/ha)			
	Blind Slough	**Blind Slough**	**Coal Creek**	**Coal Creek**
Species	**BS P1**	**BS P2**	**CC P1**	**CC P2**
Alnus rubra	36			48
Malus fusca			12	
Picea sitchensis	179		155	120
Thuja plicata	60			
Total	275		167	167

	Shrub/sapling density (stems/ha)			
	Blind Slough	**Blind Slough**	**Coal Creek**	**Coal Creek**
Species	**BS P1**	**BS P2**	**CC P1**	**CC P2**
Acer circinatum	1,458			
Cornus sericea	29,892			
Frangula purshiana			2,916	
Gaultheria shallon	16,769		31,350	101341
Hedera helix	2,187			
Lonicera involucrata	16,769	2,187	19,685	20414
Malus fusca	3,645		1,458	19685
Physocarpus capitatus	29,892			
Picea sitchensis	2,916			
Ribes sp.	729			
Rosa nutkana	25,518			
Rubus laciniatus				2187
Rubus parviflorus	13,123			
Rubus spectabilis	3,645		32,079	13852
Rubus ursinus	24,789		45,203	12394
Salix hookeriana		2,187	2,916	3645
Salix lucida ssp. lasiandra		2,187		
Salix sitchensis		29,892		
Spiraea douglasii	18,227	127,588		
Symphoricarpos albus	4,374			
Vaccinium ovatum			729	
Total	**193,934**	**164,042**	**136,337**	**173,520**

Table 5. 2007 herbaceous vegetation in scrub-shrub and forested study plots (% cover by species)

Scrub-shrub/Forested plots	**Blind Slough**		**Coal Creek**	
Herbaceous species % cover	**BS P1**	**BS P2**	**CC P1**	**CC P2**
Adiantum aleuticum	2.3			
Athyrium filix-femina	1.8	22.6	6.7	16.1
Cardamine angulata	0.1			
Carex deweyana	0.5			
Carex obnupta	0.1	4.6	12.2	17.0
Equisetum arvense	0.2			
Equisetum fluviatile		4.1		
Impatiens capensis	1.2	16.8		
Lysichiton americanus	5.0	6.4		
Maianthemum dilatatum				2.8
Oenanthe sarmentosa	7.7	2.3	0.5	0.1
Phragmites australis	2.3			
Polypodium glycyrrhiza	0.5		0.6	0.1
Polystichum munitum	1.5		1.9	8.9
Rubus spectabilis (seedling)				0.1
Scirpus microcarpus		12.8		
Typha sp.		0.5		
Vicia nigricans ssp. *gigantea*			0.3	

Table 6. 2007 herbaceous vegetation in low marsh study plots (% cover by species)

Low Marsh plots	**Siletz Keys**		**Hidden Creek Marsh**	
Herbaceous species % cover	**SK P1**	**SK P2**	**HM P1**	**HM P2**
Algal mat	0.5			
Atriplex gmelinii	0.1	0.1		0.1
Carex lyngbyei	9.8			2.3
Cuscuta salina			5.9	4.6
Deschampsia caespitosa	0.7	0.2	9.1	17.6
Distichlis spicata	25.6	53.0	7.3	18.6
Glaux maritima				0.3
Hordeum brachyantherum				0.1
Hordeum jubatum	0.2			
Jaumea carnosa	36.5	33.0	21.3	37.3
Plantago maritima	5.6	0.2	15.4	0.3
Salicornia depressa	12.3	12.3	20.6	8.1
Spergularia sp.	0.7	0.4		
Triglochin maritimum	2.9	2.4	16.9	12.5
Mud		0.3		
Bare ground			5.3	1.9
Water	10.2		0.1	

Table 7. 2007 herbaceous vegetation in high marsh plots (% cover by species)

High Marsh plots	**Millport Slough**		**Hidden Creek Marsh**	
Herbaceous species % cover	**MH P1**	**MH P2**	**HM P3***	**HM P4**
Achillea millefolium	5.6	3.3		
Agrostis stolonifera	20.0	14.2	8.2	29.5
Angelica lucida	2.3	2.5		0.9
Argentina egedii	28.3	24.0		5.65
Atriplex patula		0.3	0.1	0
Carex lyngbyei			3.5	1.4
Cirsium vulgare		0.1		
Cuscuta salina			1.2	
Deschampsia caespitosa	41.4	42.0	21.5	1.1
Distichlis spicata			14.9	
Epilobium ciliatum		0.1		
Festuca rubra	0.7			6
Galium aparine	0.3			
Galium trifidum	0.1	0.2		
Glaux maritima			2.3	6.3
Grindelia stricta				0.3
Heracleum maximum	0.1	0.8		
Hordeum brachyantherum	0.1	0.3	2.4	0.1
Jaumea carnosa			42.0	17.95
Juncus balticus	14.0	4.2		26.5
Lathyrus palustris	0.3			
Unknown (Umbelliferae)	0.1			
Plantago maritima				0.9
Rumex occidentalis		0.8		
Salicornia depressa			3.8	
Symphyotrichum subspicatum	12.4	10.5		0.2
Triglochin maritimum			4.9	6.3
Trifolium wormskioldii				0.7
Vicia nigricans ssp. gigantea	1.9	2.6		
Bare ground			1.6	0.3
Litter				2.3
Water		0.6	0.0	

* HM P3 is transitional between low and high marsh.

Table 8. Soil test results

Site	Site type	Sample year	Plot	Sample depth (cm)	pH	%OM by LOI	%C	EC (mS/cm)	Salinity	% sand	% silt	% clay	Texture class	Histosol threshold (%C)	Histo-sol?
Blind Slough	Tidal swamp	2007	P1	0-30	5.3	20.29	13.80	0.73	0.40	22.1	50.8	27.2	clay loam	14.7	N
Blind Slough	Tidal swamp	2007	P2	0-30	5.3	28.86	19.62	0.77	0.42	45.8	27.1	27.2	sandy clay loam	14.7	Y
Coal Creek	Tidal swamp	2007	P1	0-30	4.9	20.97	14.26	13.40	8.64	35.8	38.3	25.9	loam	14.6	N
Coal Creek	Tidal swamp	2007	P2	0-30	4.7	22.16	15.07	13.60	8.78	45.8	35.8	18.4	loam	13.8	Y
Yaquina Swamp	Tidal swamp	2006	P5	0-30	4.7	21.91	14.90	26.10	17.86	26.7	45.0	28.3	clay loam	14.8	Y
Millport Slough	High marsh	2007	P1	0-30	5.8	21.30	14.48	19.80	13.20	45.8	33.3	20.9	loam	14.1	Y
Millport Slough	High marsh	2007	P2	0-30	5.6	16.93	11.51	15.60	10.19	24.4	52.7	22.9	silt loam	14.3	N
Hidden Cr. Marsh	Low marsh	2008	P1	0-20	5.9	23.78	16.17	74.10	57.51	33.8	30.0	36.3	clay loam	15.6	Y
Hidden Cr. Marsh	Low marsh	2008	P2	0-20	5.2	19.98	13.59	64.20	48.75	26.3	31.3	42.5	clay loam	16.3	N
Hidden Cr. Marsh	Mid marsh	2008	P3	0-30	5.5	21.55	14.65	62.40	47.19	27.5	30.0	42.5	clay loam	16.3	N
Hidden Cr. Marsh	High marsh	2008	P4	0-30	4.9	32.13	21.85	37.30	26.47	46.3	26.3	27.5	loam/sandy clay loam	14.8	Y
Siletz Keys	Low marsh	2007	P1, upper	0-25	5.9	12.68	8.62	37.90	26.94	31.6	53.4	15.0	silt loam	13.5	N
Siletz Keys	Low marsh	2007	P1, lower	40-50	6.9	2.93	1.99	31.00	21.57	54.1	35.9	10.0	sandy loam	13.0	N
Siletz Keys	Low marsh	2007	P2, upper	0-20	5.8	11.47	7.80	31.40	21.88	44.1	42.2	13.8	loam	13.4	N
Siletz Keys	Low marsh	2007	P2, lower	20-30	6.5	2.99	2.03	33.10	23.19	66.6	24.7	8.8	sandy loam	12.9	N

TABLE 9. Reference conditions database, least-disturbed tidal wetlands of Oregon, U.S.A.

Site/ Estuary	Plot	Cowardin class	Habitat type	Elevation (NAVD88)	Elevation relative to MHHW [1]	Summer max. channel water salinity (ppt)	Summer soil salinity (ppt)	Soil pH	Soil % organic matter	Dominant vegetation
Blind Slough/ Columbia	P1	tidally-influenced palustrine forested	Sitka spruce swamp	2.64m 8.66ft	-0.16m -0.52ft	0	0.4	5.3	20.3	Sitka spruce / western dogwood - ninebark - Nootka rose - trailing blackberry
Blind Slough/ Columbia	P2	tidally-influenced palustrine shrub	willow swamp	2.64m 8.66ft	-0.16m -0.52ft	0	0.4	5.3	28.9	Sitka willow - Douglas' spiraea / Pacific lady-fern
Coal Creek/ Nehalem	P1	estuarine forested	Sitka spruce swamp	2.55m 8.36ft	0.11m 0.35ft	12	8.6	4.9	21.0	Sitka spruce / salal - black twinberry - salmonberry - trailing blackberry
Coal Creek/ Nehalem	P2	estuarine forested	Sitka spruce swamp	2.63m 8.62ft	0.19m 0.61ft	12	8.8	4.7	22.2	Sitka spruce / salal - black twinberry - Oregon crabapple
Yaquina Swamp (Y28)/ Yaquina	P5	estuarine scrub-shrub	twinberry swamp	2.64m 8.66ft	0.19m 0.62ft	8	17.9	4.7	21.9	Black twinberry - Oregon crabapple / Pacific silverweed
Millport Slough/ Siletz	P1	estuarine emergent	high marsh	2.42m 7.95ft	0.08m 0.27ft	27	13.2	5.8	21.3	tufted hairgrass – Pacific silverweed
Millport Slough/ Siletz	P2	estuarine emergent	high marsh	2.49m 8.17ft	0.15m 0.49ft	27	10.2	5.6	16.9	tufted hairgrass – Pacific silverweed
Hidden Cr Marsh	P1	estuarine emergent	low marsh	2.13m 7.00ft	-0.10m -0.32ft	30	57.5	5.9	23.8	glasswort - jaumea – seaside plantain
Hidden Cr Marsh	P2	estuarine emergent	low marsh	2.18m 7.14ft	-0.05m -0.17ft	30	48.8	5.2	20.0	saltgrass - jaumea
Hidden Cr Marsh	P3	estuarine emergent	mid marsh	2.22m 7.28ft	-0.01m -0.04ft	30	47.2	5.5	21.6	tufted hairgrass - jaumea
Hidden Cr Marsh	P4	estuarine emergent	high marsh	2.35m 7.70ft	0.12m 0.38ft	30	26.5	4.9	32.1	Baltic rush - creeping bentgrass

Site/ Estuary	Plot	Cowardin class	Habitat type	Elevation (NAVD88)	Elevation relative to MHHW [1]	Summer max. channel water salinity (ppt)	Summer soil salinity (ppt)	Soil pH	Soil % organic matter	Dominant vegetation
Siletz Keys/ Siletz	P1	estuarine emergent	low marsh	2.12m 6.96ft	-0.08m -0.27ft	34	26.9	5.9	12.7	saltgrass - jaumea
Siletz Keys/ Siletz	P2	estuarine emergent	low marsh	2.01m 6.59ft	-0.20m -0.64ft	34	21.9	5.8	11.5	saltgrass - jaumea

[1] Elevations relative to tidal datums are usually expressed relative to MLLW; however, local tide gauges were out of water at low tide, so low tide datums could not be determined.

TABLE 10. Reference conditions database, Least-disturbed tidal wetlands of Oregon, U.S.A.: Parameter ranges by habitat class.

Habitat class	Elevation (NAVD88)	Elevation relative to MHHW [1]	Summer max. channel water salinity (ppt)	Summer soil salinity (ppt)	Soil pH	Soil % organic matter	Number of study plots included	List of plots included
Forested tidal swamp, brackish zone, outer coast	2.55 to 2.63m 8.36 to 8.62ft	0.11 to 0.19m 0.35 to 0.61ft	12	8-9	4.7-4.9	21-22	2	Coal Creek P1 and P2
Scrub-shrub tidal swamp, brackish zone, outer coast	2.64m 8.66ft	0.19m 0.62ft	8	16.7	4.7	22	1	Yaquina Y28 P5
Emergent tidal marsh (high)	2.35 to 2.49m 7.70 to 8.17ft	0.08 to 0.15m 0.27 to 0.49ft	27-30	10-24	4.9-5.8	17-32	3	Hidden Cr Marsh P4, Millport Slough P1 and P2
Emergent tidal marsh (low)	2.01 to 2.18m 6.59 to 7.14ft	-0.20 to -0.05m -0.64 to -0.17ft	30-34	20-47	5.2-5.9	12-24	4	Hidden Cr Marsh P1 and P2, Siletz Keys P1 and P2
Forested tidal swamp, freshwater zone of Columbia R. estuary[2]	2.64m 8.66ft	-0.16m -0.52ft	0	0.5	5.3	20	1	Blind Slough P1
Scrub-shrub tidal swamp, freshwater zone of Columbia R. estuary[2]	2.64m 8.66ft	-0.16m -0.52ft	0	0.5	5.3	29	1	Blind Slough P2

[1] Elevations relative to tidal datums are usually expressed relative to MLLW; however, local tide gauges were out of water at low tide, so low tide datums could not be determined.

[2] Columbia River data are separated in this table due to their lower elevation relative to the MHHW datum, compared to outer coast tidal wetlands.

Appendix 3. Figures

Figures i1-i8: iButton temperature charts, illustrating typical temperature patterns associated with tidal inundation
Figures G1-G11: Groundwater level data
Figures S1-S4: Channel water salinity data
Figures T1-T2: Tidal datums

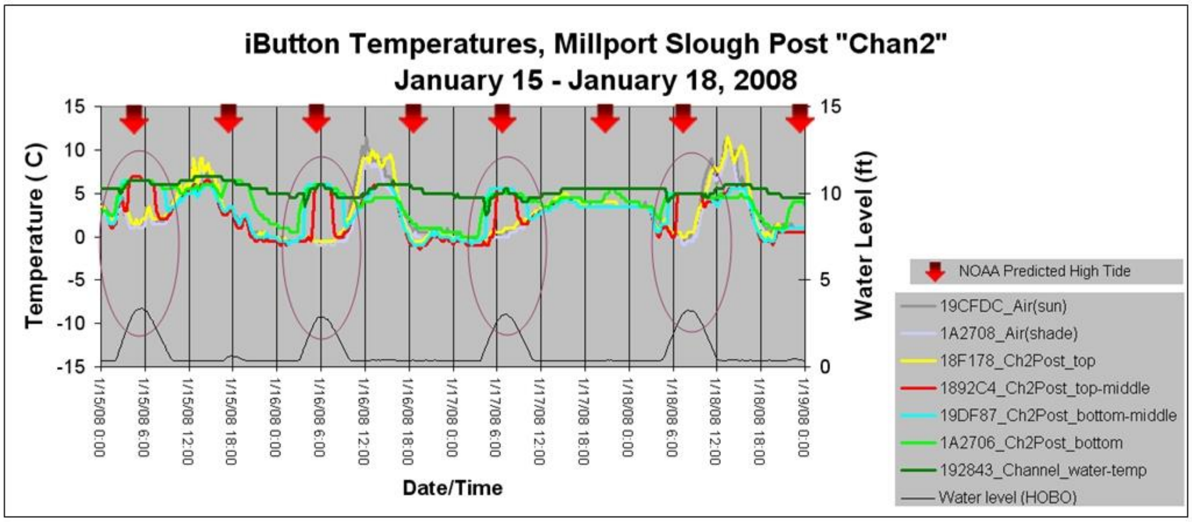


Figure i-1: Winter iButton Temperatures, Millport Slough Post "Chan2" (tidal marsh)
This is an example of a post on which all iButtons were inundated except for the top iButton (yellow curve). Night-time high tide events are circled with purple ovals. At the time of inundation, iButton temperatures increase sharply (red, blue, light green), converging with the warmer ambient water temperature (dark green). The iButtons inundate sequentially (light green first, then blue, then red). As the high tide subsides and the iButtons are exposed to the cooler ambient air, the iButton temperatures drop sequentially and converge with air temperatures (gray). The water reference iButton (dark green) is almost continuously inundated, shown by the relatively flat temperature curve at the temperature the other iButtons reach when inundated. On January 18, the high tide extended into the morning warming period, so that daytime "noise" of solar radiation began to obscure the inundation signal. Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

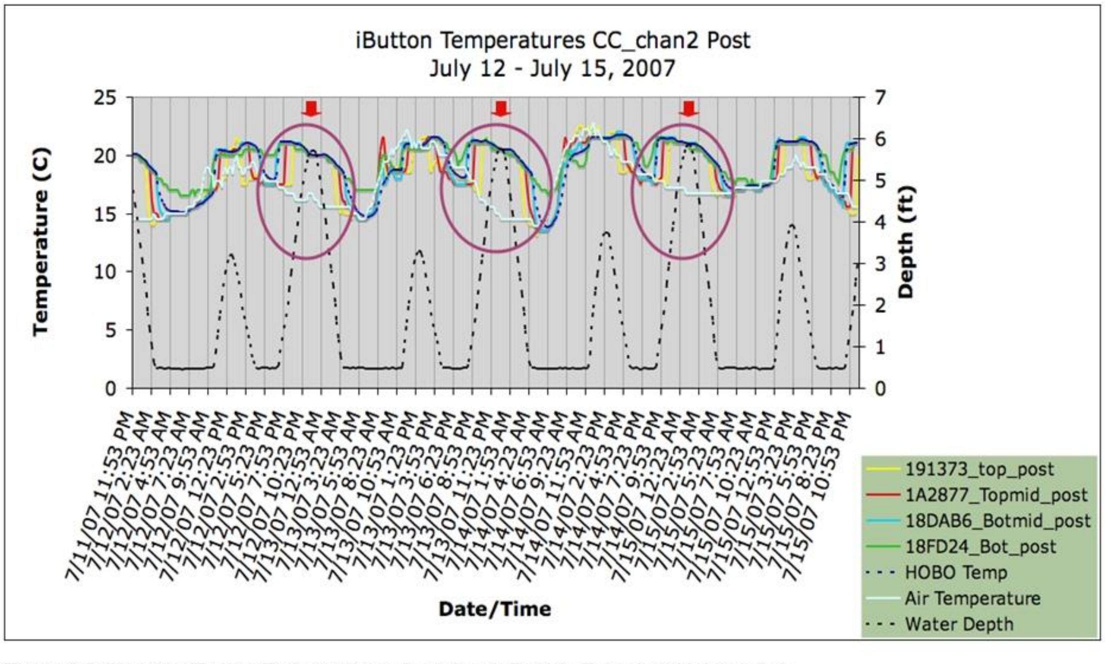


Figure i-2: Summer iButton Temperatures Coal Creek Post 2 (Forested tidal swamp)
This example of summer iButton data illustrates the challenge of detecting daytime tidal inundation based on the iButton temperature curves. Night-time inundations are circled and indicated by red arrows. This post was located very low in the tidal channel, so it inundated even during the lower, daytime high tides of the observation period. Sequential inundation of all of the buttons on the post can be clearly seen during the July 12 and July 15 lower high tide events (noon-5pm), but on other days, daytime air temperature variability ("noise") obscures the inundation signal. Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

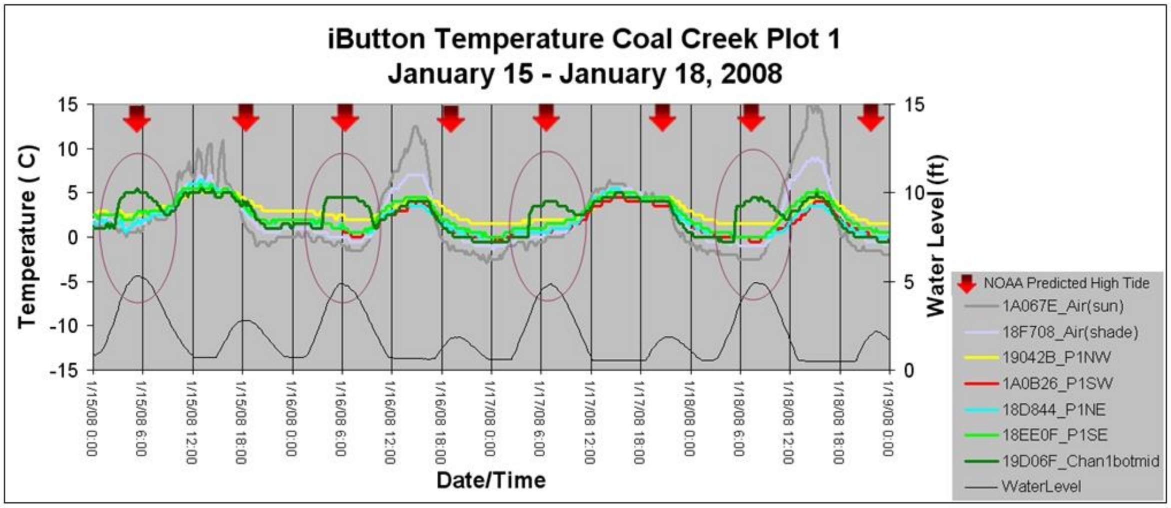


Figure i-3: iButton Temperature Coal Creek Plot 1 (Forested tidal swamp)
This is an example of “variable” surface iButtons that are not inundated. Their temperatures (yellow, red, blue, light green) roughly follow the air temperature curves (gray) and do not show distinct temperature changes during high tides. Only the channel iButton (dark green) inundates, as seen by the sudden temperature rise on rising tides. Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

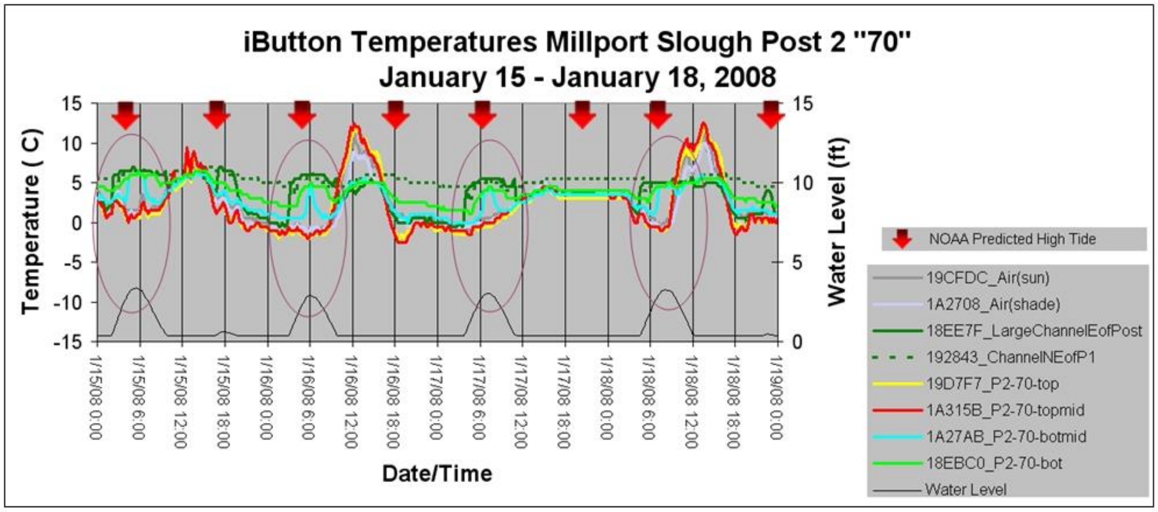


Figure i-4: iButton Temperatures Millport Slough Post 2 “70” (Marsh)
This is an example of a post on which only the bottom 2 post iButtons (blue and light green temperature curves) inundated, along with the channel iButtons (dark green solid and dotted curves). The upper two post iButtons (red and yellow) did not inundate, and they generally follow the ambient air temperature curves (gray). Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

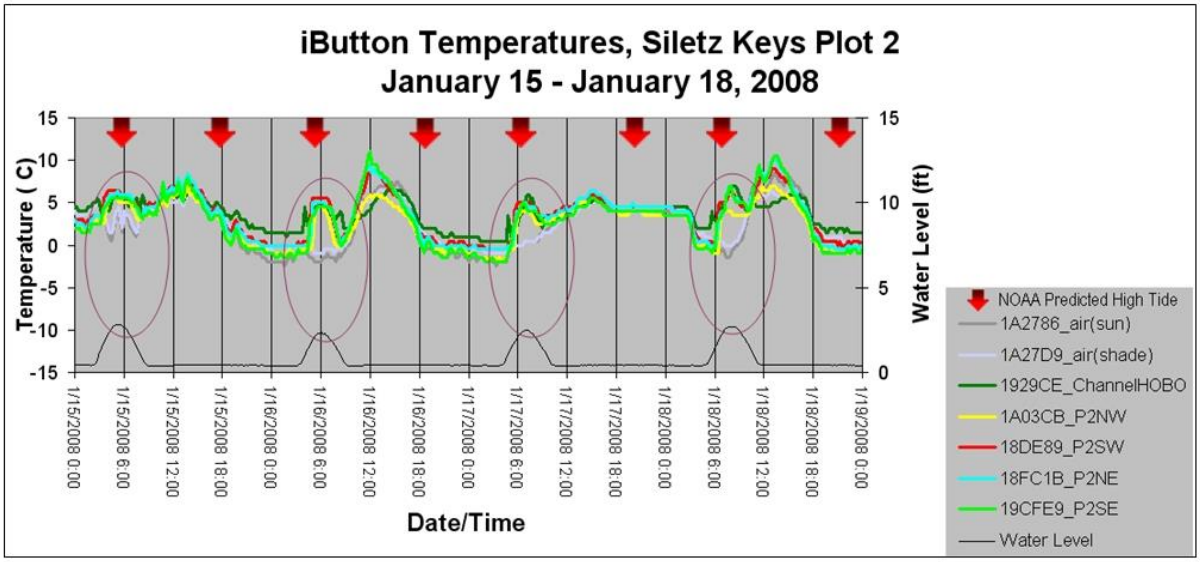


Figure i-5: iButton Temperatures Siletz Keys Plot 2 (Marsh)
This is an example of a marsh plot that clearly shows inundation. During night-time high tides, all four wetland surface iButtons (yellow, red, blue, light green) deviate sharply from air temperature (gray), and converge with the ambient water temperature (dark green). (At this site, the water reference iButton was located relatively high in the tidal range, so it inundated only slightly before the surface iButtons.) Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

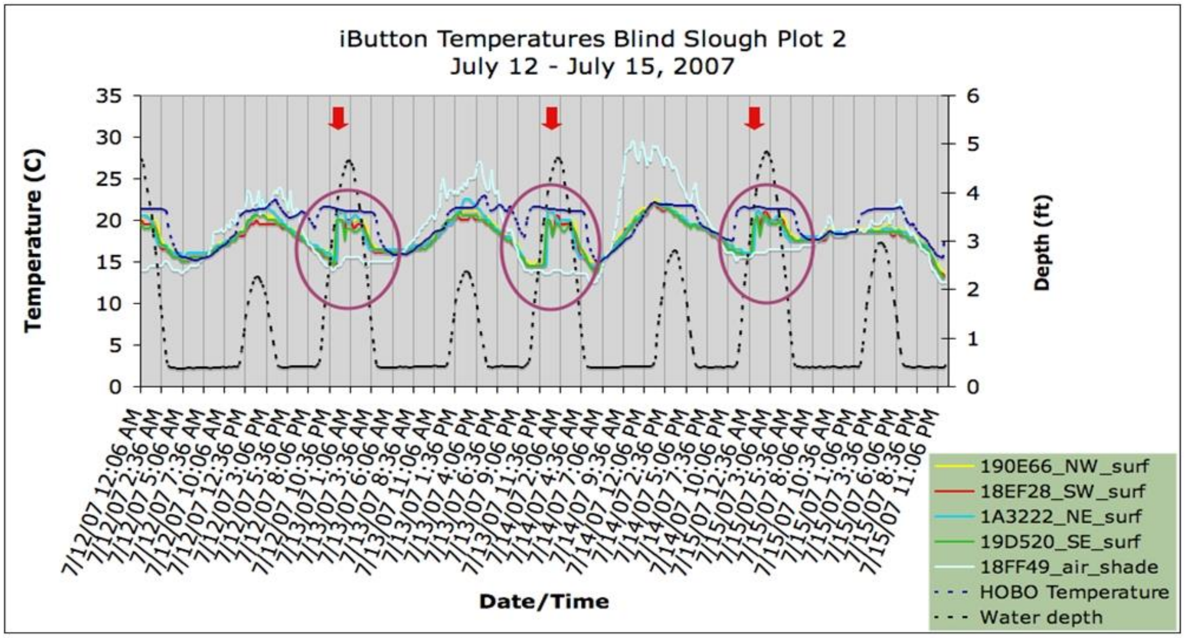


Figure i-6: iButton Temperatures Blind Slough Plot 2 (Scrub-shrub tidal swamp)
This is an example of a swamp plot that clearly shows inundation. During night-time high tides, all four wetland surface iButtons (yellow, red, blue, green) deviate sharply from air temperature (gray), and converge with the ambient water temperature (dark blue). Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

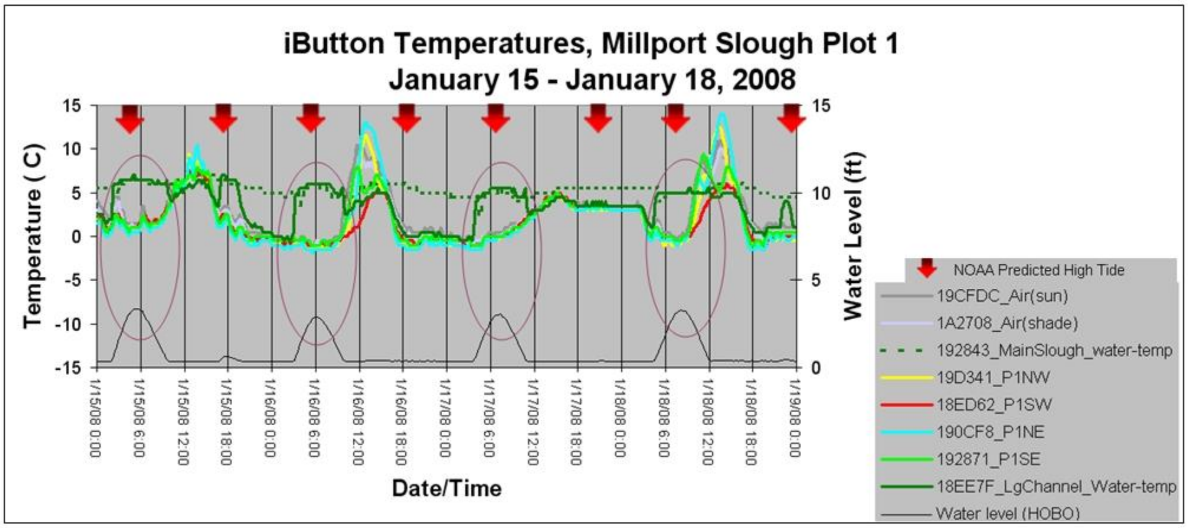


Figure i-7: iButton Temperatures Millport Slough Plot 1 (Marsh)
This is an example of a marsh plot that did not inundate, as indicated by the lack of increased temperature during high tides. All wetland surface iButton temperature curves (yellow, red, blue, light green) followed the general ambient air temperature curves (gray) through the high tide period; only the channel iButtons (dark green dotted and solid curves) inundated. The surface iButton temperatures and air temperatures increased similarly during daytime due to solar warming. Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

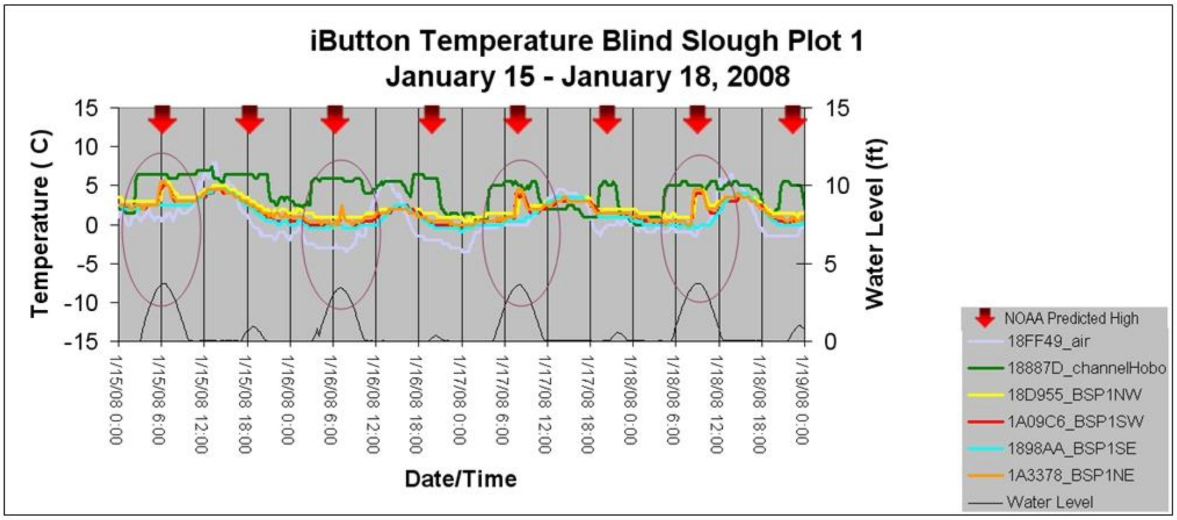


Figure i-8: iButton Temperatures Blind Slough Plot 1 (Swamp)
This graph shows that the iButton method can provide very high spatial resolution data and detect very brief inundation. The sharp peaks in temperature during night-time high tides indicate inundation of plot surface iButtons (red, orange, and yellow). The water temperature reference button is the dark green curve. On January 15, 17 and 18, the NW, SW and NE corners of the plot inundated for 2-3 hr, but the SE corner did not. On January 16, only the NE and SW corners inundated, and only for 1.5 hr. Note that the iButton temperatures (colored curves) and the depth (black curve) are on two separate axes and are independent data.

Figure G1. Groundwater levels at Blind Slough Plot 1 (Sitka spruce swamp) and Plot 2 (willow swamp), April-June 2009

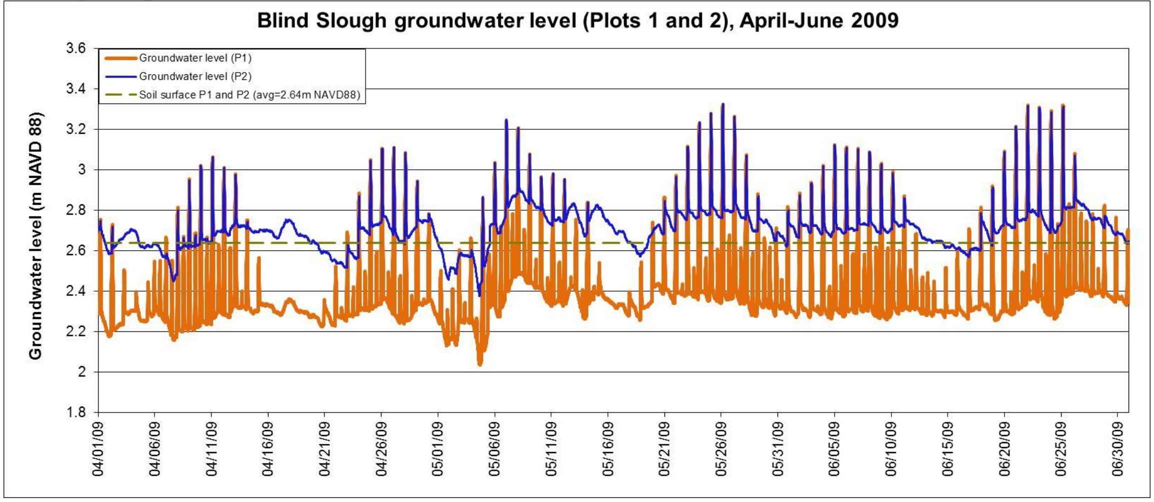


Figure G2. Groundwater levels at Blind Slough study site, July-September 2009

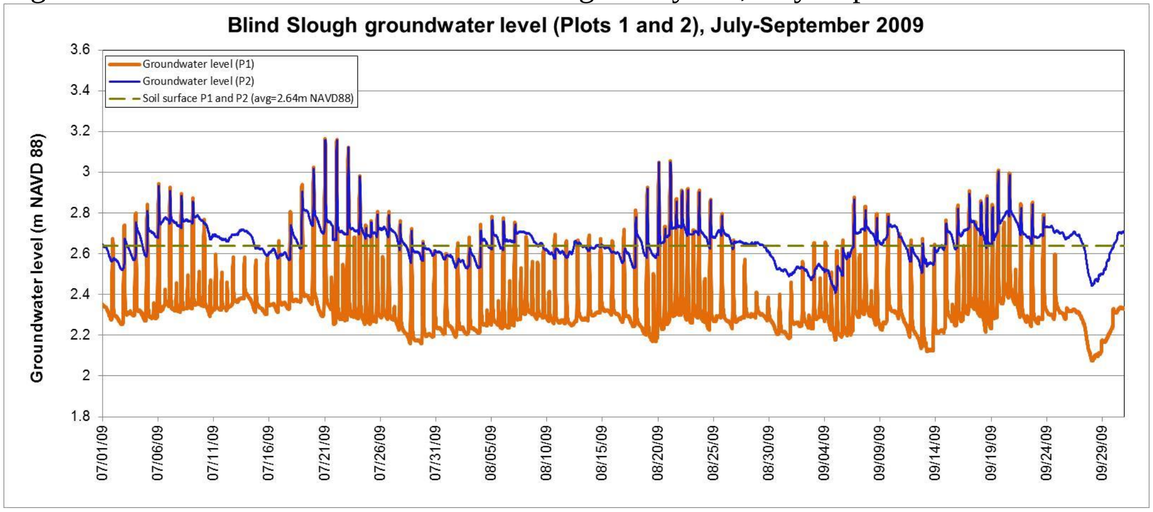


Figure G3. Groundwater levels at Blind Slough, October-December 2009

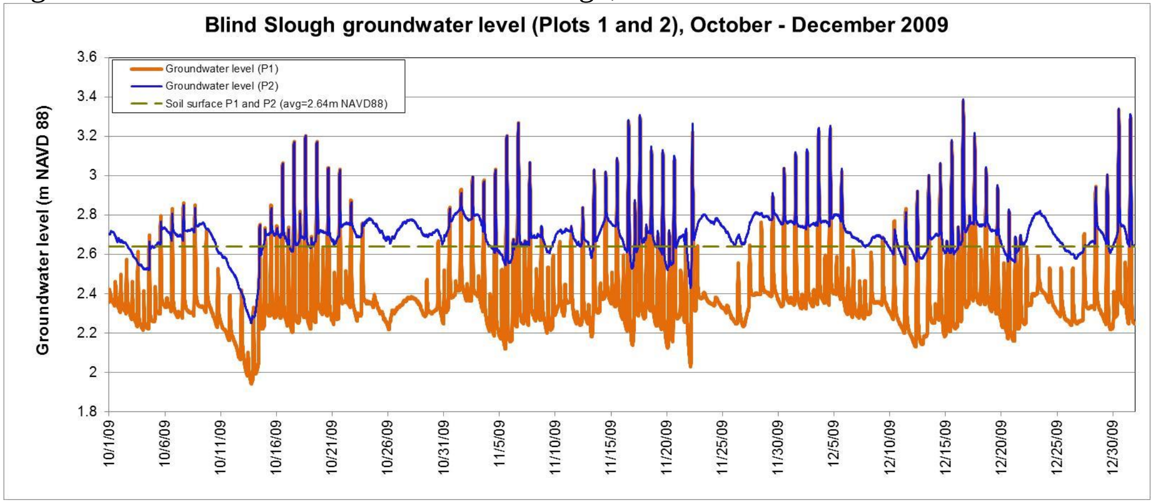


Figure G4. Groundwater levels at Coal Creek study site (Sitka spruce swamp), April-June 2009

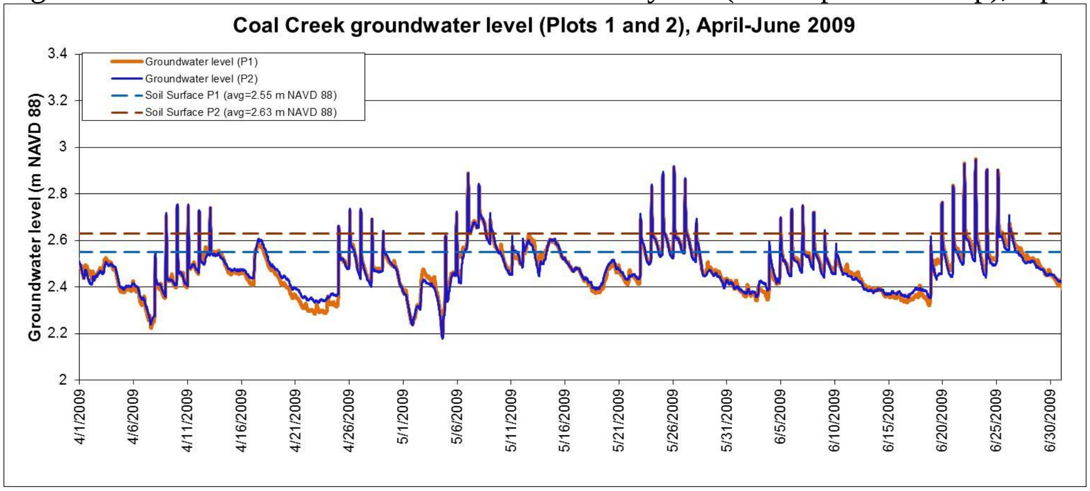


Figure G5. Groundwater levels at Coal Creek study site (Sitka spruce swamp), July-Sept. 2009

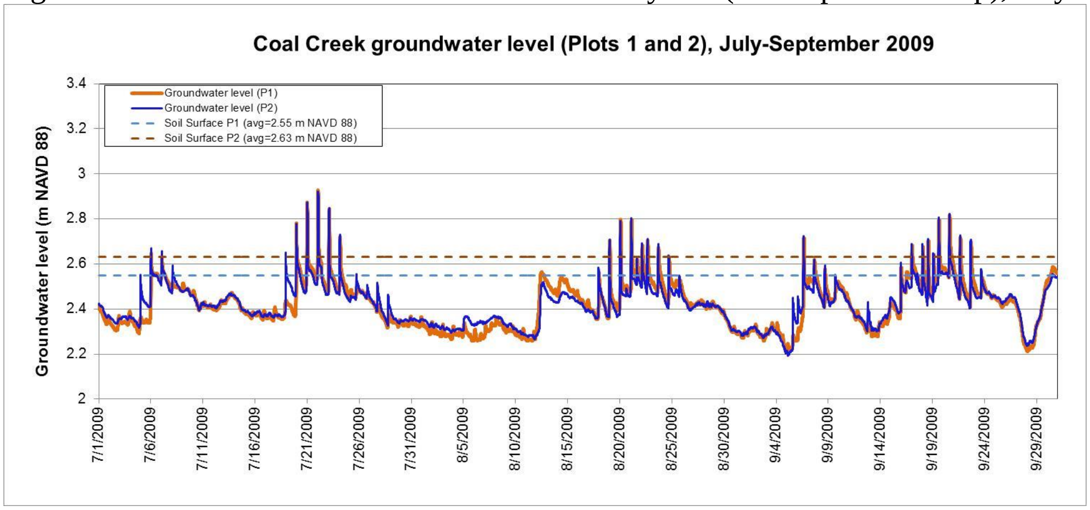


Figure G6. Groundwater levels at Coal Creek study site (Sitka spruce swamp), Oct.-Dec. 2009

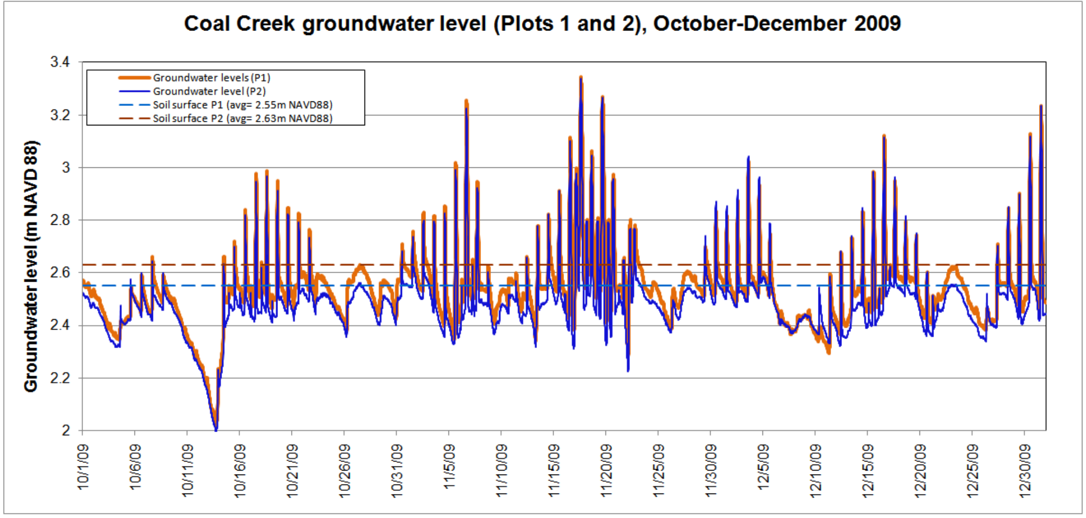


Figure G7. Groundwater levels at Millport Slough Plot 2 (high marsh), April-June 2009

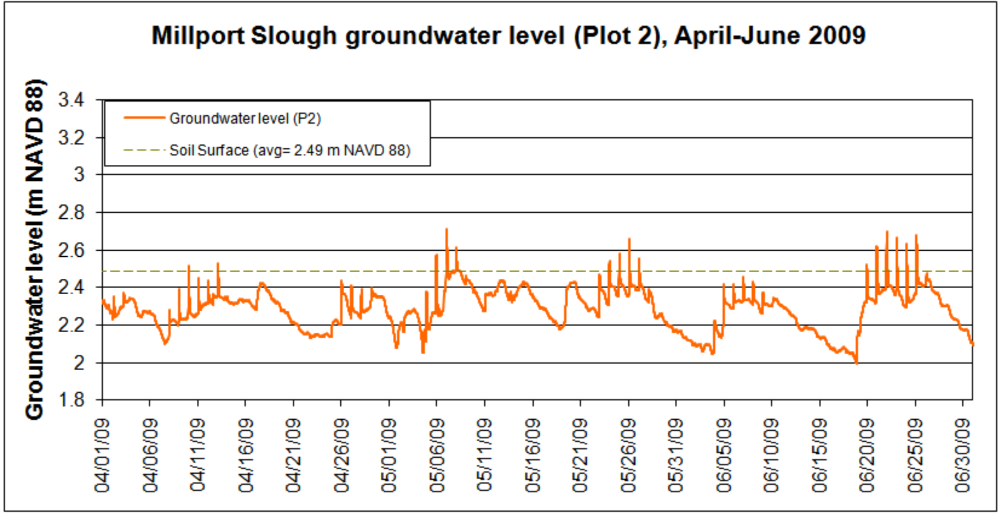


Figure G8. Groundwater levels at Millport Slough Plot 2 (high marsh), July-September 2009

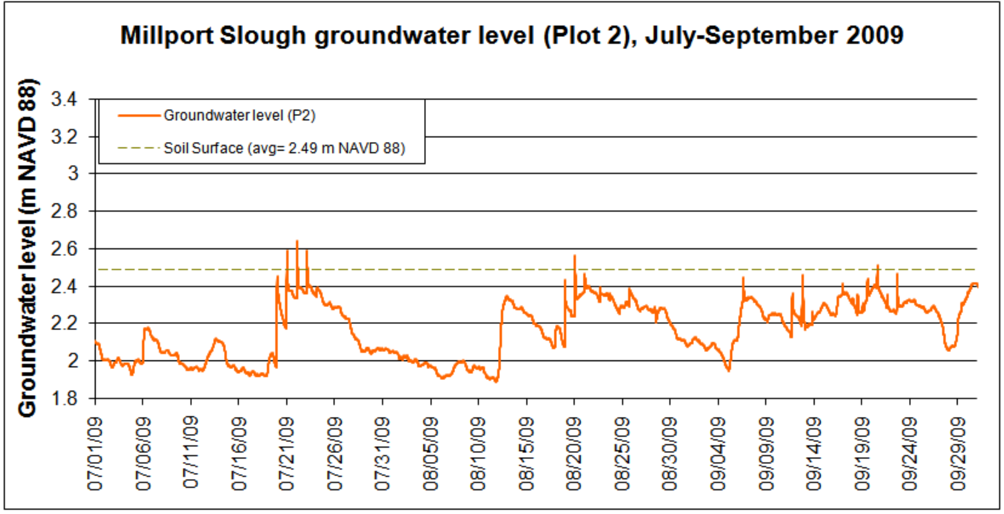


Figure G9. Groundwater levels at Millport Slough Plot 2 (high marsh), October-December 2009

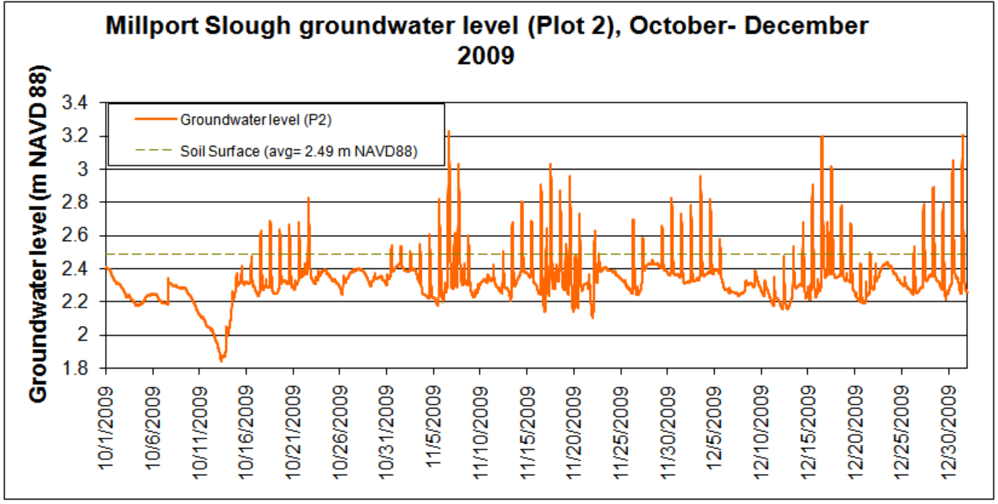


Figure G10. Groundwater levels at Hidden Creek Marsh Plot 4 (high marsh), March-July 2010

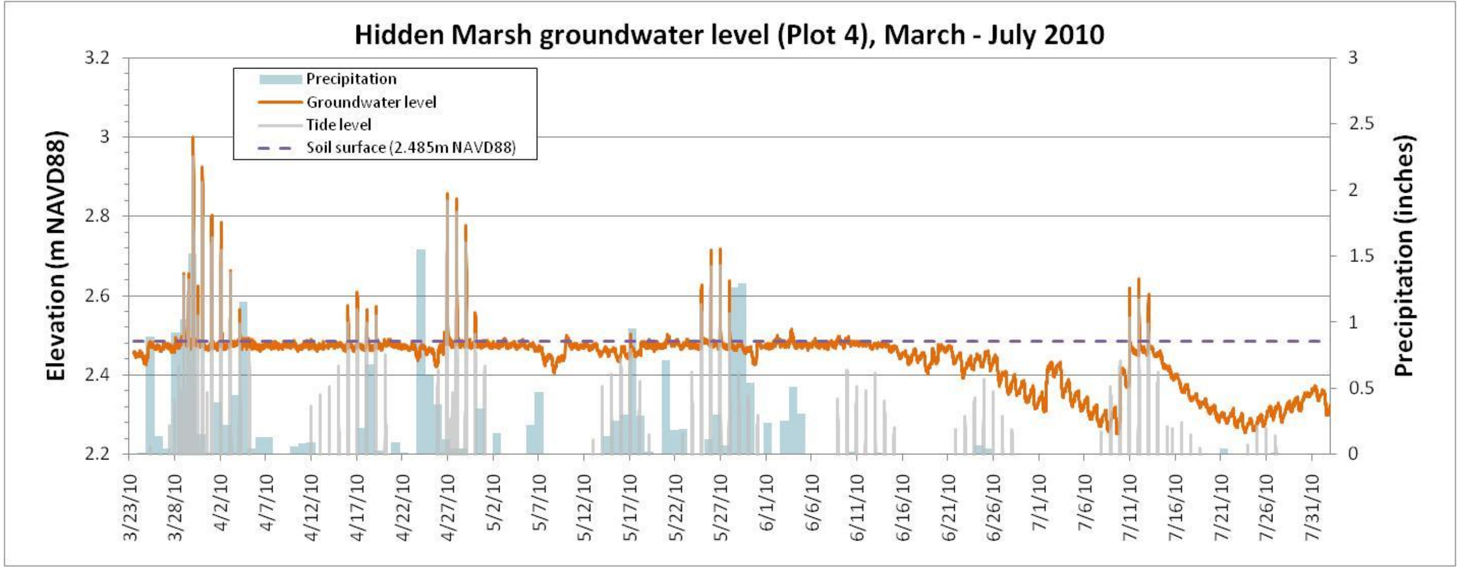


Figure G11. Groundwater levels at Hidden Creek Marsh Plot 4 (high marsh), September-December 2010

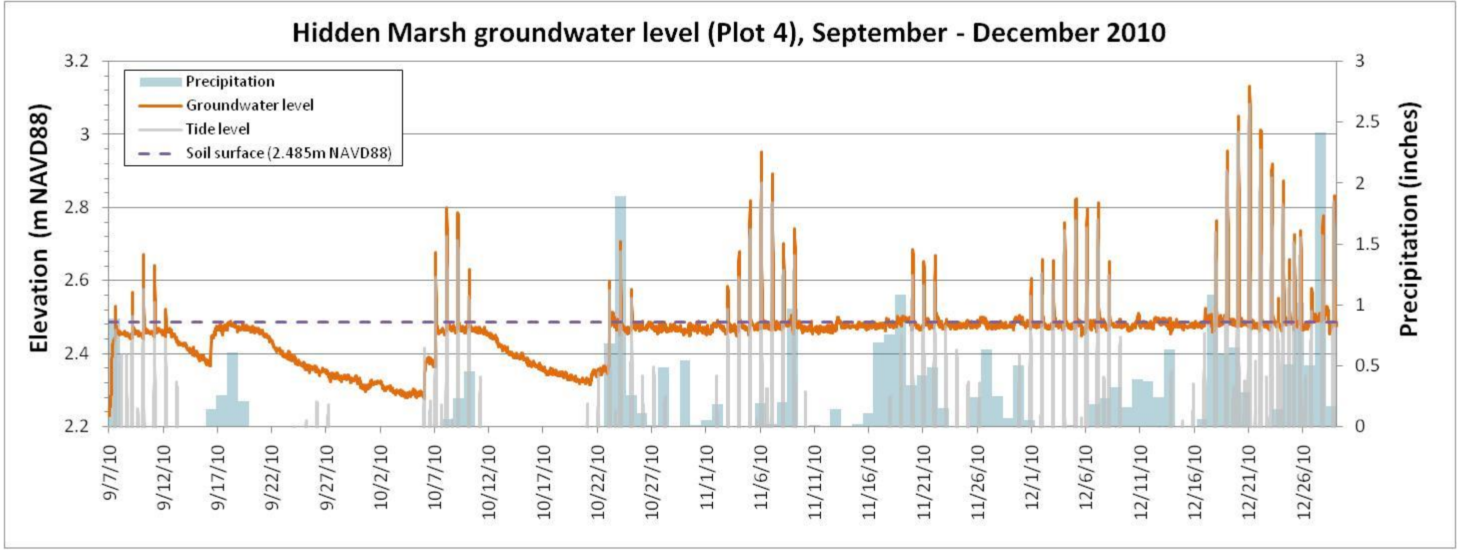


Figure S1. Channel water salinity at Coal Creek, May-August 2008.

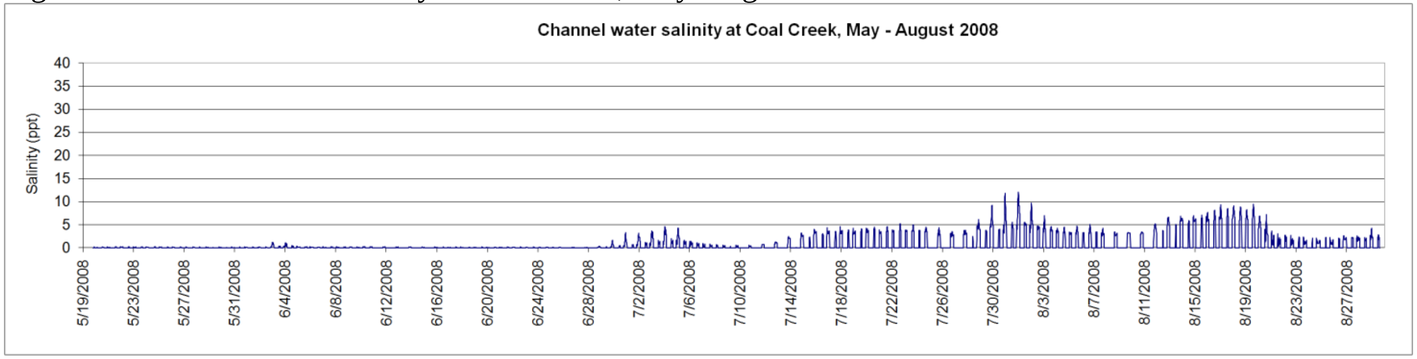


Figure S2. Channel water salinity at Millport Slough study site, March-May 2008

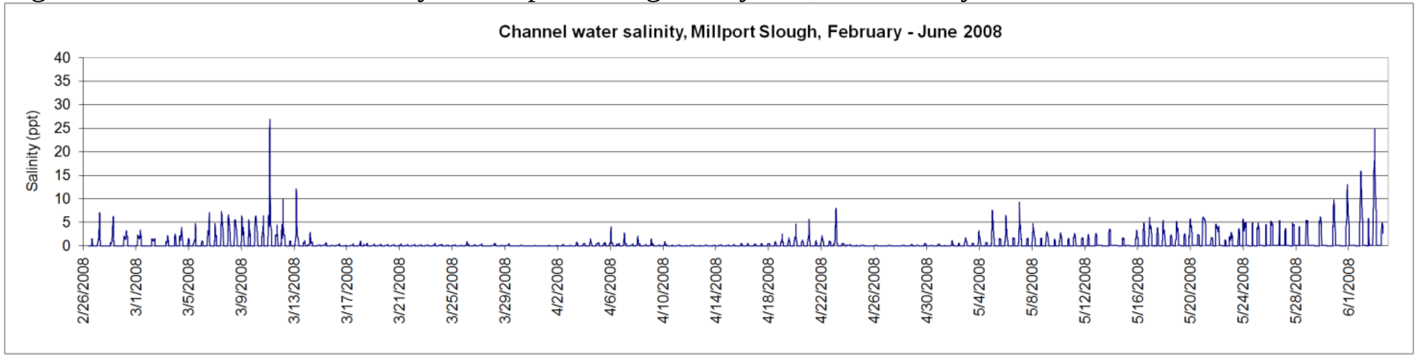


Figure S3. Channel water salinity at Siletz Keys study site, March-May 2008

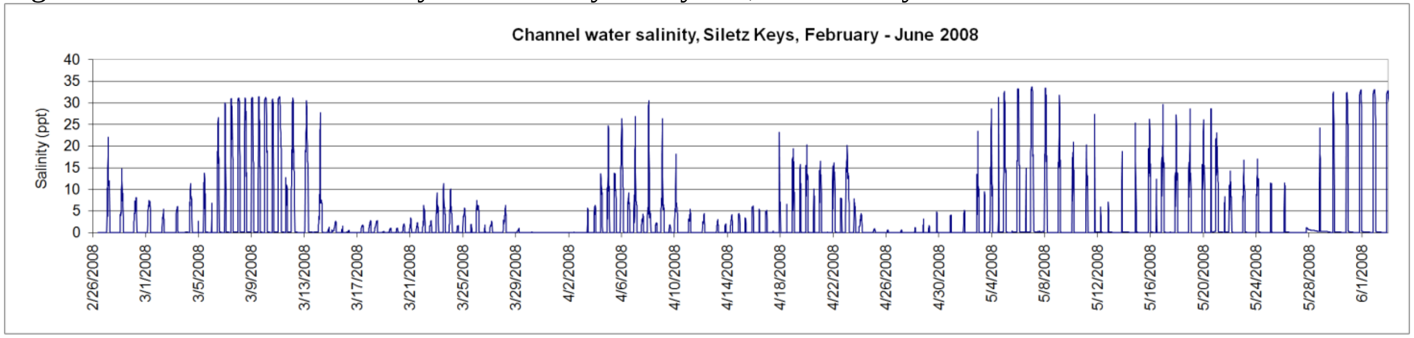


Figure S4. Annual variation in channel water salinity at Winchester Creek monitoring station, South Slough NERR (Rumrill 2006).

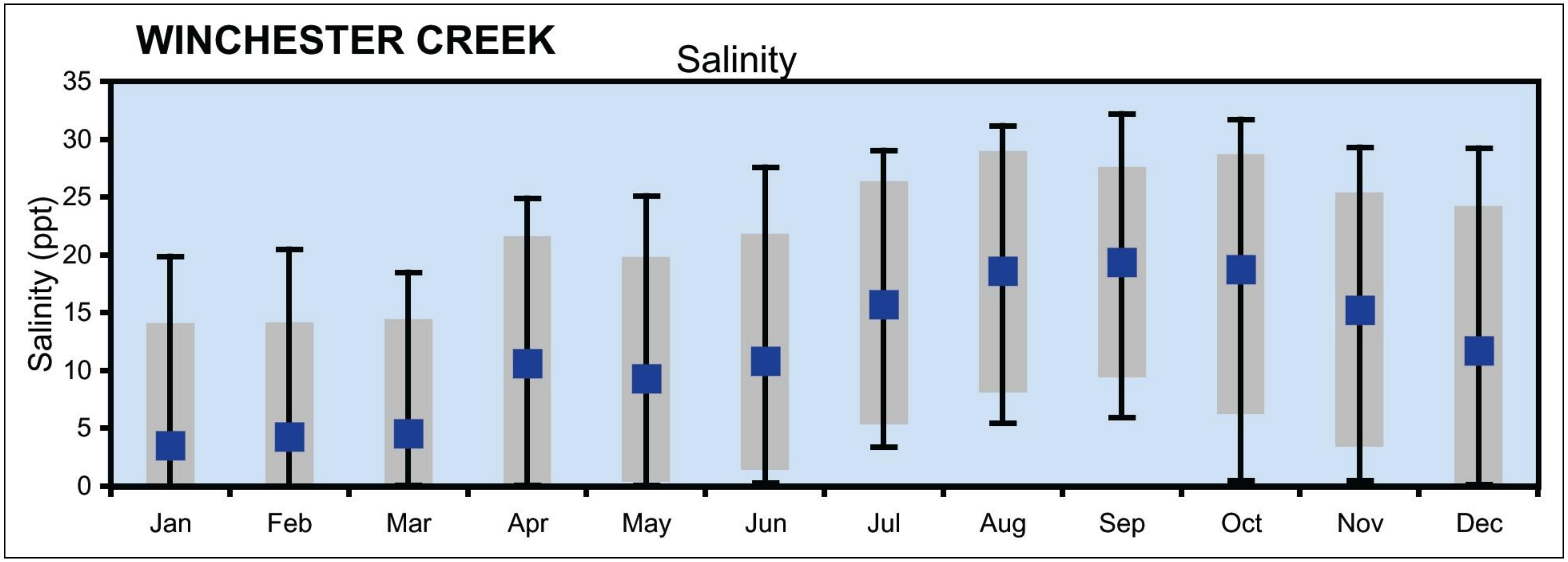
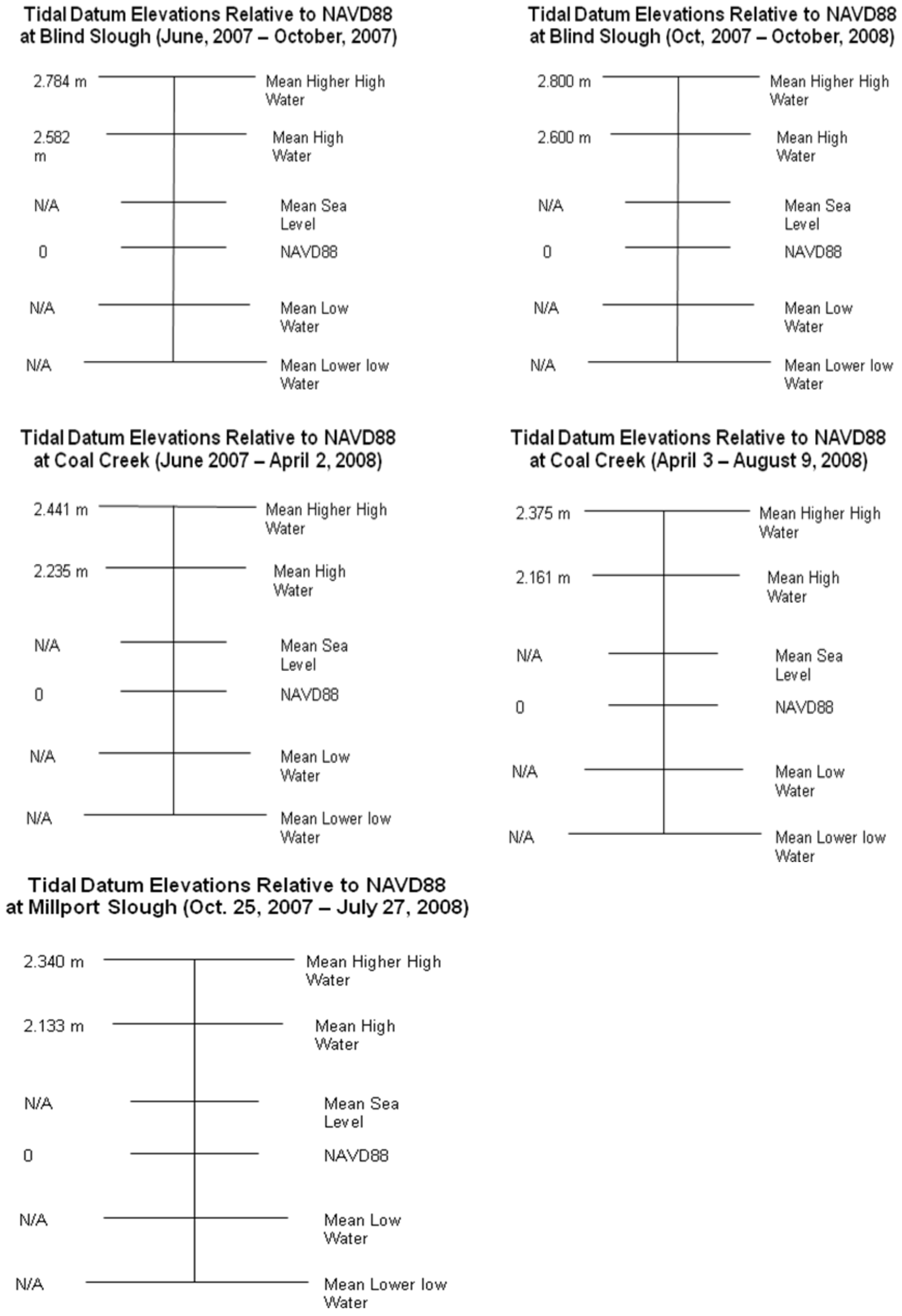


Figure T1: Tidal datums at Blind Slough, Coal Creek and Millport Slough study sites (from onsite tide gauge data), relative to NAVD88



Tidal Datum Elevations Relative to NAVD88 at Blind Slough (June, 2007 – October, 2007)

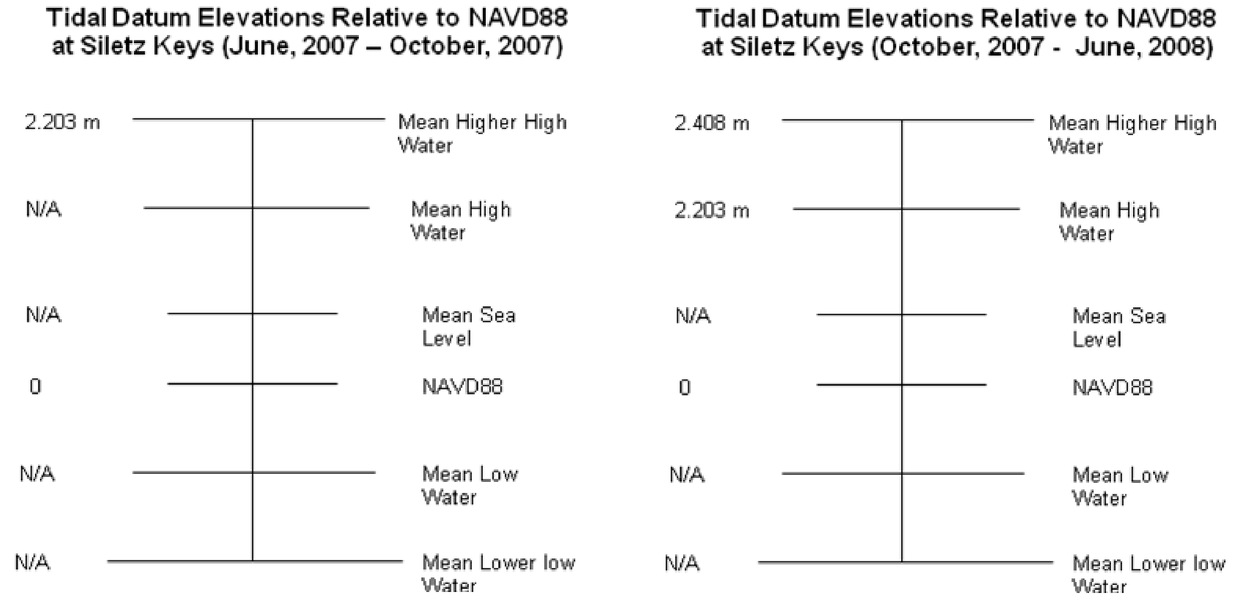
Tidal Datum Elevations Relative to NAVD88 at Blind Slough (Oct, 2007 – October, 2008)

Tidal Datum Elevations Relative to NAVD88 at Coal Creek (June 2007 – April 2, 2008)

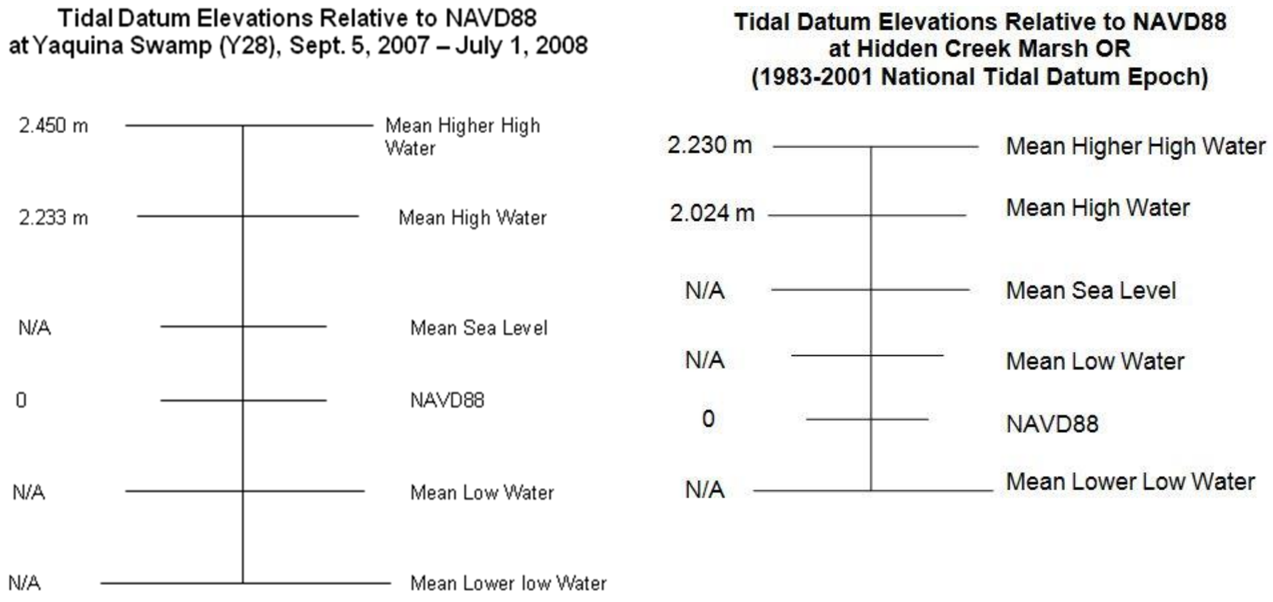
Tidal Datum Elevations Relative to NAVD88 at Coal Creek (April 3 – August 9, 2008)

Tidal Datum Elevations Relative to NAVD88 at Millport Slough (Oct. 25, 2007 – July 27, 2008)

Figures T2: Tidal datums at Siletz Keys and Yaquina Swamp study sites (from onsite tide gauge data), relative to NAVD88


Tidal Datum Elevations Relative to NAVD88 at Siletz Keys (June, 2007 – October, 2007)

Tidal Datum Elevations Relative to NAVD88 at Siletz Keys (October, 2007 - June, 2008)


Tidal Datum Elevations Relative to NAVD88 at Yaquina Swamp (Y28), Sept. 5, 2007 – July 1, 2008

Tidal Datum Elevations Relative to NAVD88 at Hidden Creek Marsh OR (1983-2001 National Tidal Datum Epoch)

Appendix 4. Photographs

All photographs are by Laura Brophy, Green Point Consulting.

Photo 1. Sitka spruce tidal swamp at high tide, Blind Slough study site, 3/28/2007

Photo 2. Project team approaches Coal Creek Swamp, 2/26/2008


Photo 3. Forb-rich brackish high marsh, Millport Slough study site, 8/23/2007


Photo 4. Low marsh, Siletz Keys study site, 4/13/2007


Photo 5. Low marsh, Hidden Creek Marsh study site, 7/17/2008


Photo 6. Shrub tidal swamp with Sitka spruce along channels, Yaquina Swamp study site, 2/28/2008

Photo 7. Rebecca Tully installing iButton vertical post assembly at Yaquina pilot test site, 4/30/2007

Photo8. Rebecca Tully installing surface iButton assembly, low marsh, Siletz Keys, 6/26/2007

Photo 9. Rebecca Tully installing iButton vertical post assembly, Millport Slough, 6/27/2007

Photo 10. Rebecca Tully installing instrumentation in tidal channel at low tide, Coal Creek, 6/28/2007

Photo 11. Galen Scott of the National Geodetic Survey recording elevation of new NGS benchmark at Siletz Keys site, 7/20/2007

Photo 12. National Geodetic Survey benchmark at Siletz Keys site, 7/20/2007

Photo 13. Steve Breidenbach and Justin Dahlberg of the National Geodetic Survey setting up RTK-GPS equipment at Millport Slough, 8/23/2007

Photo 14. Justin Dahlberg of the National Geodetic Survey measuring marsh plain elevations with RTK-GPS equipment, Millport Slough, 8/23/2007

Photo 15. Steve Breidenbach of the National Geodetic Survey recording elevation of the Millport Slough HOBO logger with RTK-GPS, Millport Slough, 8/23/2007

Photo 16. Doug Adams (L) and Kevin Jordan (R) of the National Geodetic Survey measuring elevations with RTK-GPS at Blind Slough Plot 1, 4/1/2008

Photo 17. Doug Adams (L) and Kevin Jordan (R) of the National Geodetic Survey measuring elevations with RTK-GPS at Blind Slough Plot 2, 4/1/2008

Photo 18: L to R: Laura Brophy (Green Point Consulting), Kevin Jordan (NGS), Doug Adams (NGS), and Julie Doumbia (Oregon State University) in front of wind thrown Sitka spruce root wad, Coal Creek Swamp, 4/3/2008

Photo 19. John Christy monitoring vegetation at Blind Slough Plot 1, 5/2/2007

Photo 20. Co-PI John Christy monitoring vegetation at Siletz Keys Plot 2, 7/23/2007

Photo 21. Groundwater well (shallow observation well) with tall riser to exclude surface tidal flows, Blind Slough Plot 2, 5/5/2009.

Photo 22. Groundwater well (shallow observation well) with tall riser to exclude surface tidal flows, Millport Slough Plot 2, 5/6/2009.

Appendix 5. User’s Guide to the Temperature Sensor Method for Determining Tidal Inundation Regime

Citation: Brophy, L.S., C.E. Cornu, P.R. Adamus, J.A. Christy, J. Doumbia, and R.L. Tully. 2011. User’s Guide to the Temperature Sensor Method for Determining Tidal Inundation Regime. Prepared the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), Durham, NH.

This User’s Guide is part of a larger report, which is available at http://www.ciceet.unh.edu.

Table of contents

Introduction

The temperature sensor method (hereafter, the “Method”) is a method for determining tidal inundation frequency and duration in intertidal wetlands. The Method provides a low-cost alternative to traditional water-level loggers and elevation surveys. In estuarine wetlands of Oregon, USA, we have successfully used the Method to detect tidal inundation events in all seasons and in a variety of wetland habitat classes using several deployment methods. This user's guide describes the equipment needed, deployment methods, and how to interpret the results.

Please note that this guide describes the use of the Method in outer coast estuaries of Oregon. Results and interpretation may vary in different regions and landscape settings.

How the temperature sensor method works

The Method relies on the difference between air and water temperature to detect tidal inundation. Basically, the temperature at a particular “variable” logger is compared to reference water and air temperatures (obtained with other loggers). In our region, tidal inundation at a variable logger was marked by rapid convergence between the “variable” logger’s temperature and the reference water temperature, and divergence between the “variable” logger’s temperature and the reference air temperature. We refer to this pattern as the “inundation signal.” Conversely, time of re-exposure of the “variable” logger was marked by divergence between its temperature and the reference water temperature, and convergence between the “variable” logger’s temperature and the reference air temperature (the “re-exposure signal”).

Equipment needed

Temperature loggers

There are a variety of temperature loggers available, at a range of prices and functions. Two examples are shown below. We used iButtons, because of their low price and small size (which made them very easy to deploy). In this Guide, we use the words “iButton” and “logger” interchangeably.

Examples of Low-Cost Temperature Loggers Available:

1. Maxim iButton temperature logger (part # DS1921G) (Figure 1)
   Website: http://www.maxim-ic.com/datasheet/index.mvp/id/4023
   Unit price: $14-25/logger (discounts with bulk purchase)
   Size: Approx. 1.6cm diameter, 0.6cm thick
   Memory: 2,048 measurements
   (higher capacity models available at higher cost)
   Accuracy: 1°C
   Resolution: 0.5°C

2. Onset pendant loggers (5 models available) (Figure 2)
   Website: http://www.onsetcomp.com/products/data-loggers/ua-001-08
   Unit price: $36-42/logger (discounts with bulk purchase)
   Size: 5.8 x 3.3 x 2.3cm
   Memory: 6,500 measurements
   (higher capacity models available at higher cost)
   Accuracy: 0.47°C at 25°C
   Resolution: 0.1°C at 25°C

Figure 1. iButtons

Figure 2. Onset pendant logger

Waterproofing the loggers

For this Method, the loggers must be waterproof. iButtons are water-resistant, but not waterproof. We tested three waterproofing techniques: knotting the iButtons inside small rubber balloons, sealing their seams with silicone sealant, and sealing them inside plastic bags using a household vacuum sealer. We found that the balloons leaked, and the silicone sealant tended to flake off in the field. The vacuum sealer worked very effectively and consistently, and was very durable in the field. Vacuum sealer bags were cut to size from rolls of vacuum sealer bag material; the bags were made just larger than the iButtons (allowing for adequate edge to apply the vacuum). The vacuum sealer creates close contact between iButton and the surrounding water, maximizing the speed of transmission of water temperature to the logger. Initially, we were concerned that the application of a vacuum might affect iButton function, but our tests showed no evidence of any effects on the loggers. However, we recommend testing this in your own studies and if application of a vacuum seems undesirable, the sealing function of the vacuum sealer could used without the vacuum.

If the temperature logger is directly exposed to saline water, the logger should be made of a material that won't corrode under those conditions. Because we sealed the iButtons in vacuum sealer bags, we did not test their corrodibility.

Hardware to connect to the computer

iButtons are launched and downloaded by connecting them to a computer. To do this, you will need a probe and most likely an adapter. Details are provided at the manufacturer's website, http://pdfserv.maxim-ic.com/en/an/AN4373.pdf. We used a "blue dot" probe (part # DS1402D-DR8+) USB adapter (part number DS9490R#). We recommend checking with the manufacturer for the specific parts you need.

Housings for field deployment

For best results, the iButtons should be protected from direct sun to reduce temperature changes caused by solar warming. White PVC pipe can be used to construct housings by cutting to an appropriate length, drilling for ventilation, and capping to shade the iButtons fastened inside. For further details, see "**How to deploy the loggers**" below.

Software

Interface software is needed to launch the iButtons, download the data, and interpret the results. There are several requirements for interface software for the Method:

1. The software should automatically synchronize iButtons with the computer's clock;
2. It should enable delayed, simultaneous launching of several iButtons at a specific time in the future, such as "2:00 p.m. on December 1, 2012."
3. Since data interpretation relies on visualizing temperature curves in a graph (e.g., Figures 8 and 10), the software should be able to display the temperature curves of several iButtons on the same chart. Alternatively – and for even more flexibility -- it may allow export of the temperature data to a spreadsheet or graphics program such as Microsoft Excel, where the results can be viewed graphically.

Free interface software to launch and download iButtons is available via a search engine at the manufacturer's website (http://www.maxim-ic.com/products/ibutton/example/), but neither the search engine nor the software is user-friendly. We found that third-party software for iButtons was easier to use and had better features than the manufacturer's software for the temperature sensor method. Many third-party software options for use with iButtons are listed at the manufacturer's website (URL below): (http://www.maxim-ic.com/products/ibutton/solutions/search.cfm?Action=DD&id=253). We tested several, and found that eTemperature from OnSolution worked best for us. Contact the manufacturer at sales@onsolution.com.au for current availability and pricing. If you use another type of temperature logger, the manufacturer's software may prove adequate for this Method.

Additional equipment for data validation

Data validation is described in "**How to validate your results**" below. Equipment needed includes:

1. **Water Level Loggers:** These instruments generally measure pressure and include software which converts the pressure data into water depth values. Water level loggers can be used to validate temperature logger data by comparing the time when the water reached the temperature logger's elevation to the time of the "inundation signal" at that sensor (and vice versa for re-exposure). See "**How to validate results**" below. We used Onset HOBO water level loggers (model U20-001), since we have found these to be reliable, and the accompanying software is user-friendly. However, other water level loggers would be equally suitable.

2. **Elevation survey equipment** – to determine elevations of temperature loggers and water level logger. Consult with survey professionals to find out how to get accurate elevations in your study area.

How to deploy the loggers

Timing for field deployment

The strongest "signal" of tidal inundation from temperature loggers occurs at night. During the day, temperature "noise" (variability) due to solar warming of air and soil by the sun can create too much "noise" to see the signal clearly. Therefore, plan your deployments carefully so that the tides you want to monitor occur at night. For example, in a region with mixed tides (one higher high tide and one lower high tide each day), you may find it useful to detect inundation by the higher high tides. In this case, choose a deployment period when the higher high tides occur at night.

Deployment methods

We have had useful results from two different deployment methods: loggers arrayed in strategic locations on the wetland surface ("surface loggers," red dots in Figure 3); and loggers placed vertically on posts in tidal channels ("vertical post arrangement," blue dots in Figure 3). The wetland surface arrangement is useful for gathering spatially accurate information on tidal inundation regime across an entire study area, while the vertical post arrangement is best for measuring the height or speed of inundation at a particular location.

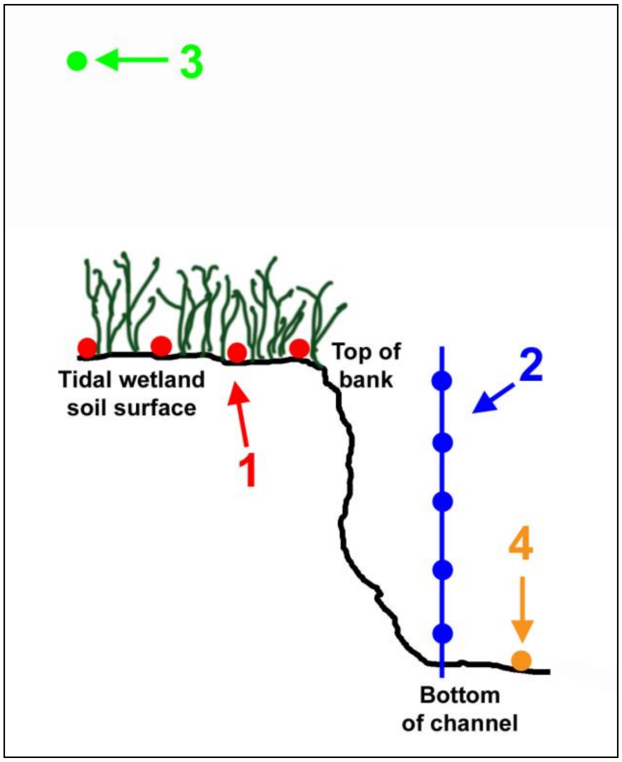


Figure 3. Temperature logger deployment methods, and reference loggers: 1) “surface loggers” placed at strategic locations on the wetland surface or channel banks (red dots); 2) “vertical post arrangement” in a tidal channel (blue dots); 3) air temperature reference logger (above highest tide, on tall post or tree – green dot); 4) water temperature reference logger (orange dot).

Housing for surface loggers

An example of a housing for a surface logger is a short PVC sleeve with the logger wired to the center of the sleeve (Figure 4). The PVC is then wired to a wooden stake which is pounded into the marsh surface. The vertical position of the logger must remain stable in wind and currents. Many other housings and installation methods would be equally effective.

Figure 4. Deploying a surface logger inside a protective PVC sleeve. PVC sleeve and temperature logger are wired to a stake which is pounded into the marsh surface. After installation, the PVC sleeve is resting directly on the surface.

Housing for vertical post arrangements

In this arrangement, iButtons are wired to a wooden dowel, which is then placed inside a heavily perforated PVC pipe (Figure 5). To reduce solar warming during daytime, the wooden dowel should remain in the center of the PVC, so the iButtons do not contact the PVC (which will be warmed by the sun). The PVC pipe is capped with a loose fitting lid (a yogurt tub works well) to shade the pipe, yet allow ventilation.

Figure 5. Deploying a vertical post arrangement in a tidal channel. The white PVC pipe contains a wooden dowel with temperature loggers attached. The pipe is wired to a metal post, which is pounded into the channel substrate.

Deploying reference temperature loggers

As described in the Introduction, the Method requires the use of reference air and water temperature data. One reference logger should be placed in a well-shaded location well above tide level to track ambient air temperature ("air temperature reference," Figures 3 and 6). A second reference logger should be placed in the lowest possible location within a tidal channel ("water temperature reference," Figures 3 and 7). Place these reference loggers near your other deployments. On a large site, you may wish to deploy several air and water reference loggers to capture variability across the site. These reference data will enable you to detect the inundation signal in data collected by marsh surface and vertical post loggers, by comparing the temperature curves.

Figure 6. Air temperature reference logger wired to a shrub well above tide level, in an Oregon scrub-shrub tidal wetland.

Figure 7. Water temperature reference logger located near the bottom of a tidal channel.

Launching the loggers and synchronizing clocks

Loggers are generally launched in the office, with a delayed start time corresponding to your planned time of field deployment. You can use manufacturer or third party software to launch the temperature loggers. Launch all loggers for a particular study with the same data collection interval and the same start time. Short logging intervals (e.g. 5min) give the most precise results, but fill up the logger's memory faster. We used 12min intervals, which gave reasonable results and allowed 21 day deployments before memory was full (for iButton model DS1921G).

Loggers obtain the time stamp from your computer when launched, so be sure your computer's clock is accurate before you launch the loggers. The best way is to synchronize your computer's clock with internet time. Note whether you launched relative to daylight savings time or standard time; this is important if you validate your results using a water level logger launched on a different date(see "**Validation with water level logger data**" below).

How to graph, visualize and interpret results

Use manufacturer or third party software to download data from the temperature loggers. After downloading, display the data in graphic format to visualize the inundation signal. You may be able to graph the data in the manufacturer's software, or you may wish to use third party software (see "**Software**" above). Temperature should be graphed on the y-axis, and date and time on the x-axis. A second y-axis may be used to incorporate validation data from a water level logger.

Inundation events are signaled by abrupt directional changes in temperature (Figure 8), which we call the "inundation signal." In our studies (Oregon outer coast tidal wetlands), the signal consists of an abrupt rise in temperature towards the water reference temperature at inundation, and an abrupt cooling towards the air reference temperature when the tide recedes. These abrupt temperature changes are best detected during night-time high tides. Daytime high tides are harder to detect, due to solar warming that obscures the signal.

Temperature curves from the vertical post arrangement show sequential inundation according to temperature logger height. In Figure 8, note the sequential night-time inundations from the bottom upwards, with the lowest temperature logger (green) inundating first and the topmost logger (yellow) inundating last. Also notice the increases in air temperature during the day, emphasizing the importance of focusing analysis on the night-time tidal inundation signals. In this deployment, however, even daytime tides were easily detected due to the deep tidal channel, forested vegetation class, and minimal solar warming.

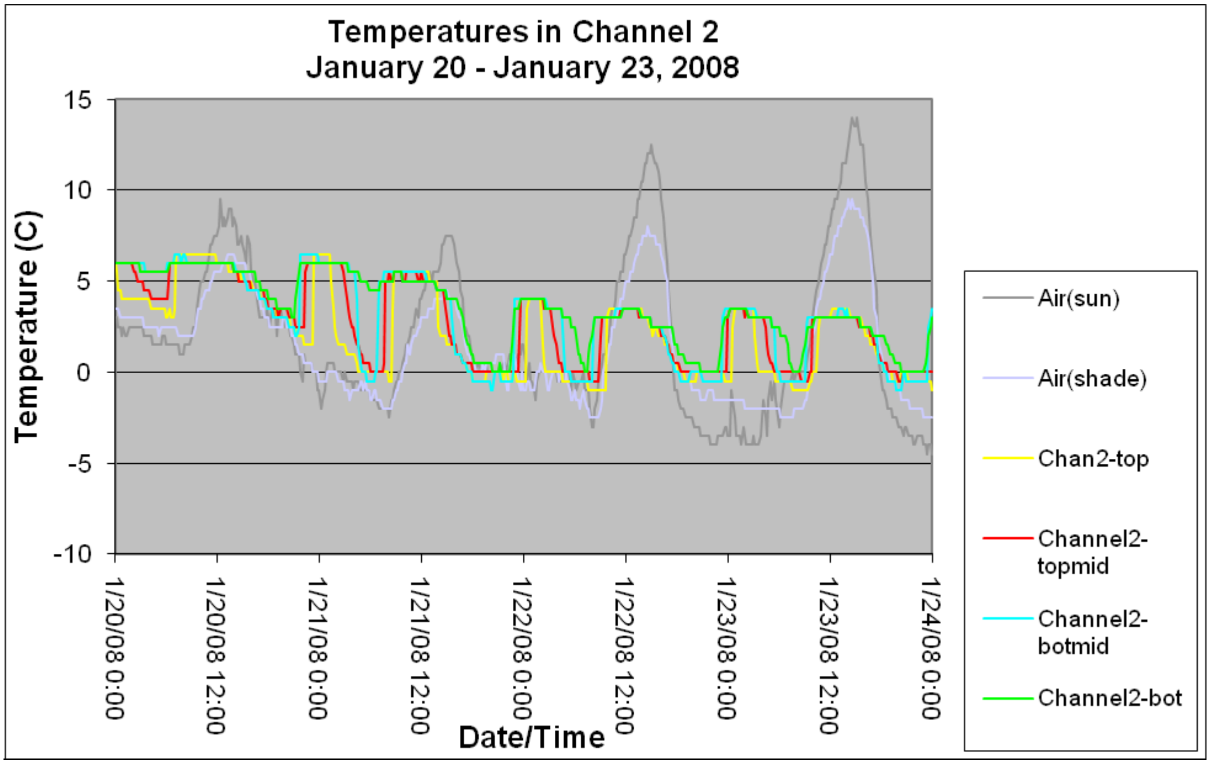


Figure 8. Graph of temperature logger data obtained from a vertical post deployment (colored lines); air temperature references in gray. An abrupt, vertical rise in temperature is the inundation signal for each temperature logger. Note: The bottom-most temperature logger (green), located deep in the channel, acted as the channel reference temperature logger.

How to validate results

Since the Method is new, we recommend validating the Method for your specific geographic region. Validation is the process of checking to make sure your results are accurate and your interpretation of the data is correct. In other words, validating your data will prove that the Method is working as expected, and the inundation and re-exposure “signals” that you are seeing in the temperature curves really did represent inundation and re-exposure events in the field. Validation is only needed once in a geographic area (though you might need to repeat the validation in different seasons if your climate is very seasonal). Once you have validated the Method, others can use the Method with confidence in the same area.

Your results can be validated using visual observation or a commercially available water level logger.

Using the vertical post arrangement for validation

For validation of the Method, it’s easier to interpret data from a vertical post deployment. This is because the vertical post loggers inundate sequentially over a relatively short time, and if the Method is working properly, the temperature curves clearly show this sequential inundation (see **Figure 8**). However, validation can also be performed using wetland surface loggers (see the example in **Figure 10**).

Validation by visual observation

The simplest way to validate your temperature logger results is to observe the incoming tide as it inundates your deployed temperature loggers. Record the time when each iButton inundates, using an accurate timekeeping device that is automatically updated (e.g. GPS unit or cell phone). After downloading the temperature logger data, you will be able to compare your visual observations to the “inundation signal” shown by the temperature curves. Make sure your timekeeping device (watch, cell phone, etc.) is synchronized with the temperature loggers. Since the time clocks of temperature loggers generally synchronize to the clock of the computer used to launch the loggers, you should synchronize your field timekeeping device with your computer when you launch your temperature loggers.

Validation with water level logger data

For a more rigorous validation, you can use a water level logger which continuously records water levels. You can leave the temperature loggers and water level logger in place for many tide cycles, unlike visual validation, which is generally limited to a single inundation event. Validation across multiple tide cycles can help you learn to interpret different inundation signals – valuable for guiding your future work with the Method.

For water level logger validation, you need accurate elevation data for the water level logger and for each temperature logger. In the test setup illustrated in Figure 9, where the water level logger is deployed right next to a vertical post deployment of temperature loggers, you can simply measure the relative elevations of all instruments with a bubble or laser level and a tape measure. If the level logger and temperature sensors are not directly adjacent (for example, to validate results from temperature sensors arrayed across a large tidal wetland site), you will need high-accuracy elevation survey data to determine the relative elevations.

Figure 9. Side-by-side installations of a water level logger (in white PVC pipe “stilling well” at left),and vertical post deployment of several iButton temperature loggers (in vertical perforated PVC pipe at right). Deployment is located in a deep tidal channel in a forested tidal wetland in Oregon.

When you launch the water level logger and temperature loggers, set them to the same data collection interval and make sure all time clocks are synchronized (see “**Launching the loggers and synchronizing clocks**” above). To validate your results, compare the predicted time of inundation for each temperature logger to that temperature logger’s “inundation signal” (Figure 10). The predicted time of inundation based on level logger data is the time at which the level logger shows a water level equal to the elevation of the temperature logger.

For accurate validation, it is very important to follow all recommended procedures to make your water level logger data as accurate as possible. For example, a water level logger that uses a pressure sensor needs to be adjusted for barometric pressure. Some water level loggers make this adjustment internally using a “vent,” but others require “barometric pressure compensation” after data collection. The accuracy of your water level logger should also be checked immediately before it is used. Consult your water level logger manual for correct procedures.

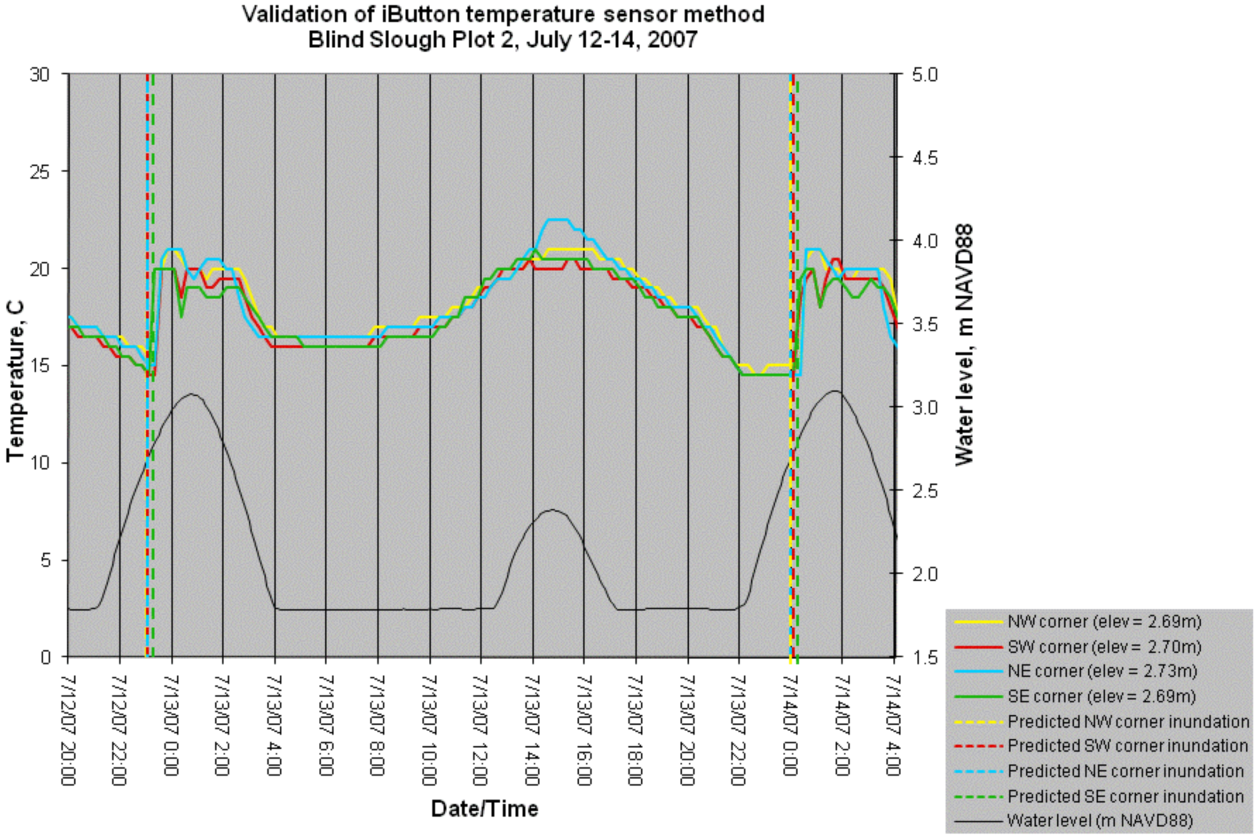


Figure 10. Validation of the temperature sensor method at a tidal swamp in the Columbia River estuary of Oregon, USA. Colored lines are the temperatures from several wetland surface loggers at varying elevations (scale on left axis). The water level from the water level logger is the black curve (scale on right axis) recorded in the channel with a water level logger. Vertical lines represent the predicted inundation time for each temperature logger (colors match the temperature curves). ***Note that only the sudden temperature changes correspond to inundation events; the broader upward temperature curve during daytime represents solar warming of the wetland surface.***

Using the Temperature Sensor Method for spatial analysis of tidal inundation

When using a water level logger to predict inundation time for distant temperature loggers, there will generally be a delay between the predicted inundation times and the actual inundation times, with a longer delay for more distant sensors. In other cases, delays between predicted and actual inundation times may be associated with dense vegetation, highly sinuous channel morphology, beaver dams, or other factors. You can use temperature sensors to study these factors and precisely determine differences in inundation regime across a large site.

Advantages and disadvantages of the method

Advantages

The Method is a low-cost and high-resolution way to measure and monitor tidal inundation regime. Compared to the traditional approach of establishing a tide gauge (water level logger) and surveying elevations to characterize tidal inundation across an entire wetland site, the Method provides inundation information at much higher temporal and spatial resolution, because temperature sensors are placed directly on the wetland surface of interest. Because of their low cost, many temperature sensors may be deployed at a fraction of the combined cost of a single water level logger and survey equipment or survey contractor.

For an intensive site study, multiple temperature loggers can be deployed in combination with a single water level logger to precisely track differences in inundation regime across a large site. The water level logger is used to provide a predicted inundation time for each temperature logger, and delays in inundation can be visualized. These delays may correspond to distance from the water level logger, or may be due to highly sinuous channels, dense vegetation, beaver dams, or other factors. Using traditional methods, such as a single water level logger, the investigator must extrapolate inundation times from a single source. Such extrapolation may be inaccurate because water does not move instantaneously across a site.

Disadvantages

On the negative side, the data collected from temperature loggers is "binary" – it only shows whether or not the logger is inundated at a particular time. If the temperature logger did not inundate, there is no way to determine how close the water came to the logger's spatial location and elevation. By contrast, a water level logger shows the depth of water above the logger. Luckily, this disadvantage can be greatly reduced by using the vertical post deployment method, which reveals depth of inundation by comparing the sequential inundation times for each temperature logger in the vertical array.

The true time of inundation can be obscured if the loggers are launched with a long data recording interval. It is therefore important to balance the frequency of logger readings with the data capacity of the logger over the monitoring time period. Twelve minute intervals were adequate for our purposes in Oregon estuaries, but the interval between readings can be shortened for greater temporal accuracy.

The inundation signal may also be difficult to interpret if there is only a gradual temperature change (no abrupt signal). This can happen if a logger was gradually inundated, for example when the incoming tide peaks near the elevation of the temperature logger. Speed of inundation can be slow near peak tide; speed of inundation is usually more rapid during spring tide cycles, compared to neap tide cycles.

Conclusions and reminders

The temperature sensor method is a relatively low cost method for measuring the frequency and duration of tidal inundation without installing a series of water level loggers and conducting elevation surveys. The following guidelines will help you achieve optimum results when using the Method:

- If daytime solar warming tends to obscure the inundation signal, deploy temperature sensors during a period when the tides of interest are occurring at night. (Pilot deployments will help you determine whether this is necessary in your area.)
- If you use non-waterproof loggers like iButtons, you will need to waterproof them using a vacuum sealer or other method.

- The inundation signal is likely to be clearer with faster inundations, so when possible, monitor during higher high tides and spring tide cycles.
- Using shorter data recording intervals (e.g. 5min) will help detect the inundation signals on a finer scale. However, more frequent logging fills the logger's memory more rapidly.
- Visual observation can be used for a quick validation of the temperature logger method. For more rigorous validation, use a water level logger deployed near the temperature loggers. Once validated, the Method can be used in the same habitat types without further validation.
- Delays between the predicted time of inundation and the actual observed "inundation signal" provide valuable information on speed of water movement through a tidal channel system or across a large area.

For more information

Detailed information on the development of the Method can be found in Tully (2007) and in the full report from this project (Brophy *et al*. 2011).

References

Citation: Brophy, L.S., C.E. Cornu, P.R. Adamus, J.A. Christy, A. Gray, L. Huang, M.A. MacClellan, J.A. Doumbia, and R.L. Tully. 2011. New tools for Tidal Wetland Restoration: Development of a Reference Conditions Database and a Temperature Sensor Method for Detecting Tidal Inundation in Least-disturbed Tidal Wetlands of Oregon, USA. Prepared for the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET).

Tully, R. 2007. The Use of Low Cost "iButton" Temperature Logger Arrays to Generate High Spatial Resolution Tidal Inundation Regime Data. Master's Project Research Report, Marine Resource Management Program, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR. 62pp. Accessed March 6, 2011 at http://hdl.handle.net/1957/15744

Appendix 6. M.S. Research Report, Julie Doumbia

The Use of the Temperature Sensor Method for Detecting Tidal Inundation Regime in Chinese Mangrove Swamps

Julie Doumbia’s Master’s degree research project was conducted with support from the National Science Foundation’s East Asia and Pacific Summer Institute and the National Natural Science Foundation of China. The project was an outgrowth of the current CICEET study. Using equipment provided by our CICEET grant (iButtons), Doumbia demonstrated the applicability of the temperature sensor method in mangrove swamp habitats in China.

Ms. Doumbia’s project report is in preparation (Doumbia 2011); the following abstract provides a brief description of the project.

Citation: Doumbia, J.A. 2011 (in preparation). The Use of the Temperature Sensor Method for Detecting Tidal Inundation Regime in Mangrove Swamps in China. Master's Project Research Report, Marine Resource Management Program, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR.

ABSTRACT

The purpose of this study was to test the temperature sensor method for detecting tidal inundation regime in Chinese mangrove swamps. This method was previously validated in Oregon tidal wetlands and testing in other climates was needed for broader application. Three Ramsar sites were selected along the latitudinal range of naturally occurring Chinese mangrove swamps: 1) Dongzhiagang Reserve; 2) Shankou Reserve; and 3) Zhangjiangkou Reserve. At these sites, daytime inundation events were signaled by a sharp decrease in temperature relative to air temperature at inundation. Nighttime inundation events were signaled by a sharp increase in temperature relative to air temperature at inundation. On average, temperature signals of inundation at the three reserves were weaker during the daytime (1.8°±0.8°C) than nighttime temperature signals indicating inundation (3.5°±1.6°C). The magnitude of temperature change during nighttime inundation and emersion events varied according to tidal cycle, temporal proximity to daytime solar warming, and physical environment in the estuary. This method proved to be a valuable tool for detecting tidal inundation regime in Chinese mangrove swamps and has the potential for wider application.

Appendix 7. M.S. Research Report, Rebecca Tully

In her Master's degree research at Oregon State University, Rebecca Tully developed and tested the temperature sensor method for determination of tidal inundation regime. Her abstract is provided below. Tully's full project report is not included here due to its length, but it is available online at http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/15744/Tully.pdf?sequence=1

Citation: Tully, R. 2007. The Use of Low Cost "iButton" Temperature Logger Arrays to Generate High Spatial Resolution Tidal Inundation Regime Data. Master's Project Research Report, Marine Resource Management Program, College of Oceanic and Atmospheric Sciences, Oregon State Univ., Corvallis, OR. 62pp.

ABSTRACT

Loss of wetlands within Oregon has led to strong interest in restoring wetlands that once existed. Restoration practitioners are currently using knowledge they have gained from many years of working with wetlands to design and carry out restoration projects. There is much variability between tidal wetlands within coastal Oregon and a lack of reference data on the least-disturbed wetlands. Scrub-shrub, emergent, and forested wetlands are the major types of tidal wetlands in Oregon that wetland practitioners and landowners are working to restore. Within each of these habitat classes, hydrology plays a major role in the characteristics of the wetland. Using Thermochron iButtons this study attempts to see if tidal inundation regimes can be determined based on temperature changes on the wetland surface. Using the iButton temperature data in conjunction with GPS derived elevations of the iButtons/wetland surface the tidal inundation patterns can be measured. iButtons will make it easier and more affordable for watershed councils to be able to conduct wetlands inundation studies with higher spatial resolution than tide gauges. The information from this study will be put into a reference data base open to the public in the hope that it will be used to help design restoration projects and help determine success of the project when compared to reference data from a similar type of wetland.

Appendix 8. M.S. Research Report, Megan MacClellan

In her Master's degree research at Oregon State University, Megan MacClellan investigated carbon content of tidal wetland soils at our CICEET study sites and thirteen additional tidal wetlands on the Oregon coast. Her full report is provided below.

Citation: MacClellan, M.A. 2011. Carbon content in Oregon tidal wetland soils. Master's Project Research Report, Marine Resource Management Program, College of Oceanic and Atmospheric Sciences, Oregon State Univ., Corvallis, OR. 30pp.

CARBON CONTENT IN OREGON TIDAL WETLAND SOILS

ABSTRACT

Tidal wetlands are a powerful carbon sink. They can sequester an order of magnitude more carbon than any other type of wetland system, and emit only negligible amounts of methane compared with freshwater wetlands (Brigham *et al.* 2006, Whiting and Chanton 2001). Soil carbon in tidal wetlands can also affect soil ecology and influence wetland functions such as nutrient processing and foodweb support. We quantified carbon content in the top 30 cm of soil in 17 tidal wetlands in Oregon and tested the hypothesis that there is a difference in the soil carbon content of unrestored, restored, and least-disturbed tidal wetlands. Sampling occurred in three unrestored sites; four restored sites; and ten least-disturbed reference sites. The average concentration of soil organic carbon in reference site soils was 15.7%, 13.5% in restored soils, and 8.6% in unrestored soils. Percent carbon values in unrestored sites were significantly different from the other two groups ($p < 0.001$), but values from reference and restored sites were not significantly different ($p > 0.1$). The similarity between soil carbon in reference and restored sites may support previous work that suggests rapid carbon accumulation after restoration (Craft 2007).

Introduction and Background

Soil organic matter, and thus carbon, can affect hydraulic conductivity, soil biota, and aboveground plant communities in tidal wetlands (Gray 2009, Bezemer 2005). In addition to value for understanding fundamental ecological processes, tidal wetlands have also become notable in the field of carbon sequestration because they are, per unit area, among the most effective carbon sequestering ecosystems (Laffoley and Grimsditch 2009, Chmura *et al.* 2003). Despite the significant ecological role of soil carbon in tidal wetlands and its strong potential as a climate mitigation tool, a large research gap exists in the Pacific Northwest, and in Oregon in particular. This study serves two primary functions: it initiates a database for tidal wetland soil characteristics in the Pacific Northwest, and examines differences in soil carbon under three land management scenarios.

Of all estuarine ecosystems, high marsh and swamp are two of the most highly impacted in Oregon. Because most of these tidal wetlands in Oregon are managed, we investigate differences in soil carbon content between three management types: sites that have been actively or recently grazed and diked, sites that have undergone hydrologic restoration, and least-disturbed reference sites, which are referred to here as unrestored, restored, and reference, respectively.

In Oregon, nearly 70% of historic tidal wetlands have been converted to agricultural uses (Good 2000, Christy 2004). Losses of scrub-shrub and forested tidal wetlands (*i.e.* tidal swamps) have been much higher, as documented in basin-scale studies (Brophy 2005a, Graves *et al.* 1995). Diking, ditching, draining, and livestock grazing are common land management practices in tidal wetlands, and can result in a comprehensive change in aboveground plant communities (Roman *et al.* 1984). This process frequently results in subsidence of the soil surface due to oxidation of organic matter and direct compaction by livestock (Frenkel and Morlan 1991, Callaway 2001). A conceptual model of a tidal wetland ecosystem is illustrated below in Figure 1 (Roegner *et al.* 2008). The model shows how tidal wetland sediment characteristics relate to ecosystem structures such as vegetation type and tidal channel formation, which in turn are closely related to ecosystem processes and functions. Awareness of the critical ecological functions provided by tidal wetlands led to the state of Oregon adopting estuarine restoration and conservation as policy in land use planning Goal 16. Since the establishment of Goal 16 in 1977, tidal wetland restoration has made a significant contribution to Oregon's restoration economy (Good 2000).

Soil organic matter is a particularly significant component of soil ecology (Kennedy and Smith 1995). It has been positively correlated with hydraulic conductivity; as when higher organic matter results in a soil with low bulk density (extremely low in some tidal wetland cases), which reflects the porosity of the soil matrix (Craft *et al.* 1988). This porosity allows water to pass through the soil profile much more freely than in soils with low organic matter (Mitchell 1993, Judson and Odum 1990). In brackish, tidally influenced soils, this subsurface flow can distribute marine-derived nutrients and salts throughout the site (Judson and Odum 1990). The control exerted by organic matter on soil biota and hydrology can influence surrounding plant communities and the higher trophic levels that rely on them (Hines *et al.* 2006, Oliver *et al.* 2009, Bezemer *et al.* 2005). For example, in their analysis of Californian coastal wetlands, Kwak and Zedler (1996) describe the role of organic matter as the foundation of the marsh food web, which extends through trophic orders to fishes and birds. Because of these important characteristics, soil organic matter, salinity, and pH have been listed as high priority monitoring parameters for tidal wetland restoration projects (Zedler 2001, Simenstad *et al.* 1991).

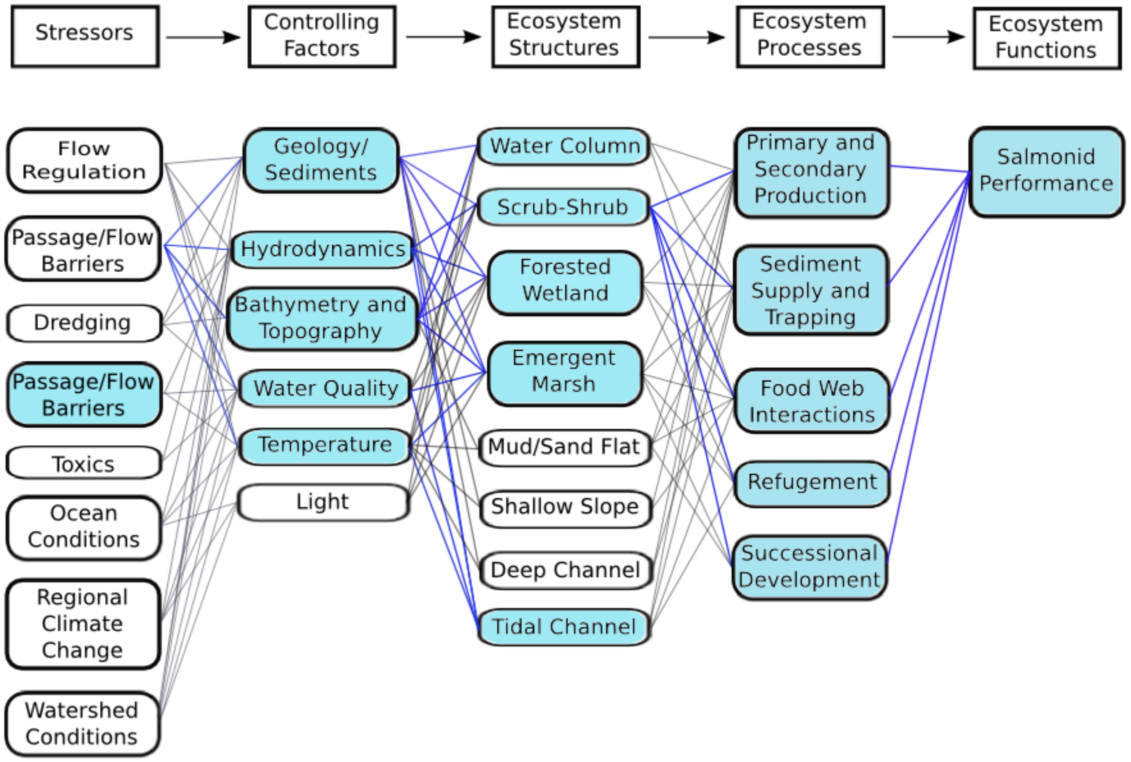


***Figure 1**. Tidal wetland ecosystem conceptual model (Roegner et al. 2008).*

Because soil is a stable, long term surface reservoir for carbon, it has drawn global attention as a strategic element of greenhouse gas mitigation. Within the scope of soil carbon storage, wetlands stand out. Freshwater wetlands can act as both sinks and sources of greenhouse gases. Large stores of carbon-sequestering organic matter are developed over long periods of time (*e.g.* peat bogs), yet methane is also produced as a byproduct of biotic respiration. In saline tidal wetlands, organic matter can be rapidly buried by tidal sediments, and saline water favors sulfate reduction, reducing methane production to negligible amounts (Whiting and Chanton 2001, King *et al.* 2007). High levels of soil carbon in tidal wetlands have recently brought these systems to the forefront of the global discussion of carbon sequestration and ecosystem-based climate change mitigation (Laffoley and Grimsditch 2009, Crooks *et al.* 2009, Crooks *et al.* 2011). Research has also shown that tidal wetlands with higher soil carbon content may be more resilient to sea level rise (Cahoon *et al.* 2006, Cahoon *et al.* 2004, Craft 2007, Nyman *et al.* 2006, Morris *et al.* 2002).

Lastly, tidal wetland soils research in the US has been concentrated in the Gulf and Atlantic Coasts, where topography, bathymetry, vegetation, and land management practices drive estuarine dynamics and ecological communities that are very different from those of the West Coast. This research is motivated in part by the lack of data that represents the Pacific Northwest where estuarine processes are driven by uniquely regional conditions such as the input of sediment from upland forest management (Pakenham 2009, Hickey and Banas 2003). At the time of writing, two studies of tidal wetland soil carbon have been conducted in the Pacific Northwest. In his 1996 paper, Ronald Thom (Pacific Northwest National Laboratory) presents percent carbon data collected from two sites in Washington and Oregon (and accretion data from six sites). Soil organic matter data may have been collected as part of several regional accretion studies, though it is not presented in respective literature (*e.g.* Johnson and Diefenderfer 2009). Here, we build on unpublished data collected by Laura Brophy (Green Point Consulting) in a series of monitoring studies conducted on the Oregon Coast (*e.g*. Brophy 2005b) to test the hypothesis that soil carbon content differs in unrestored, restored, and reference tidal wetland soils.

Methods

Sampling Design

Eight estuaries from the Columbia River estuary in northern Oregon to the Coquille estuary in southern Oregon (Figure 2) were included in this study. A total of 75 samples were collected from 17 sites in the estuaries illustrated in Figure 2. We focused sampling in forested tidal wetland (i.e., tidal swamp) and high marsh wetland habitat classes because, as opposed to low marsh, these classes have typically been impacted by human activities in our area. Sampling occurred in three recently grazed sites; four sites that had been previously diked, drained and grazed but have undergone hydrologic restoration; and ten least-disturbed reference sites. These groups are referred to here as unrestored, restored, and reference, respectively. To test the hypothesis that soil carbon content in reference sites differs from that in restored and unrestored sites, we distributed the sampling effort between reference, restored and unrestored sites. Twenty five samples were taken from ten reference sites, 25 from four restored sites, and 25 from two unrestored sites (Table 1). A table of detailed site histories and characteristics is provided in the Appendix.

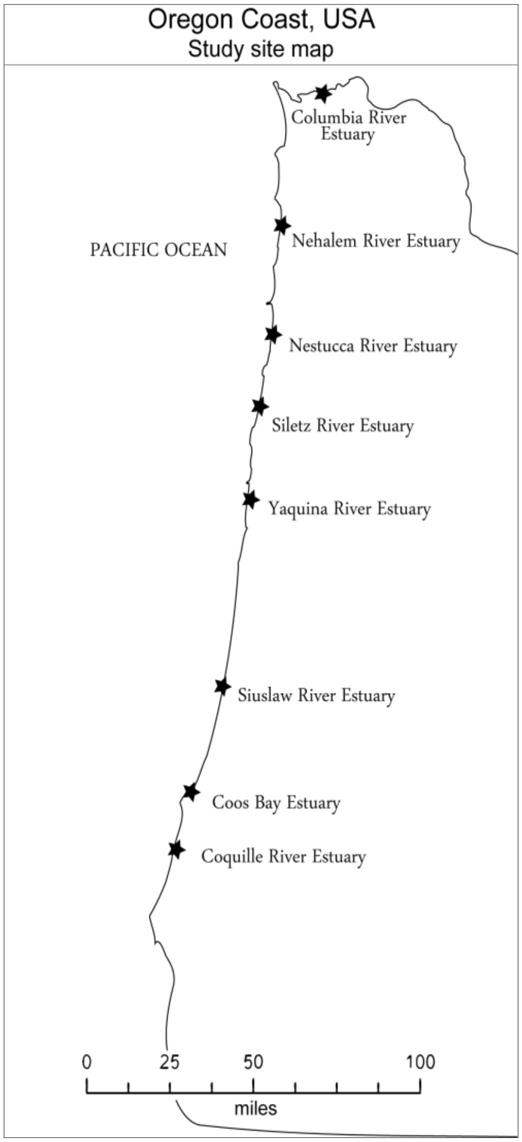


Figure 2*. Study sites*

Study sites included tidal swamp, high marsh, low marsh, and transitional zones. To leverage study results and provide detailed data on site history, vegetation and hydrology, we selected sites that had previously been monitored for other purposes. Those details are provided in earlier reports (Brophy 2009, 2005b, 2004, 2002). Among the sites were several restoration-reference site pairs with similar historic habitat class and landscape setting (Appendix).

***Table 1**. Study sites and estuaries*

REFERENCE		**DISTURBED**			
Reference (10)	***n***	**Restored** (4)	***n***	**Unrestored** (3)	***n***
Bandon Marsh (*Coquille R.*)	4	Millport South (*Siletz R.*)	8	S65 (*Siuslaw R.*)	3
Blind Slough (*Columbia R.*)	2	Nestucca East (*Nestucca R.*)	5	Ni-les'tun (*Coquille R.*)	14
Coal Creek (*Nehalem R.*)	2	S59 (*Siuslaw R.*)	3	Waite Ranch (*Siuslaw R.*)	8
Cox Island (*Siuslaw R.*)	2	Y27 (*Yaquina R.*)	9		
Duncan Island (*Siuslaw R.*)	2				
Hidden Creek Marsh (*Coos R.*)	2				
Millport North (*Siletz R.*)	5				
S63 (*Siuslaw R.*)	2				
Y13A (*Yaquina R.*)	2				
Y28 (*Yaquina R.*)	2				

Samples were collected along pre-existing 100m transects which had been distributed in study sites within major elevation strata (Brophy 2002). Because of the strong relationships between tidal marsh plant communities, elevation, hydrology, and topography, we assumed that soil characteristics would also be affected by these conditions, and this transect placement would therefore be appropriate for soil sampling. Previously-established transect markers (PVC posts) aided in transect location. GPS units were used to validate locations or locate transects in the field when necessary.

Samples were collected from the rooting zone (soil surface to 30 centimeters depth), using a Dutch auger following a standard agricultural soil sampling method (Gardner and Hart 1995). When the sample extended into a horizon that clearly lacked any roots (*e.g.* a gleyed clay horizon with no evidence of root growth), that portion of the sample was excluded. Each soil sample was composed of multiple auger cores which were systematically distributed along each transect. Auger cores were then bulked into a single sample per transect for delivery to the laboratory. Each bulked sample was placed in a plastic zip-lock bag and stored at 2°C until processing in the lab. Sample date varied by location; month of sampling ranged from July to January, and samples were collected from 2006 through 2011. We make the assumption that, given the accuracy and resolution of our sampling technique, soil carbon remains relatively stable through the study period despite the potential for seasonal shifts in carbon metabolism by soil biota and vegetation (Neubauer *et al*. 2005).

Laboratory Methods

Laboratory analysis was conducted at Oregon State University's Central Analytical Laboratory. Samples were dried, homogenized, and a subsample was extracted for analysis. Before homogenization, large roots were removed from samples by hand, introducing potential for bias in the data. Electrical conductivity and pH were measured using an electrical conductivity meter and a reference electrode with a pH meter, respectively. Lastly, percent organic matter was measured using Loss on Ignition (LOI) (Nelson and Sommers 1996, Craft *et al.* 1991). Samples were burned in a kiln at approximately 450°C for eight hours.

Data Analysis

Percent soil carbon was calculated from percent organic matter values yielded by LOI using a conversion specific to high organic soils (0.68 x %OM) presented in Kasozi *et al.* (2009). Soil salinity was calculated from electrical conductivity values using a constant multiplier of 0.64, modeled after an online conversion utility (Chapman 2006). For our range of conductivity values (62.4 to 0.22), this constant introduced an average error of 4% compared with the conversion utility. We used one way analysis of variance (ANOVA) to determine whether the percent of soil carbon differed among reference, restored, or unrestored tidal wetland sites. To identify which of the categories in the ANOVA drove the identified difference, we applied the post-hoc Scheffé procedure. We determined that a p value of 0.05 was appropriate for this study. All analyses were performed using SPSS (PSAW Statistics 18, Release Version 18.0.0).

In order to test the ANOVA procedure for sensitivity to a violation of its independence assumption, a multilevel analysis was conducted parallel to the ANOVA described above (Dr. John Light, Oregon Research Institute, personal communication). Spatial autocorrelation is a violation of the independence assumption inherent to ANOVA and may be associated with this dataset due to the proximity of sample transects to each other in each sampling site (Ramsey and Schafer 2002). Multilevel analysis is a method of comparing means which, by utilizing a model with nested sample units, allows for correlation and does not assume independence (Snijders 2003).

Potential sampling bias

Site conditions and differences in plant structure can affect soil sampling results. In our study sites, cespitose (clump-forming) grasses or other dense vegetation often occurred adjacent to areas of exposed soil at sampling sites. These conditions presented potential for sampling bias due to the relative amount of effort it takes to collect a sample in dense vegetation compared with bare ground. In light of this, an effort was made to distribute samples representatively in these conditions. Also, soils associated with certain vegetation types occasionally yielded smaller samples. For example, when drilling the auger into well-established stands of slough sedge (*Carex obnupta*), which has thick and dense root systems, some soil can be pushed out from the sample as roots are cut with the auger blades. Lastly, when sampling in extremely porous soil (as inside a cespitose grass) the high porosity generally led to a smaller sample size. In any case, if the auger was less than 2/3 full, the sample was repeated. Otherwise, no effort was made to correct for these circumstances, to maintain a consistent protocol. Since samples with higher bulk density or fewer large roots had the potential to yield more actual mass, these soils could be overrepresented in the bulked sample.

Results and Discussion

All data are presented in Table 6 below.

Soil Carbon

One-way ANOVA results showed significant differences in average concentration of soil organic carbon among the three groups (*F*(2,72) = 19.18, $p < 0.001$). Reference sites showed the highest percent carbon (*M* = 15.69, S.E. = 0.887), restored sites somewhat less (*M* = 13.52, S.E. = .794), and unrestored sites showed the least soil carbon (*M* = 8.57, S.E. = 0.814) (Table 2, Figure 3). Post-hoc Scheffé tests showed that unrestored sites differed significantly from each of the other two groups ($p < 0.001$), but the difference between reference and restored groups was not statistically significant ($p > 0.1$) (Table 3, Figure 3).

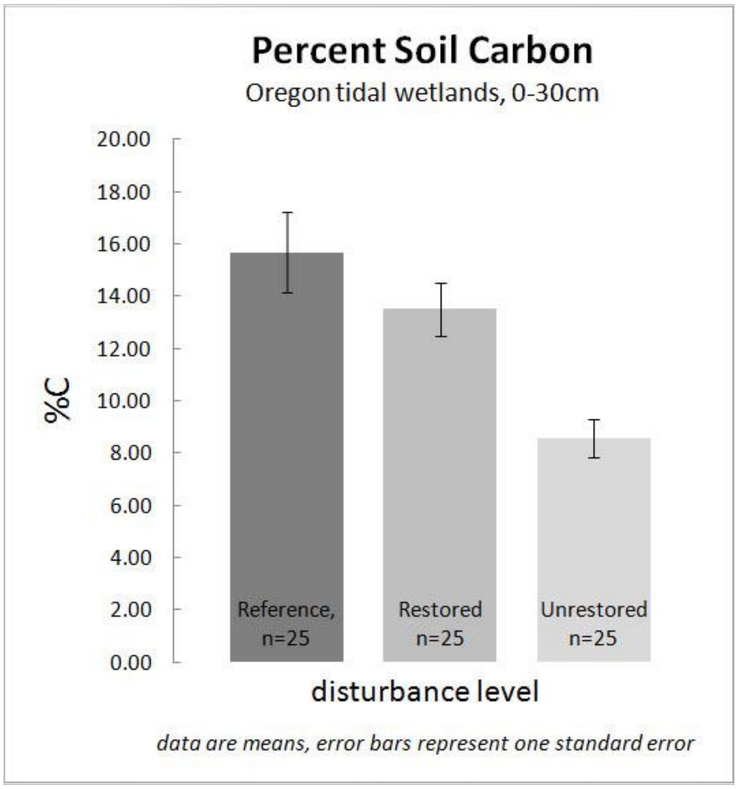


***Figure 3**. Percent soil carbon across site disturbance levels*

Table 2. *Soil characteristics by site condition with one-way ANOVA results at p=0.05**

		% carbon			Salinity		
Site type	**n**	**Mean**	**Significance**	**Std error**	**Mean**	**Significance**	**Std error**
Reference	25	15.69	a	0.89	12.32	ab	1.55
Restored	25	13.52	a	0.79	5.98	b	1.11
Unrestored	25	8.57	b	0.81	4.05	c	0.81

*Means having a common letter in the significance column are not significantly different at the 5% level of significance (*p*=0.05).

Table 3*. Scheffé means comparison of percent carbon across three site disturbance levels*

(I) DISTURBANCE	(J) DISTURBANCE	Mean Difference (I-J)	Std. Error	Significance	95% Confidence Interval Lower	95% Confidence Interval Upper
reference	restored	2.17	1.178	0.19	-0.77	5.12
	unrestored	7.12*	1.178	0.00	4.17	10.06
restored	reference	-2.17	1.178	0.19	-5.12	0.77
	unrestored	4.94*	1.178	0.00	2.00	7.89
unrestored	reference	-7.12*	1.178	0.00	-10.06	-4.17
	restored	-4.94*	1.178	0.00	-7.89	-2.00

*The mean difference is significant at the 0.05 level.

These results were generally validated by the multilevel analysis. In both soil carbon and salinity analyses, comparisons that were significant in the ANOVA were also significant in the multilevel analysis, although *p*-values were at times an order of magnitude higher in the multilevel analysis. Since the multilevel analysis partitions the error between more model parameters, and therefore is likely to reduce the significance of the "treatment" parameter (in this case, disturbance level), a more conservative *p*-value is a predictable response.

The lower carbon content at unrestored sites compared to reference sites strongly suggests that drainage and agricultural use of these former tidal wetlands caused loss of stored soil carbon. Worldwide, wetland drainage is usually associated with large releases of carbon dioxide to the atmosphere, a phenomenon of global importance in the face of rising atmospheric carbon and resultant climate change (Armentano 1980). Frenkel and Morlan (1991) measured 35cm of subsidence at a diked tidal wetland in the Salmon River estuary of Oregon. At South Slough National Estuarine Research Reserve, the pre-restoration soil surface elevation at the diked, drained Kunz Marsh site was about 1m lower than the adjacent reference site (Cornu and Sadro, 2002). In both cases, the authors attributed the subsidence at the diked, drained sites to oxidation of soil organic matter, loss of buoyancy, and compaction by livestock and farm machinery. This subsidence rate rivals those regularly called out in climate change discussions such as that of Indonesia's coastal peat swamps (5cm per year) (Page *et al.* 2002; Dr. Heather Tallis, Natural Capital Project, personal communication).

Although we saw a significant difference in mean soil carbon between unrestored and reference sites, the sample number was small and further studies are warranted. The higher mean soil carbon in restored sites (compared to unrestored sites) may be due to initially high levels of organic matter (before diking and draining), or to accretion of organic matter since restoration.

Three sample values in the dataset are notable. Transect 1 in the Bandon Marsh reference site yielded 7.9% C, a value that was among the lowest in the data set and one that challenges the trend we found of higher C content in reference sites and lower C content in disturbed sites. Much of this site is a relatively young tidal marsh, accreted within the last 150 years, and a 2005 plant community study suggests the site may still be undergoing rapid accretion (Witter *et al.* 2003, Brophy 2005b). Recent and rapid accretion at this site may relate to the changes in sediment regime after human settlement that have been described in the Coquille watershed (Benner 1992). Accelerated sedimentation in the lower Coquille estuary could relate to the low carbon content at the Bandon Marsh reference site, as could the site's landscape setting in the relatively high-energy environment of the lower estuary where larger particles with generally lower carbon content would likely accumulate.

Two other exceptions to the trend of lower C content in disturbed sites were particularly high carbon content in two historically disturbed sites: Transect 4 (T4) at Waite Ranch, an unrestored site (20.4% C), and Transect P3 at S59, a restored site (23.1% C). The Waite Ranch site also showed the highest within-site variability (6.9 to 20.4% C, n=8). In both cases, these observations may relate to the site's historic vegetation class, geomorphology and elevation range. Both sites were historically tidal swamps. The historic vegetation class of the Waite Ranch site was Pacific crabapple swamp, currently a rare ecosystem on the Oregon coast with few remaining examples. Analysis of soil carbon content at a freshwater (diked) crabapple swamp on Oregon's south coast showed unusually high organic matter (25.0% C) (Brophy 2005b). The historic vegetation class of site S59 was Sitka spruce swamp. Studies of soil carbon at least-disturbed willow and Sitka spruce tidal swamps on Oregon's outer coast have shown high organic matter content (12.7 to 26.2% C) (Brophy 2009), so there is a high likelihood that S59 and the Waite Ranch had very high soil organic matter content prior to diking and conversion to agriculture, which may have been preserved in low, wet parts of the sites.

Soils high in organic matter are likely to undergo substantial elevation subsidence after diking and drainage (Frenkel and Morlan 1991, Callaway 2001). Based on nearby reference sites, we estimate that the lower portions of Waite Ranch have subsided over 1.5m, and S59 is estimated to have subsided up to 1 meter. The resulting low elevations remain saturated much of the year (Brophy 2011), likely conserving organic matter that would have been oxidized under drier conditions. By contrast, higher parts of the site such as the natural levee (e.g. Waite Ranch T7, which had only 8.5% C) have subsided considerably less, probably due to their geomorphic setting. Alluvial deposition processes on natural levees create higher elevations and coarser soil textures, with corresponding better drainage and lower soil organic matter content.

Salinity

Our analysis showed that salinity differed significantly among reference, restored, or unrestored tidal wetland sites ($F(2, 72) = 16.60$, $p<0.001$) (Figure 4, Table 2). Reference sites were most saline ($M = 11.45$, S.E. = 1.56), restored sites showed more moderate salinity ($M = 8.64$, S.E. = 1.02), and unrestored sites showed much less salinity ($M = 2.26$, S.E. = 0.74). The post-hoc Scheffé tests showed statistically significant differences between soil salinity in unrestored sites and each of the other two groups ($p<0.001$), but no statistically significant difference between salinity in reference and restored sites ($p>0.2$) (Figure 4, Table 5).

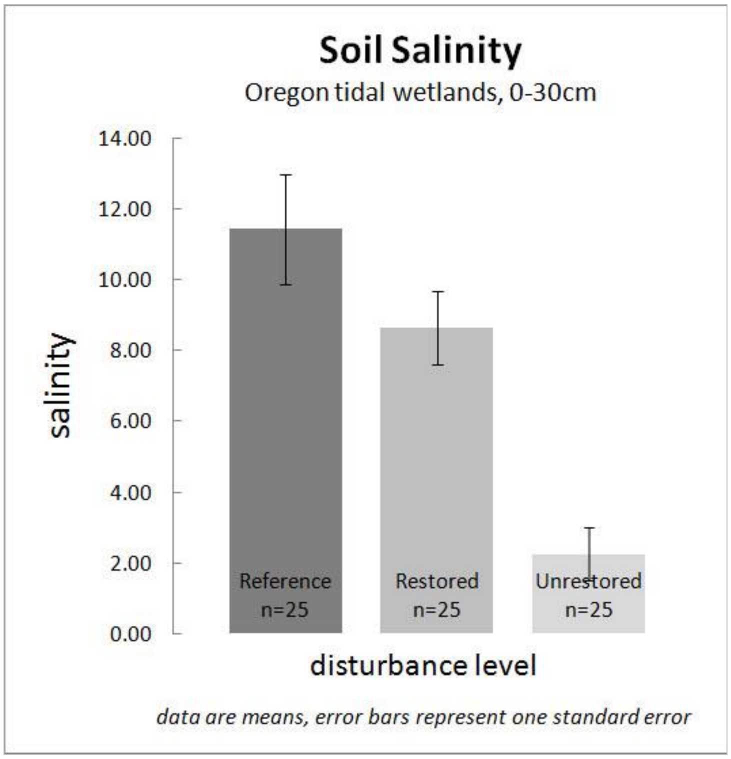


***Figure 4**. Soil salinity across site disturbance levels*

***Table 5**. Scheffé means comparison of salinity across three site disturbance levels*

(I) DISTURBANCE	(J) DISTURBANCE	Mean Difference (I-J)	Std. Error	Significance	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
reference	restored	2.80	1.636	0.24	-1.29	6.89
	unrestored	9.19*	1.636	0.00	5.10	13.28
restored	reference	-2.80	1.636	0.24	-6.89	1.29
	unrestored	6.39*	1.636	0.00	2.30	10.48
unrestored	reference	-9.19*	1.636	0.00	-13.28	-5.10
	restored	-6.39*	1.636	0.00	-10.48	-2.30

*The mean difference is significant at the 0.05 level.

***Table 6.** Soil characteristics by site.*

Site	Number of Samples (n)	Disturbance level (Reference = 1, Restored = 2, Unrestored = 3)	Sampling Date	%OM	%C*	Salinity
Bandon Marsh	4	1	7/22/2010	17.59	11.96	14.7
Blind Slough	2	1	8/28/2007	24.58	16.71	0.48
Coal Creek	2	1	8/30/2007	21.57	14.66	8.64
Cox Island	2	1	8/6/2010	23.68	16.1	14.53
Duncan Island	2	1	8/6/2010	19.21	13.06	11.39
Hidden Creek Marsh	2	1	7/17/2008	26.84	18.25	27.62
Millport North	5	1	9/22/2010	26.51	18.03	7.69
S63	2	1	8/14/2007	27.75	18.87	11.71
Y13A	2	1	12/28/2010	19.67	13.38	9.79
Y28	2	1	11/7/2010	23.11	16.12	12.8
Millport South	8	2	9/21/2010	22.27	15.14	14.86
Nestucca East	5	2	1/19/2010	20.5	13.94	3.56
Y27	9	2	12/28/2010	15.56	10.58	5.11
S59	3	2	8/18/2006	25.42	17.28	11.24
S65	3	3	8/18/2006	12.56	8.54	0.94
Waite Ranch	8	3	8/7/2010, 9/22/10	18.45	12.55	0.21
Ni-les'tun	14	3	7/22/2010	9.28	6.31	3.7

**%C calculated using (0.68 x %OM) following Kasozi et al. 2009.*

Conclusions and Future Research

Our data suggest that restoration of impacted sites could effectively recover the carbon storage role of tidal wetlands, as long as changes in bulk density don't negate that pattern. These results support previous findings in Craft's study (2007b) of created *Spartina* marshes.

As a rough guide, the decomposition rate of upland soil organic matter is understood to double as soil temperature increases by 10°C (Davidson and Janssens 2006). This rule of thumb illustrates the potential that carbon sequestration efforts may be offset by increased carbon dioxide and methane releases from warming soils in the future. In their review of the Intergovernmental Panel on Climate Change Fourth Assessment Report climate models, Mote and Salathé describe a projected increase of 3°C in the Pacific Northwest by 2080, suggesting a 30% increase in soil organic matter decomposition rates (Mote and Salathé 2009). However, environmental constraints (*e.g*. flooding and soil structure) complicate this projection, and the fact that the rule of thumb describes upland soils cannot be overlooked. Wetland soil respiration under projected climate change regimes, particularly in brackish or tidal wetlands, is a rich area for future study.

The methods presented here provide preliminary data on carbon content in Oregon tidal wetland soils but cannot quantify carbon stocks without supplemental information on bulk density that would allow carbon stock estimation. In addition, accretion data would enable carbon sequestration rates to be estimated. Accretion rates have been calculated in some Oregon estuaries (*e.g.* Pakenham 2009, Thom 1992) and provide additional value to collecting supplemental data on bulk density. Because samples in this study were collected along established vegetation monitoring transects, future research into soil bulk density for these sites could be conducted in association with other monitoring activities. Finally, the relatively small amount of field effort necessary for the data collection method presented here could complement rapid assessment protocols (*e.g.* Adamus 2010), if more detailed information on soil carbon is of interest in such assessments.

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Appendix

Study Site Characteristics

Alternating colors indicate paired site groups. "X" indicates the attribute is not applicable to the site.

Estuary	Site name and number*	Number of transects sampled	Site category (**Unrest**ored, **Rest**ored or **Ref**erence)	Impact type	Impact began	Year of restoration (approx)	Restoration activities	Pair ID	Historic vegetation type
Coquille	Bandon Marsh	4	Ref	X	X	X	X	1	marsh and open water
Coquille	Ni-les'tun	14	Unrest	Diked, ditched, drained, grazed	> 100 years ago	X	X	1	high marsh
Siuslaw	Cox Island (S11)	2	Ref	X	X	X	X	2	high marsh, swamp on E portion
Siuslaw	S59	3	Rest	Diked, ditched, drained, grazed	before 1939	2001	1996 dike breach and tide gate failure, two dike breaches in 2001	2	swamp
Siuslaw	S63	2	Ref	X	X	X	Diked but breached; never ditched	3	swamp
Siuslaw	S65	3	Unrest	Diked, ditched, drained, grazed	before 1939	2007	Breached dike, filled ditches, planted with tidal swamp species.	3	swamp
Siuslaw	Duncan Island (S30)	2	Ref	X	X	X	X	4	high marsh
Siuslaw	Waite Ranch (S26)	8	Unrest	Diked, ditched, drained,	before 1909	active	none	4	swamp

Estuary	**Site name and number***	**Number of transects sampled**	**Site category (Unrestored, Restored or Reference)**	**Impact type**	**Impact began**	**Year of restoration (approx)**	**Restoration activities**	**Pair ID**	**Historic vegetation type**
				grazed					
Siletz	Millport North	5	Ref	X	X	X	X	5	high marsh
Siletz	Millport South	8	Rest	Diked, dammed, partially ditched, drained, grazed	1929	2003	Removed outer and one inner dike, filled borrow ditch, connected historic sloughs, LWD	5	high marsh
Yaquina	Y13A	2	Ref	X	X	X	X	6	marsh
Yaquina	Y27	9	Rest	Diked, ditched, drained, grazed	1930s and 1940s	2002	Dikes breached in 2001, channels excavated, large woody debris placed, seeded, ditches filled	6	swamp and high marsh
Yaquina	Y28	2	Ref	X	X	X	X	6	swamp

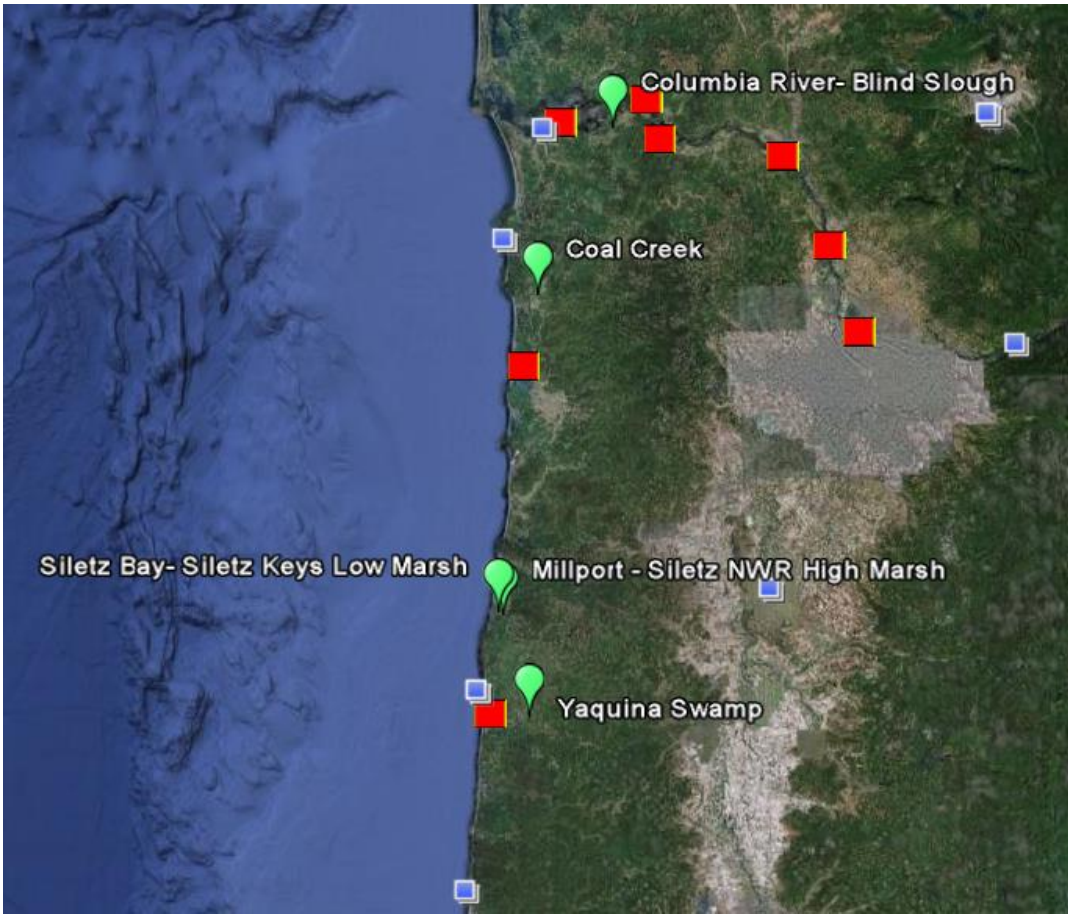
Estuary	Site name and number*	Number of transects sampled	Site category (**Unrest**ored, **Rest**ored or **Ref**erence)	Impact type	Impact began	Year of restoration (approx)	Restoration activities	Pair ID	Historic vegetation type
Nestucca	Nestucca East (Little Nestucca)	5	Rest	Diked, ditched (berms on some ditches), drained, grazed	before 1939	2007	Created channels, connected channels, built levees to protect highway, added large woody debris		marsh
Nehalem	Coal Creek	2	Ref	X	X	X	X		swamp
Columbia	Blind Slough	2	Ref	X	X	X	X		swamp
Coos	Hidden Creek Marsh	2	Ref	X	X	X	X		marsh

*site numbers refer to whole-estuary studies (Brophy 1999, 2005).

Appendix 9. CICEET Water Level Data Analysis

Prepared by Lijuan Huang

NOAA Center for Operational Oceanographic Products and Services (CO-OPS)



Center for Operational Oceanographic Products and Services (CO-OPS)
National Ocean Service
National Oceanographic and Atmospheric Administration
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1. Introduction

This report was prepared in response to a request by Laura Brophy in support of her team's Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) project; this report is an appendix to that project's final report. The purpose of the CICEET project is to collect and analyze the physical and biological data of least-disturbed wetlands to guide restoration design, evaluate restoration projects and conduct adaptive management. Wetland surface elevations relative to tidal datums, the duration and frequency of tidal inundation, and river discharge impacts on wetland inundation regimes are fundamental components of restoration planning. Five stations were installed in the estuaries along Oregon Coast at Yaquina Swamp (Y28), Millport Slough, Siletz Key, Coal Creek and Blind Slough from June, 2007 to August, 2008 to collect one-year water level data (Brophy *et al*. 2011). Table 1 shows the sensor elevation at each site relative to North America Vertical Datum of 1988 (NAVD88). Tide gauges at Blind Slough, Coal Creek and Siletz Keys were moved during the study due to problems with the original sites. For Blind Slough and Siletz Keys, the location change occurred immediately after completing the summer deployment. For Coal Creek, the gauge was moved in April 2008 due to possible damage to the original installation the record-breaking winter storm of December 2007.

This report describes our investigation of the fluvial contribution to frequency and duration of inundation at these tidal wetlands, and provides graphics of monthly variation in inundation events showing the fluvial contribution. Our study builds upon a method first developed for use in determining coastal uplift rates (Burgette *et al.*, 2009). The method was subsequently modified for use in the Siuslaw River estuary of Oregon (Weldon, 2006), and has been used to guide wetland restoration planning and evaluate restoration results in that estuary (Brophy, 2009).

Table 1. Sensor deployment periods and elevations relative to NAVD88 (m) for the five CICEET study sites.

Site	Sensor elevation relative to NAVD88 (m)	Applicable date of sensor elevation
Blind Slough	1.664	July 1 to October 23, 2007
	1.609	October 24, 2007 to July 29, 2008
Coal Creek	1.076	June 29, 2007 to April 2, 2008
	1.420	April 3 to August 9, 2008
Millport Slough	1.416	June 28, 2007 to June 27, 2008
Siletz Keys	1.908	June 26 to October 25, 2007
	1.605	October 26, 2007 to August 28, 2008
Yaquina (Y28)	1.365	June 14, 2007 to July 1, 2008

2. Datum Computation

Tides in the project areas are mixed, mainly semidiurnal with a large diurnal inequality in higher high and lower high waters and/or higher low and lower low waters. The Great Diurnal Range (GT) is about 2.5 m. GT is the difference in height between Mean Higher Water (MHHW) and Mean Lower Low Water (MLLW). The water level sensors were leveled to reference points with known elevations of North America Vertical Datum of 1988 (NAVD88) and thus sensor "zeros" can be related to NAVD88 at each location. Tidal datums at the 5 stations were calculated by simultaneous comparison with the long-term stations operated and maintained by CO-OPS to get the equivalent 19-year National Tidal Datum Epoch (NTDE) datum (NOAA, 2003). An example of the simultaneous comparison method is shown in Figure 1. The CO-OPS station at Astoria 943-9040 was used to control Blind Slough, Garibaldi 943-7540 to control Coal Creek and South Beach 943-5380 to control Yaquina, Millport and Siletz Key. MHHW was used as the reference datum to analyze the frequency and duration of inundation. Table 2 shows the MHW and MHHW datums at the 5 stations.

The equations for computation of MHW and MHHW by direct comparison are (NOAA, 2003):

$$MHW_{Short-term\ Station} = MHW_{Control\ station} + \left(\frac{1}{N}\right)$$
$$\sum_{I=1}^{N}\left(MHW_{Short-term\ Station}(I) - MHW_{Control\ station}(I)\right)$$

$$MHHW_{Short-term\ Station} = MHHW_{Control\ station} + \left(\frac{1}{N}\right)$$
$$\sum_{I=1}^{N}\left(MHHW_{Short-term\ Station}(I) - MHHW_{Control\ station}(I)\right)$$

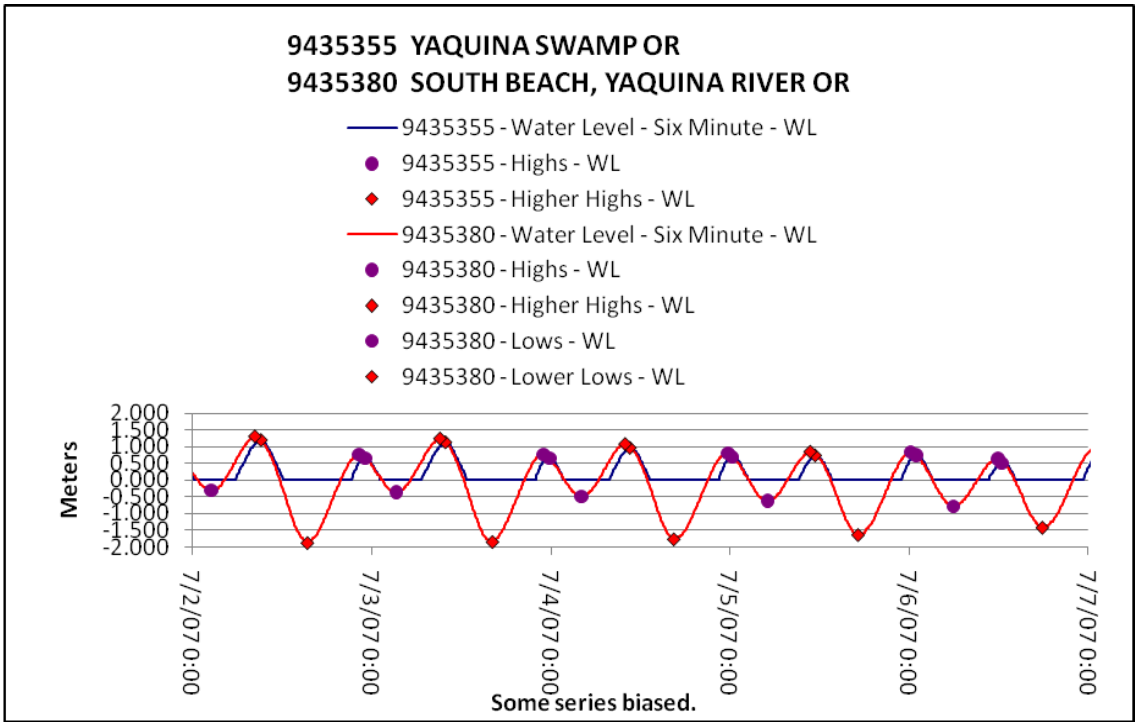


Figure 1. Tidal datums at Yaquina Site Y28, calculated by direct comparison with the CO-OPS long-term station at South Beach.

Table 2. MHW and MHHW datums relative to NAVD88 at the CICEET stations.

Site	CO-OPS control station	Tidal Datum relative to NAVD88 (m)		Applicable date of sensor elevation
Blind Slough	Astoria (943-9040)	MHHW	2.784	July 1 to October 23, 2007
		MHW	2.582	
		MHHW	2.800	October 24, 2007 to July 29, 2008
		MHW	2.600	
Coal Creek	Garibaldi (943-7540)	MHHW	2.441	June 2007 to April 2, 2008
		MHW	2.235	
		MHHW	2.375	April 3 to August 9, 2008
		MHW	2.161	
Millport Slough	South Beach	MHHW	2.340	June 28, 2007 to June 27, 2008
		MHW	2.133	
Siletz Keys	South Beach (943-5380)	MHHW	2.203	June 26 to October 25, 2007
		MHW	N/A	
		MHHW	2.408	October 26, 2007 to August 28, 2008
		MHW	2.203	
Yaquina (Y28)	South Beach	MHHW	2.450	June 14, 2007 to July 1, 2008
		MHW	2.233	

3. Fluvial Component Analysis

3.1. Segmented linear regression between river discharge and detided data at CICEET stations

River discharges have a major influence on inundation regime for the research areas. Therefore, it is important to determine the fluvial contribution to water level elevation. The daily river discharge data (cubic feet) were obtained from U.S. Geological Survey (USGS) river gauges located above head of tide. The USGS gauge used for each study site is listed below.

Coal Creek site: We used the Nehalem River station 14301000 (Nehalem River near Foss, OR)
http://waterdata.usgs.gov/or/nwis/dv/?site_no=14301000&referred_module=sw

Siletz Keys and Millport Slough sites: We used the Siletz River station 14305500 (Siletz River at Siletz, OR)
http://waterdata.usgs.gov/or/nwis/dv/?site_no=14305500&referred_module=sw

Yaquina: there are no current data. The best station is 14306030 (Yaquina River near Chitwood, OR), but this gauge was active only from 1972 through 1991.
http://waterdata.usgs.gov/or/nwis/dv/?site_no=14306030&referred_module=sw

Therefore, for current data, the "surrogate discharge record" approach (Weldon, 2006) was used: That is, we determined the linear relationship between flows on the Yaquina for the period of record (1972-1991) and flows for that same period at the Siletz River gauge above (14305500) and using that relationship, created a surrogate discharge record for the Yaquina for the current period (Figure 2). Figure 2 shows the linear relationship between river discharge at the USGS gauges on the Siletz and Yaquina.

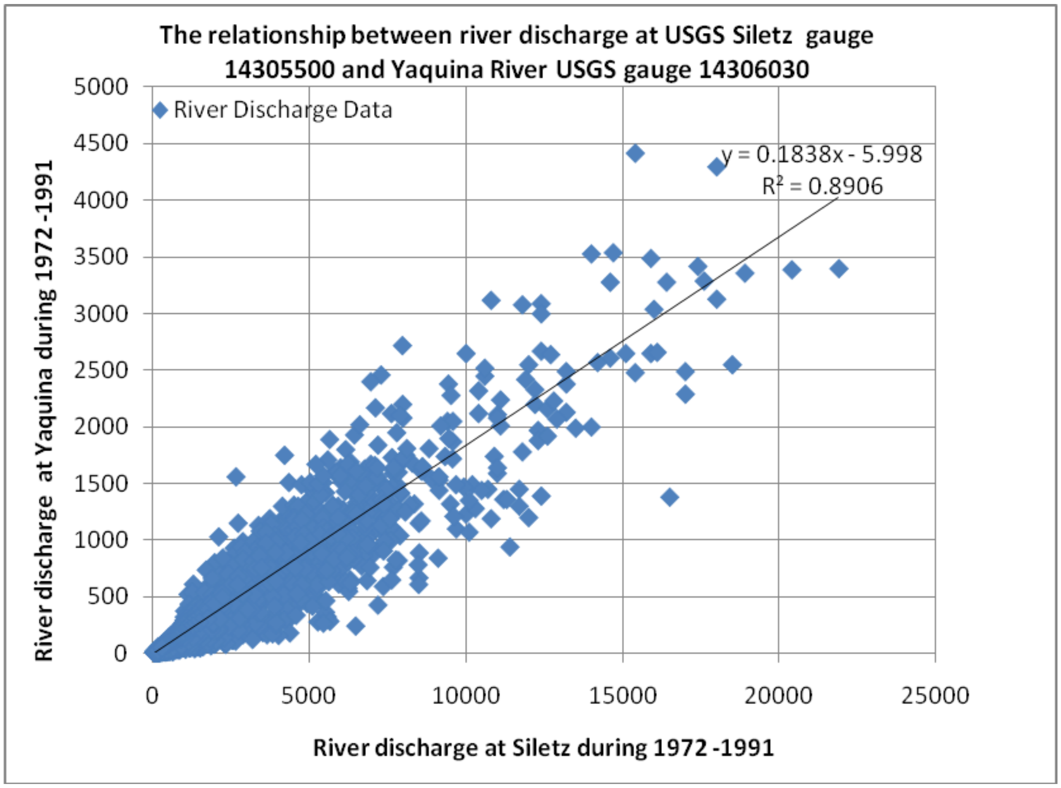


Figure 2. The relationship between river discharge at the USGS Siletz and Yaquina river gauges

In order to study the effects of lower frequency phenomena (such as river flows) on tidal records, it is advantageous to first filter out the energy at tidal frequencies. A Doodson 39-hour Filter method was used to eliminate tidal energy from observed water level data. The Doodson Filter is one of the earliest and most commonly applied tidal filters, used to eliminate tidal energy from observed water level data (Parker, 2007). The Doodson Filter eliminates 99.94% of the tidal energy at the semidiurnal frequencies, 99.79% of the tidal energy at the diurnal frequencies and 99.38 % of the tidal energy at the overtide frequencies (Grove, 1955). The filtered water level data contain only non-tidal energy such as wind and river runoff (blue line in Figure 3). We subtracted the filtered water level data from the observed water levels to obtain “residuals” (orange line in Figure 3), which represent water levels due to tides (astronomical water levels) without the effects of river flows, wind, and other nontidal forces.

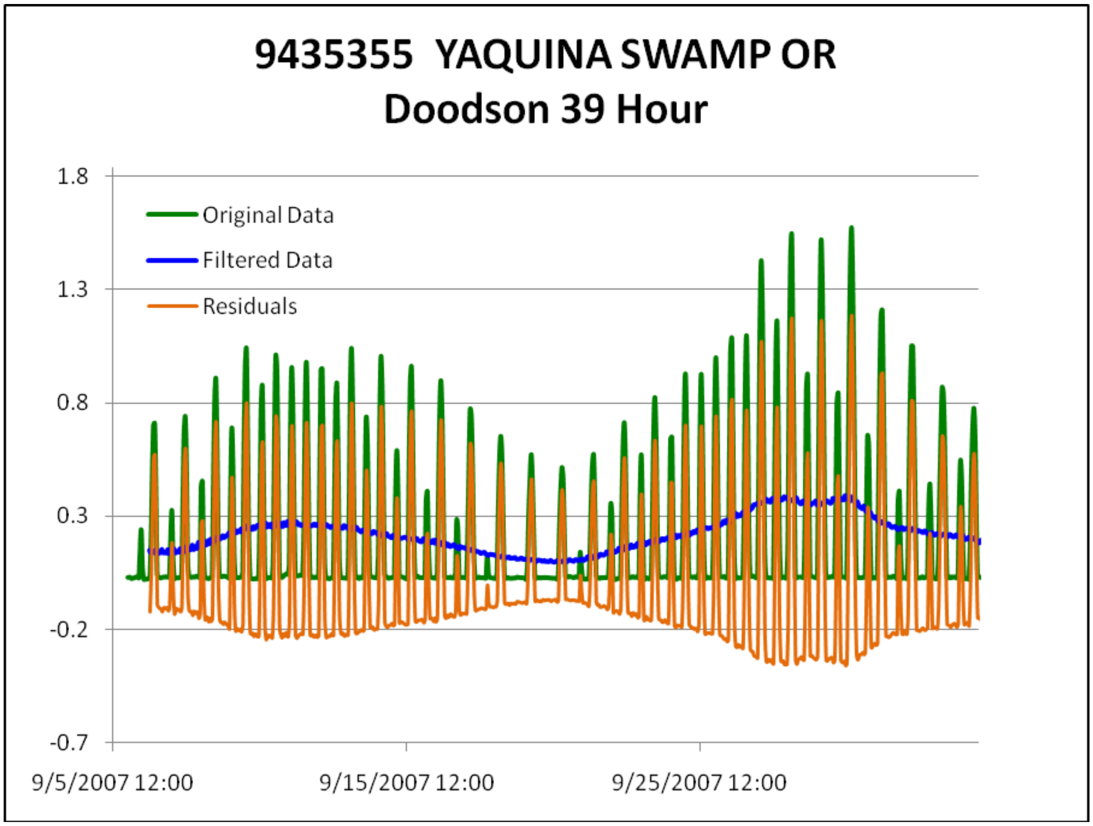


Figure 3. Doodson Filter. Observed data (green line) were filtered to remove tidal effects; the resulting filtered data show water levels due to non-tidal forces (blue line). Filtered data were subtracted from observed data to obtain residuals (water levels due to tidal forces = orange line). Low tides are not shown because the sensor was out of water at low tide.

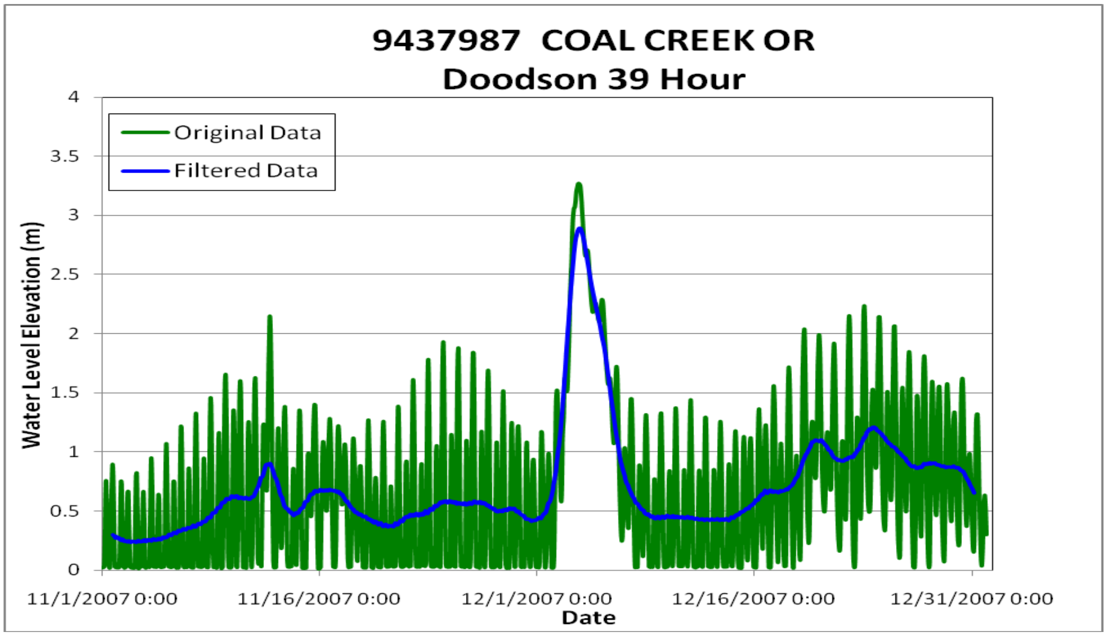


Figure 4. The measured water level data and the filtered (detided) data at Coal Creek. The baseline (sensor elevation) is 1.076 m above NAVD88

During the Great Coastal Gale of December 2007, the maximum observed water level was 4.330 m above NAVD88 and 1.889 m above MHHW and the corresponding detided water level elevation at Coal Creek was 3.947 m above NAVD88 and 1.506 m above MHHW (Figure 4). As illustrated by this example, the river flow effect on the inundation regime is prominent at Coal Creek in the winter season, and this is observed in many Oregon estuaries. Therefore, it is important to determine the fluvial contribution to water level elevation.

To determine the fluvial contribution, the daily mean river discharge data (cubic feet) was obtained from U.S. Geological Survey (USGS) river gauge 14301000 on the Nehalem River near Foss, OR, which is located above head of tide (Figure 5). Comparison of the detided water level measured by tide gauge at Coal Creek (Figure 4) and the Nehalem River discharge at the USGS gauge near Foss (Figure 5) shows a strong relationship between the two datasets.

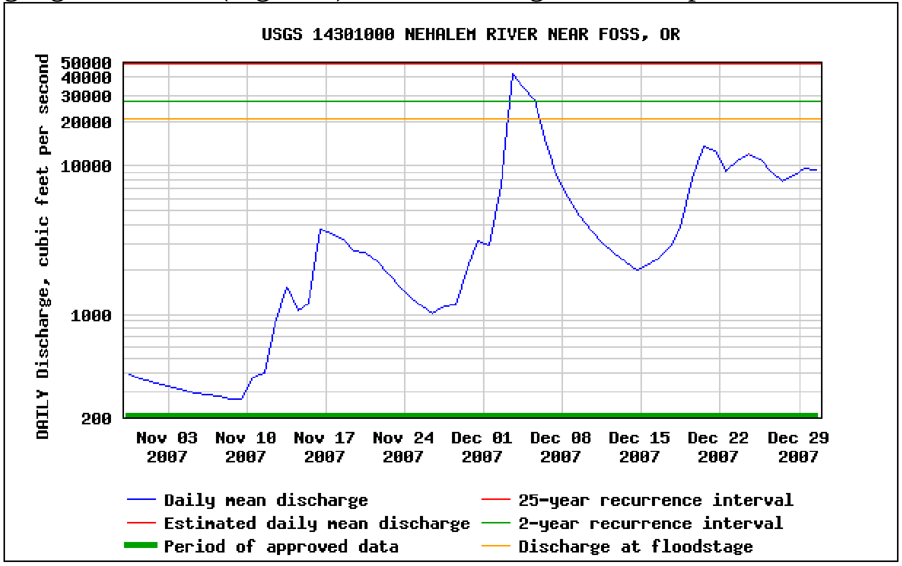


Figure 5. Daily mean river discharge at USGS gauge 14301000 (Nehalem River near Foss, OR) between November 1 and December 31 , 2007

The detided data was then plotted against normalized, log10-transformed river discharge data for the period of observation (Figure 6, 7, 8, 9 and 10). “Normalized” means discharge relative to average summer low discharge, that is, summer low discharge is subtracted from each flow value to get the normalized discharge value (Brophy, 2009). Based on the scatter plots at 5 stations, there is a relationship between (log10-transformed) river discharge and detided water level at Coal Creek, Millport Slough, Siletz Keys and Yaquina Site Y28. Blind Slough shows a random distribution with respect to river discharge, probably due to the Columbia River’s very large, non-coastal watershed and the system’s highly regulated flows.

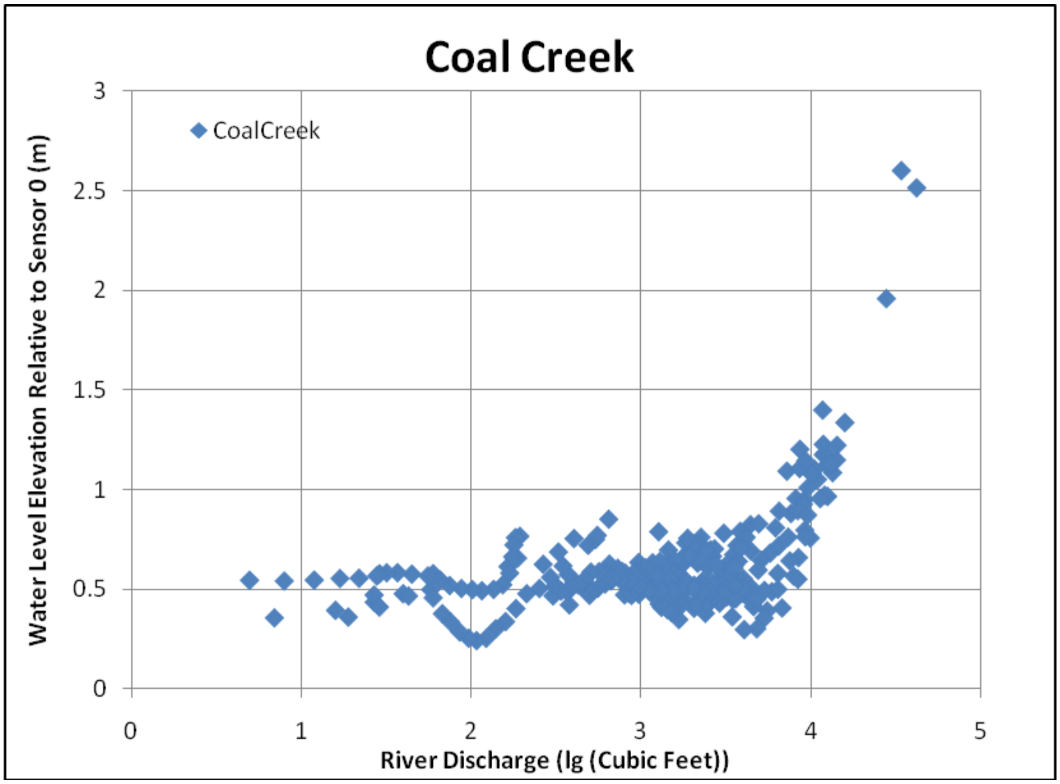


Figure 6. Detided data vs. normalized, log10-transformed daily river discharge data at Coal Creek

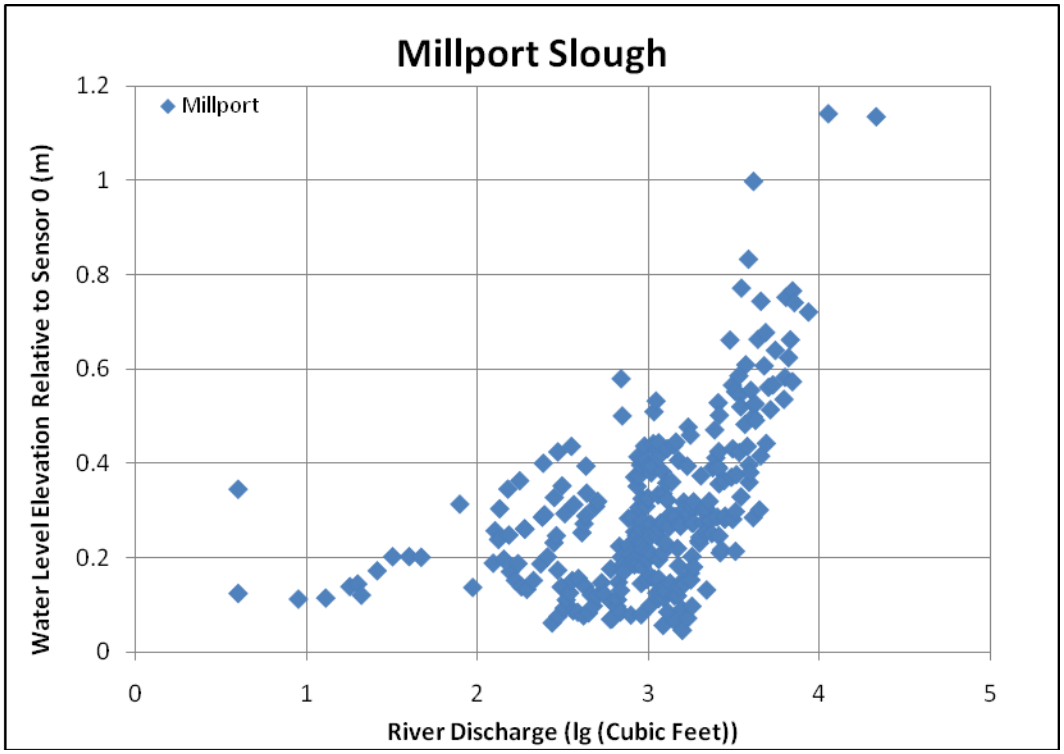


Figure 7. Detided data vs. normalized, log10-transformed daily river discharge data at Millport Slough

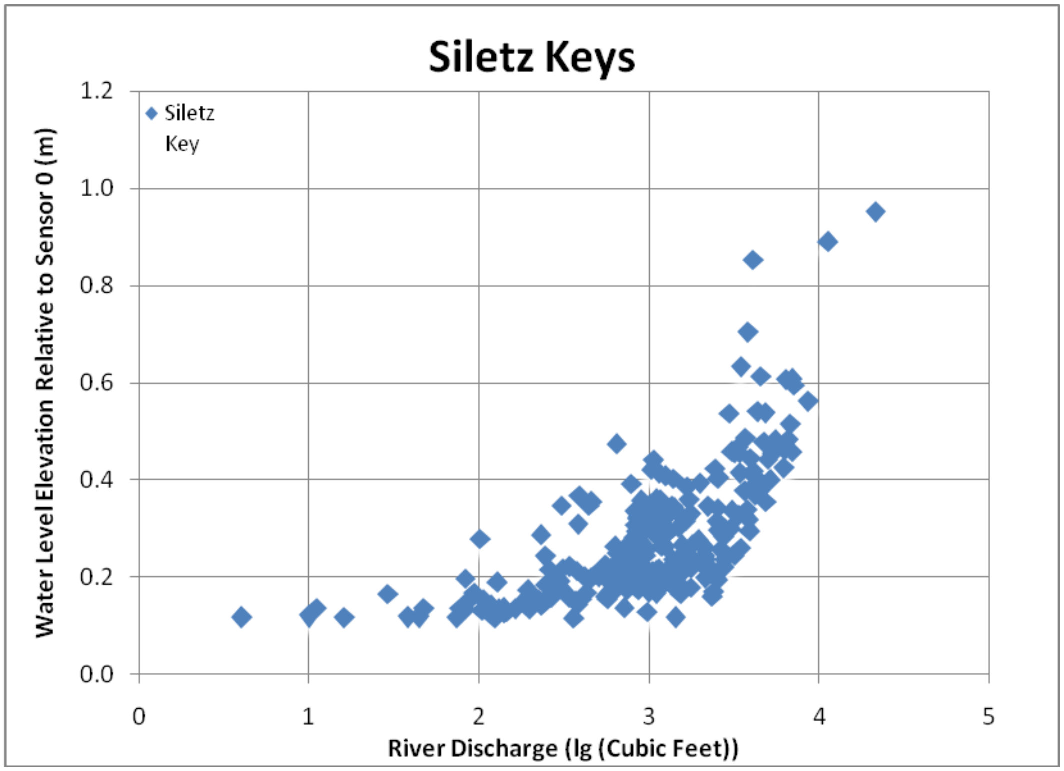


Figure 8. Detided data vs. normalized, log10-transformed daily river discharge data at Siletz Keys

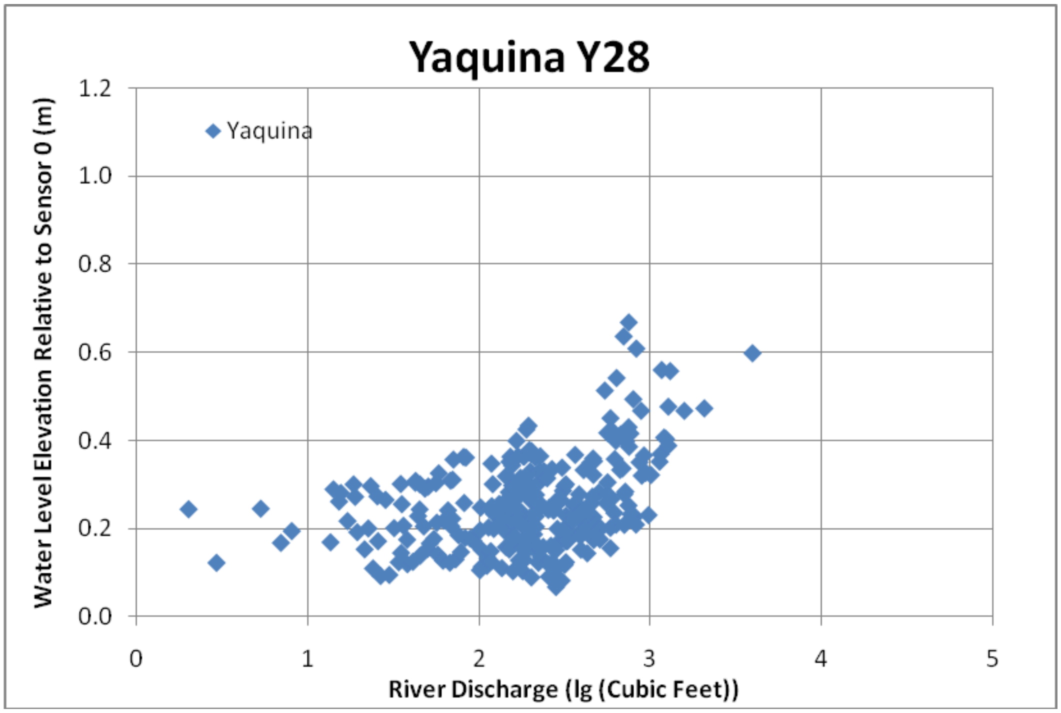


Figure 9. Detided data vs. normalized, log10-transformed daily river discharge data at Yaquina Swamp (Site Y28)

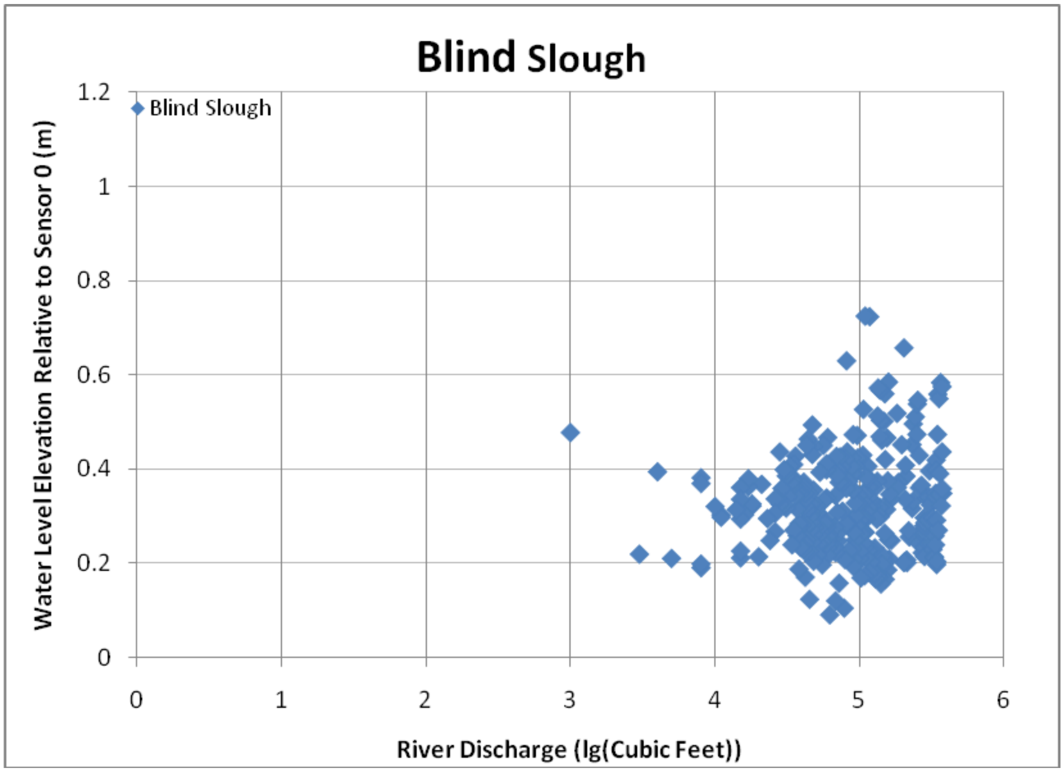


Figure 10. Detided data vs. normalized, log10-transformed daily river discharge data at Blind Slough

There is no linear relationship between the detided data and river discharge data at Coal Creek, Millport and Yaquina Y28 stations at low river discharges. Therefore, the data was broken up into two segments and fitted within a given segment by using the Curve Fitting Toolbox in MATLAB (Figures 11 and 12). Figures 13, 14, 15, and 16 show the segmented linear relationship at these 4 stations based on the equations derived from MATLAB.

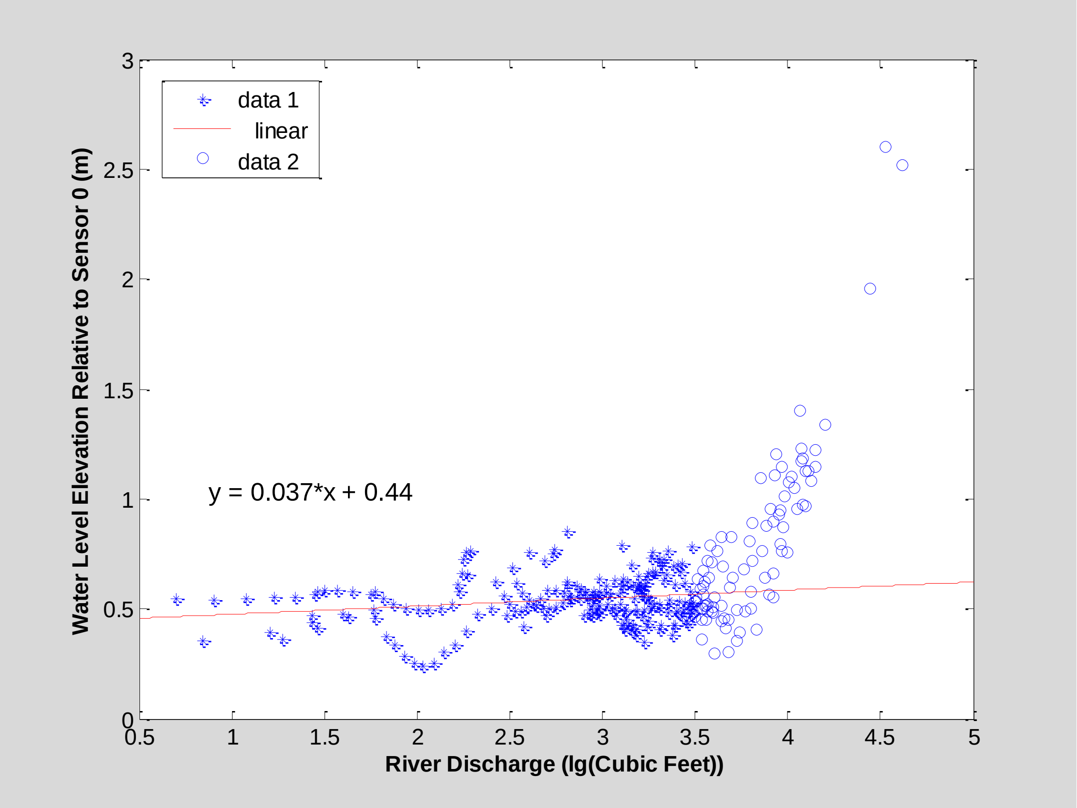


Figure 11. Example of a segmented linear regression fit by MATLAB – segment 1

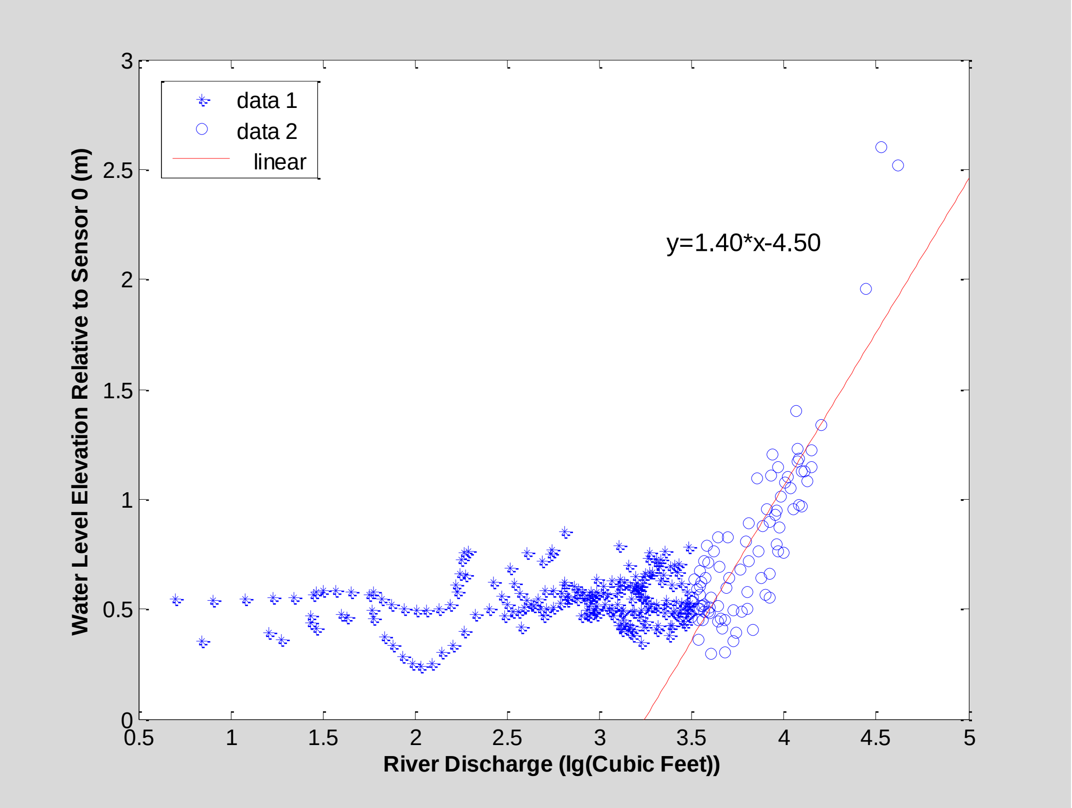


Figure 12. Example of a segmented linear regression fit by MATLAB – segment 2

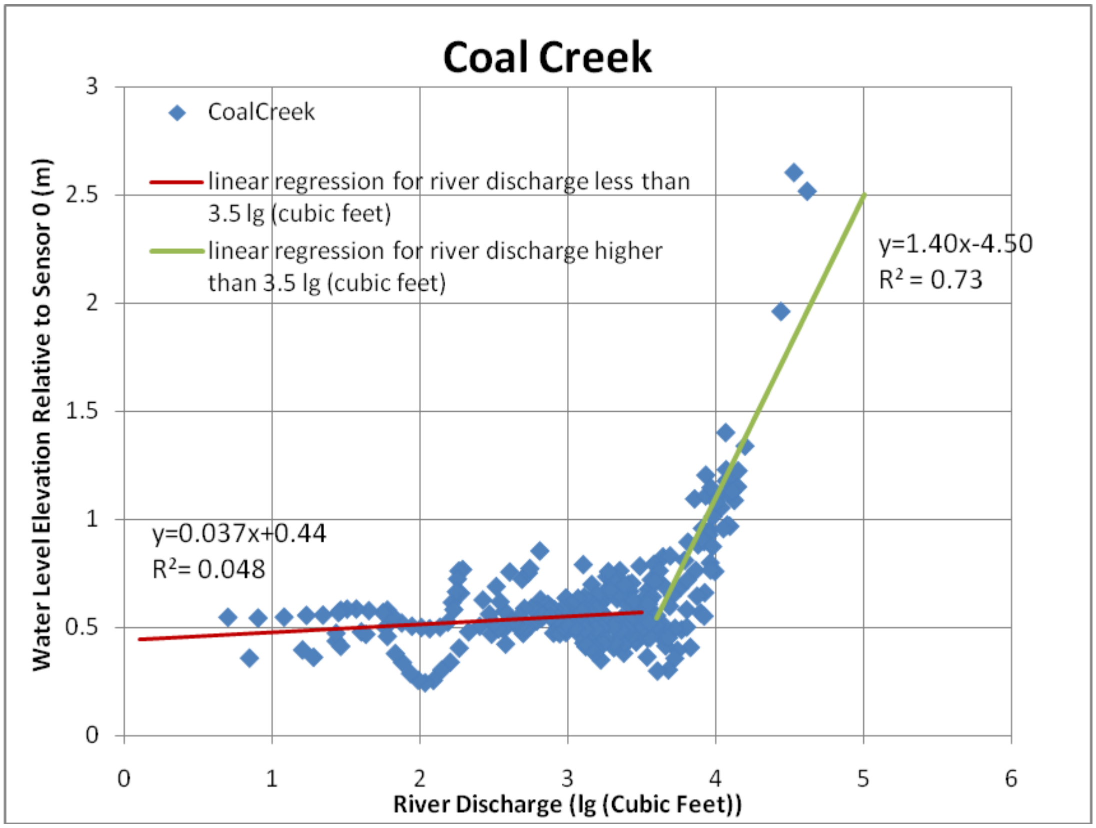


Figure 13. Segmented linear regression fit at Coal Creek

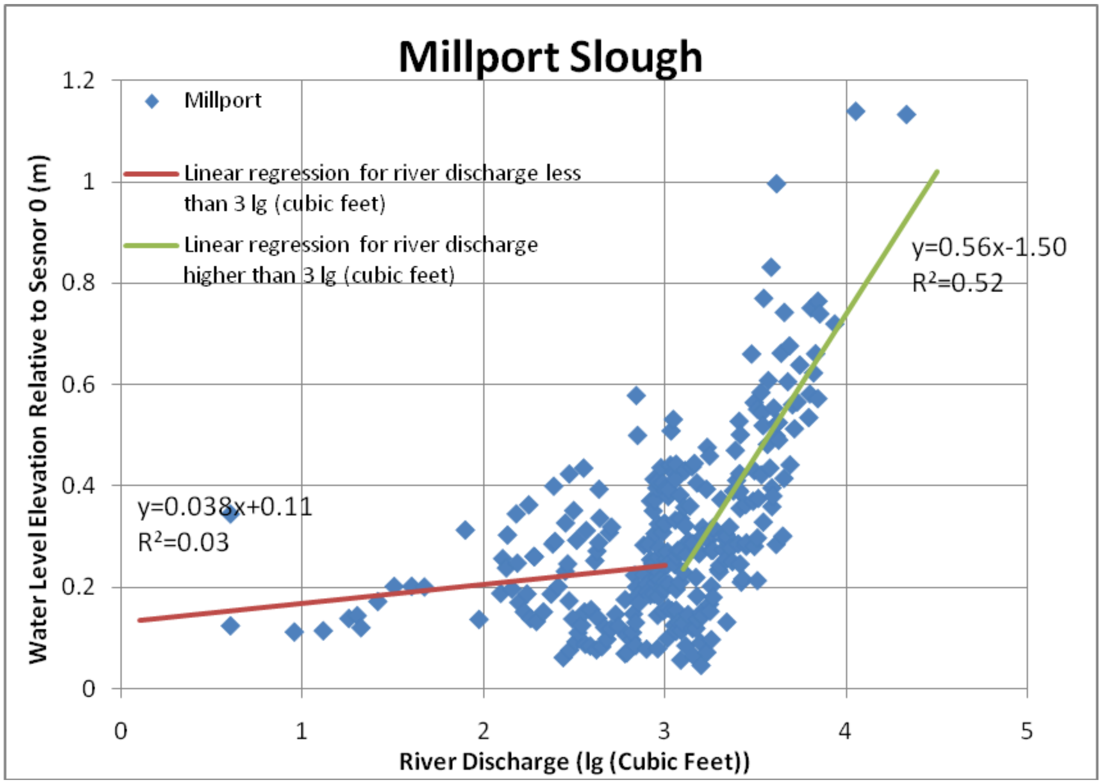


Figure 14. Segmented linear regression fit at Millport Slough

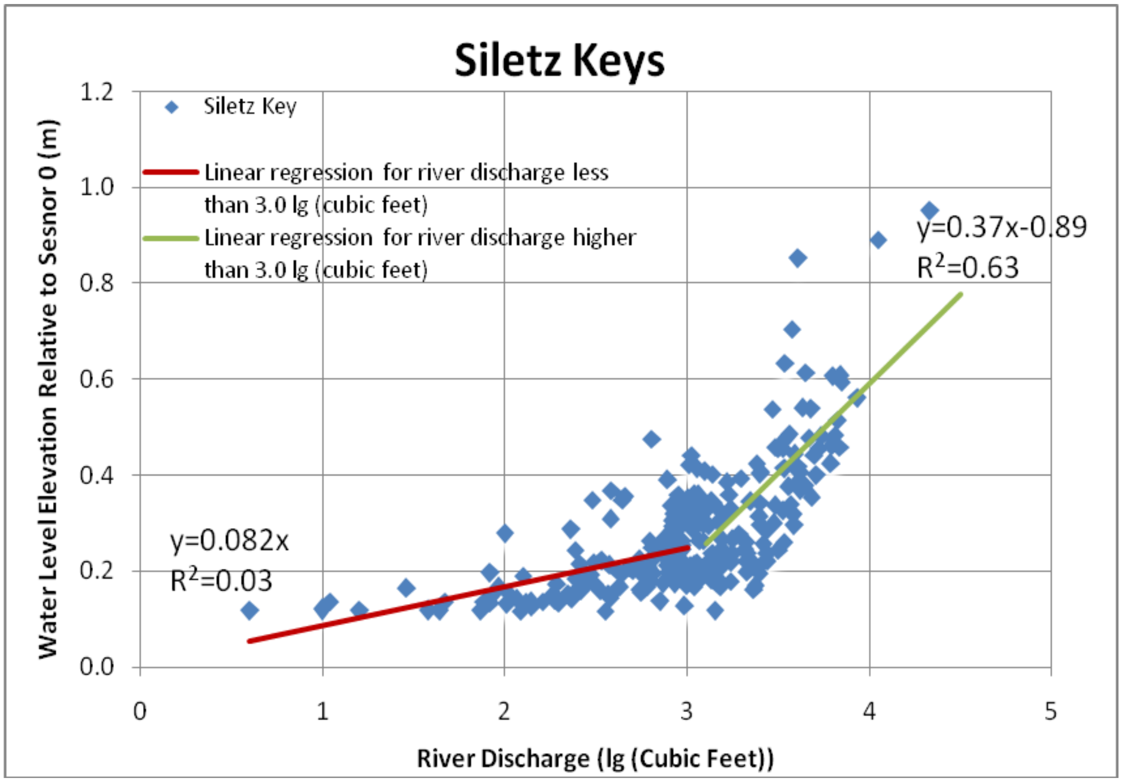


Figure 15. Segmented linear regression fit at Siletz Keys

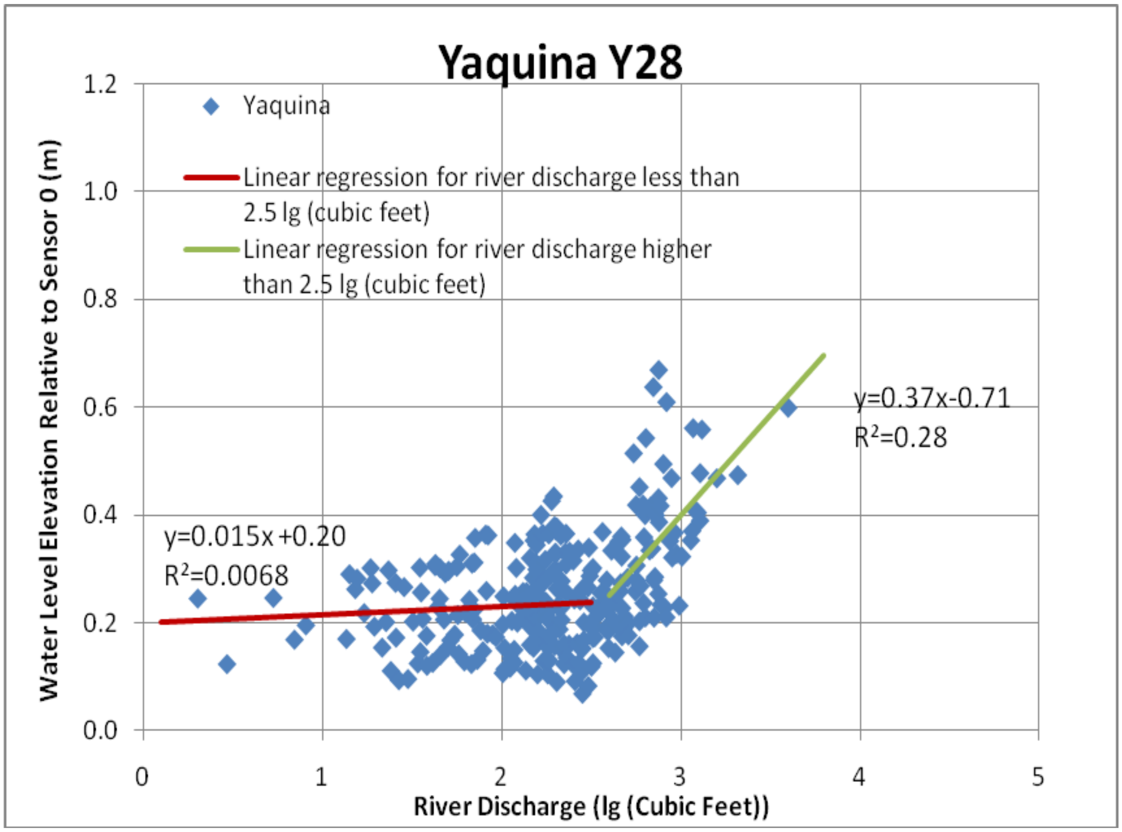
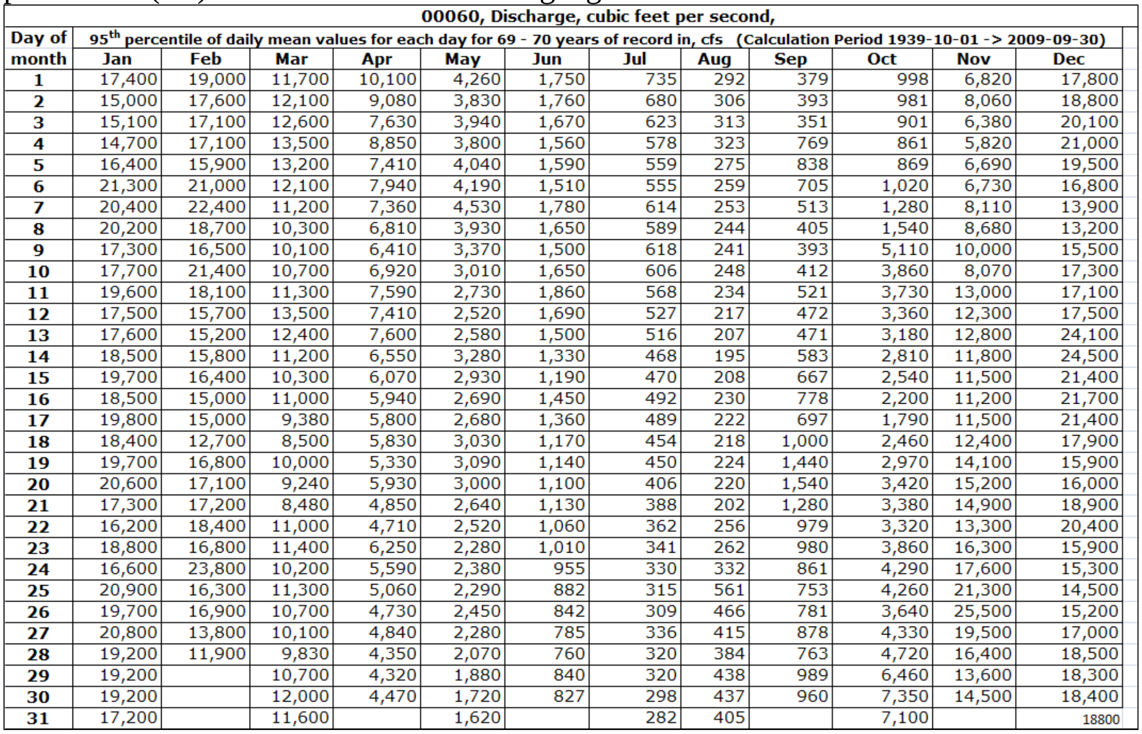


Figure 16. Segmented linear regression fit at Yaquina Site Y28

3.2. Water level elevation derived from 50% and 95% flow data based on the segmented linear equations

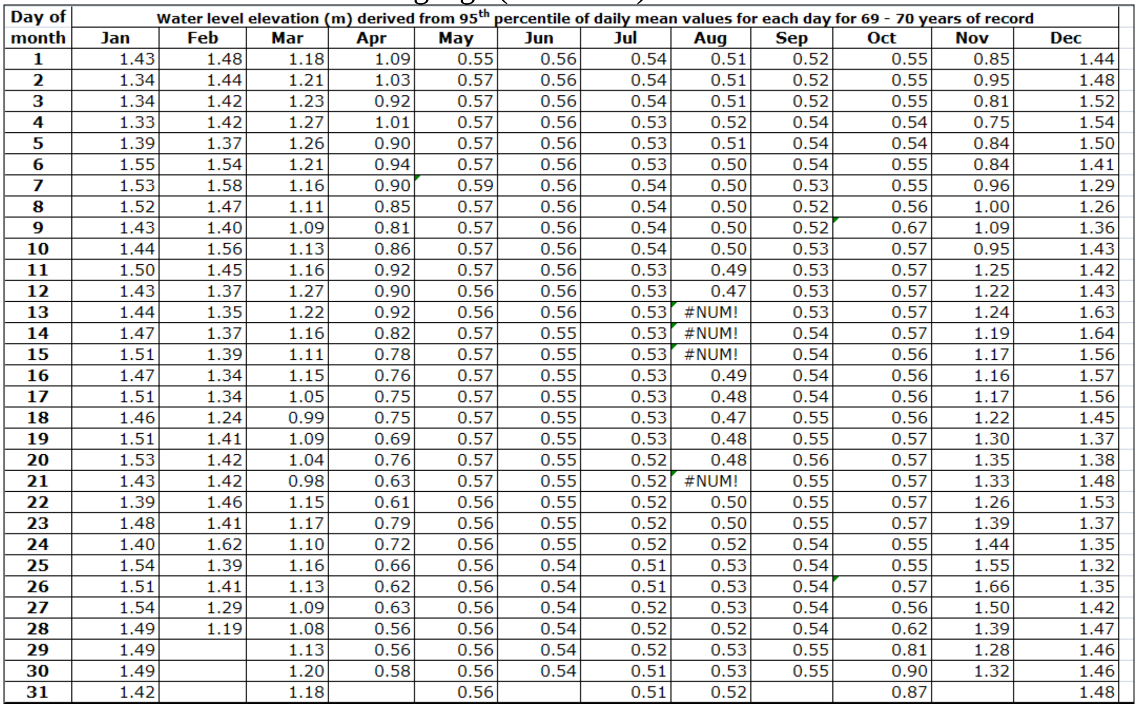
The 50% and 95% flow values can be retrieved from USGS surface-water daily statistics. 50% and 95% flow levels refer to the fact that in a 100 year record, there are 100 discharge values for any given date. When these values are sorted by flow, the 50% value is the middle value, and the 95% value is the 5th from the top. Table 3 shows the percentile of daily mean flow values for a 69-70 year record at the USGS Nehalem River gauge (in cfs). Table 4 shows the predicted increase in the water level elevation at the Coal Creek site at the 95% flow level, calculated from these 95% flow values using the regression equations in Figure 12 above. This is referred to as the "95% river flow adjustment" value. The "50% river flow adjustment" value was obtained in the same way, using the 50th percentile of daily mean flows for the same 69-70 year record. These flow adjustment values were added to the predicted tide height to get the 50% and 95% total water level elevation for each day of the year at each site (see Section 3.3 below).

Table 3. 95th percentile of daily mean values for each day for 69-70 years record in cubic feet per second (cfs) at USGS Nehalem River gauge.



00060, Discharge, cubic feet per second,												
Day of month	95th percentile of daily mean values for each day for 69 - 70 years of record in, cfs (Calculation Period 1939-10-01 -> 2009-09-30)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	17,400	19,000	11,700	10,100	4,260	1,750	735	292	379	998	6,820	17,800
2	15,000	17,600	12,100	9,080	3,830	1,760	680	306	393	981	8,060	18,800
3	15,100	17,100	12,600	7,630	3,940	1,670	623	313	351	901	6,380	20,100
4	14,700	17,100	13,500	8,850	3,800	1,560	578	323	769	861	5,820	21,000
5	16,400	15,900	13,200	7,410	4,040	1,590	559	275	838	869	6,690	19,500
6	21,300	21,000	12,100	7,940	4,190	1,510	555	259	705	1,020	6,730	16,800
7	20,400	22,400	11,200	7,360	4,530	1,780	614	253	513	1,280	8,110	13,900
8	20,200	18,700	10,300	6,810	3,930	1,650	589	244	405	1,540	8,680	13,200
9	17,300	16,500	10,100	6,410	3,370	1,500	618	241	393	5,110	10,000	15,500
10	17,700	21,400	10,700	6,920	3,010	1,650	606	248	412	3,860	8,070	17,300
11	19,600	18,100	11,300	7,590	2,730	1,860	568	234	521	3,730	13,000	17,100
12	17,500	15,700	13,500	7,410	2,520	1,690	527	217	472	3,360	12,300	17,500
13	17,600	15,200	12,400	7,600	2,580	1,500	516	207	471	3,180	12,800	24,100
14	18,500	15,800	11,200	6,550	3,280	1,330	468	195	583	2,810	11,800	24,500
15	19,700	16,400	10,300	6,070	2,930	1,190	470	208	667	2,540	11,500	21,400
16	18,500	15,000	11,000	5,940	2,690	1,450	492	230	778	2,200	11,200	21,700
17	19,800	15,000	9,380	5,800	2,680	1,360	489	222	697	1,790	11,500	21,400
18	18,400	12,700	8,500	5,830	3,030	1,170	454	218	1,000	2,460	12,400	17,900
19	19,700	16,800	10,000	5,330	3,090	1,140	450	224	1,440	2,970	14,100	15,900
20	20,600	17,100	9,240	5,930	3,000	1,100	406	220	1,540	3,420	15,200	16,000
21	17,300	17,200	8,480	4,850	2,640	1,130	388	202	1,280	3,380	14,900	18,900
22	16,200	18,400	11,000	4,710	2,520	1,060	362	256	979	3,320	13,300	20,400
23	18,800	16,800	11,400	6,250	2,280	1,010	341	262	980	3,860	16,300	15,900
24	16,600	23,800	10,200	5,590	2,380	955	330	332	861	4,290	17,600	15,300
25	20,900	16,300	11,300	5,060	2,290	882	315	561	753	4,260	21,300	14,500
26	19,700	16,900	10,700	4,730	2,450	842	309	466	781	3,640	25,500	15,200
27	20,800	13,800	10,100	4,840	2,280	785	336	415	878	4,330	19,500	17,000
28	19,200	11,900	9,830	4,350	2,070	760	320	384	763	4,720	16,400	18,500
29	19,200		10,700	4,320	1,880	840	320	438	989	6,460	13,600	18,300
30	19,200		12,000	4,470	1,720	827	298	437	960	7,350	14,500	18,400
31	17,200		11,600		1,620		282	405		7,100		18800

Table 4. Water level elevation increments (meters) at Coal Creek site, derived from 95% flow values based on the segmented linear equations above (“95% river flow adjustment”) and data from the USGS Nehalem River gauge (14301000).



Day of month	Water level elevation (m) derived from 95th percentile of daily mean values for each day for 69 - 70 years of record										
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.43	1.48	1.18	1.09	0.55	0.56	0.54	0.51	0.52	0.55	0.85	1.44
2	1.34	1.44	1.21	1.03	0.57	0.56	0.54	0.51	0.52	0.55	0.95	1.48
3	1.34	1.42	1.23	0.92	0.57	0.56	0.54	0.51	0.52	0.55	0.81	1.52
4	1.33	1.42	1.27	1.01	0.57	0.56	0.53	0.52	0.54	0.54	0.75	1.54
5	1.39	1.37	1.26	0.90	0.57	0.56	0.53	0.51	0.54	0.54	0.84	1.50
6	1.55	1.54	1.21	0.94	0.57	0.56	0.53	0.50	0.54	0.55	0.84	1.41
7	1.53	1.58	1.16	0.90	0.59	0.56	0.54	0.50	0.53	0.55	0.96	1.29
8	1.52	1.47	1.11	0.85	0.57	0.56	0.54	0.50	0.52	0.56	1.00	1.26
9	1.43	1.40	1.09	0.81	0.57	0.56	0.54	0.50	0.52	0.67	1.09	1.36
10	1.44	1.56	1.13	0.86	0.57	0.56	0.54	0.50	0.53	0.57	0.95	1.43
11	1.50	1.45	1.16	0.92	0.57	0.56	0.53	0.49	0.53	0.57	1.25	1.42
12	1.43	1.37	1.27	0.90	0.56	0.56	0.53	0.47	0.53	0.57	1.22	1.43
13	1.44	1.35	1.22	0.92	0.56	0.56	0.53	#NUM!	0.53	0.57	1.24	1.63
14	1.47	1.37	1.16	0.82	0.57	0.55	0.53	#NUM!	0.54	0.57	1.19	1.64
15	1.51	1.39	1.11	0.78	0.57	0.55	0.53	#NUM!	0.54	0.56	1.17	1.56
16	1.47	1.34	1.15	0.76	0.57	0.55	0.53	0.49	0.54	0.56	1.16	1.57
17	1.51	1.34	1.05	0.75	0.57	0.55	0.53	0.48	0.54	0.56	1.17	1.56
18	1.46	1.24	0.99	0.75	0.57	0.55	0.53	0.47	0.55	0.56	1.22	1.45
19	1.51	1.41	1.09	0.69	0.57	0.55	0.53	0.48	0.55	0.57	1.30	1.37
20	1.53	1.42	1.04	0.76	0.57	0.55	0.52	0.48	0.56	0.57	1.35	1.38
21	1.43	1.42	0.98	0.63	0.57	0.55	0.52	#NUM!	0.55	0.57	1.33	1.48
22	1.39	1.46	1.15	0.61	0.56	0.55	0.52	0.50	0.55	0.57	1.26	1.53
23	1.48	1.41	1.17	0.79	0.56	0.55	0.52	0.50	0.55	0.57	1.39	1.37
24	1.40	1.62	1.10	0.72	0.56	0.55	0.52	0.52	0.54	0.55	1.44	1.35
25	1.54	1.39	1.16	0.66	0.56	0.54	0.51	0.53	0.54	0.55	1.55	1.32
26	1.51	1.41	1.13	0.62	0.56	0.54	0.51	0.53	0.54	0.57	1.66	1.35
27	1.54	1.29	1.09	0.63	0.56	0.54	0.52	0.53	0.54	0.56	1.50	1.42
28	1.49	1.19	1.08	0.56	0.56	0.54	0.52	0.52	0.54	0.62	1.39	1.47
29	1.49		1.13	0.56	0.56	0.54	0.52	0.53	0.55	0.81	1.28	1.46
30	1.49		1.20	0.58	0.56	0.54	0.51	0.53	0.55	0.90	1.32	1.46
31	1.42		1.18		0.56		0.51	0.52		0.87		1.48

3. 3. Monthly variation in inundation and fluvial contribution

The methods above were used to predict monthly inundation days and duration for each study plot at the study sites. First, predicted inundation due to astronomical forces (“tides only” water levels) was obtained at each site by filtering out meteorological effects (in this case, mainly river effects) from observed data. These values are the “residuals” shown in Figure 3. Then, water level elevation increments (such as those shown in Tables 3 and 4 for Coal Creek) were added to the “tides only” water levels. Predicted inundation regimes were then calculated for the elevation of each study plot (Table 5), at three levels of river flow: “tides only,” 50% flow and 95% flow. “Tides only” values are water level elevations resulting from astronomical forces (i.e., tidal forces); 50% flow data consist of the “tides only” data plus the 50% “river flow adjustment” value, and 95% flow data consist of the “tides only” data plus the 95% “river flow adjustment” value. Figure 17 shows an example of results at Coal Creek. Low tides are not shown in Figure 17, because we did not model the full tidal cycle. The full tidal cycle could not be modeled for our CICEET study sites because the sensors were out of water at low tide, and suitable long term NOAA/CO-OPS tide stations (connected to the NAVD88 datum) were not available for all of our study sites.

Table 5. Study plot elevations (used to calculate inundation days and durations)

Site	Estuary	Plot	Elevation (m NAVD88)	Cowardin class	Habitat description
Blind Slough	Columbia	P1	2.64	tidally-influenced palustrine forested	Sitka spruce swamp
		P2	2.64	tidally-influenced palustrine scrub-shrub	willow swamp
Coal Creek	Nehalem	P1	2.55	estuarine forested	Sitka spruce swamp
		P2	2.63	estuarine forested	Sitka spruce swamp
Millport Slough	Siletz	P1	2.42	estuarine emergent	high marsh
		P2	2.48	estuarine emergent	high marsh
Siletz Keys	Siletz	P1	2.14	estuarine emergent	low marsh
		P2	2.01	estuarine emergent	low marsh
Yaquina Y28	Yaquina	P5	2.61	estuarine scrub-shrub	twinberry swamp

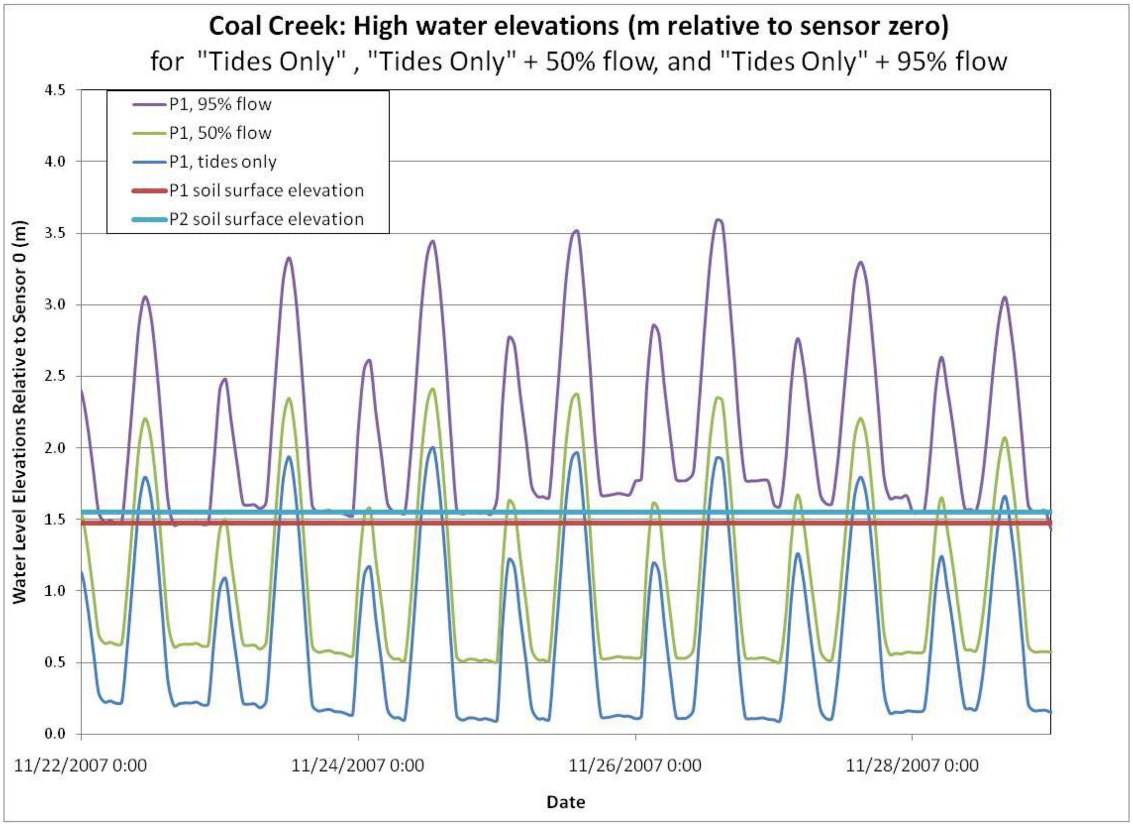


Figure 17. Predicted combined high water levels (tides plus fluvial contribution) at Coal Creek study plots 1 and 2, for three scenarios: “Tides only,” 50th percentile river flows, and 95th percentile river flows. Plot elevations (P1 and P2, 1.47m and 155m above sensor zero respectively) are shown as horizontal lines. Low tides are not shown because sensor was out of water at low tide (see above).

3.4. Inundation Metrics

Inundation frequency and duration for study plots at each site were calculated for the “tides only,” 50% river flow and 95% river flow scenarios; results are shown in Figures 18- 25.

Inundation frequency is the sums of days that get inundated at least 6 minutes in each month. Inundation duration is the hours of inundation divided by the total hours per month (744 hours for 31 days, 720 for 30 days). Inundation frequency and duration at Coal Creek in August and October are artificially low due to the missing data during those two months, and inundation frequency in November through March is overestimated due to the truncation of low waters due to the location of the tide gauge in a channel that dried at low tide. (The truncation of low waters "zeros out" low water values during the modeling process, which increases low water elevations and raises the frequency of inundation.) Inundation frequency and duration at Siletz Keys in March were generated by comparing with nearby months due to the missing data. The inundation frequency and duration relative to P2 at Siletz Keys in July, August, September and October are high due to the mud fill of site, which increases the sensor baseline.

For the Coal Creek site, we applied a refinement of this method using predicted astronomical water levels generated using harmonic constituents. This method is described in Huang *et al*. (2011), which is included as Appendix 10 of this report.

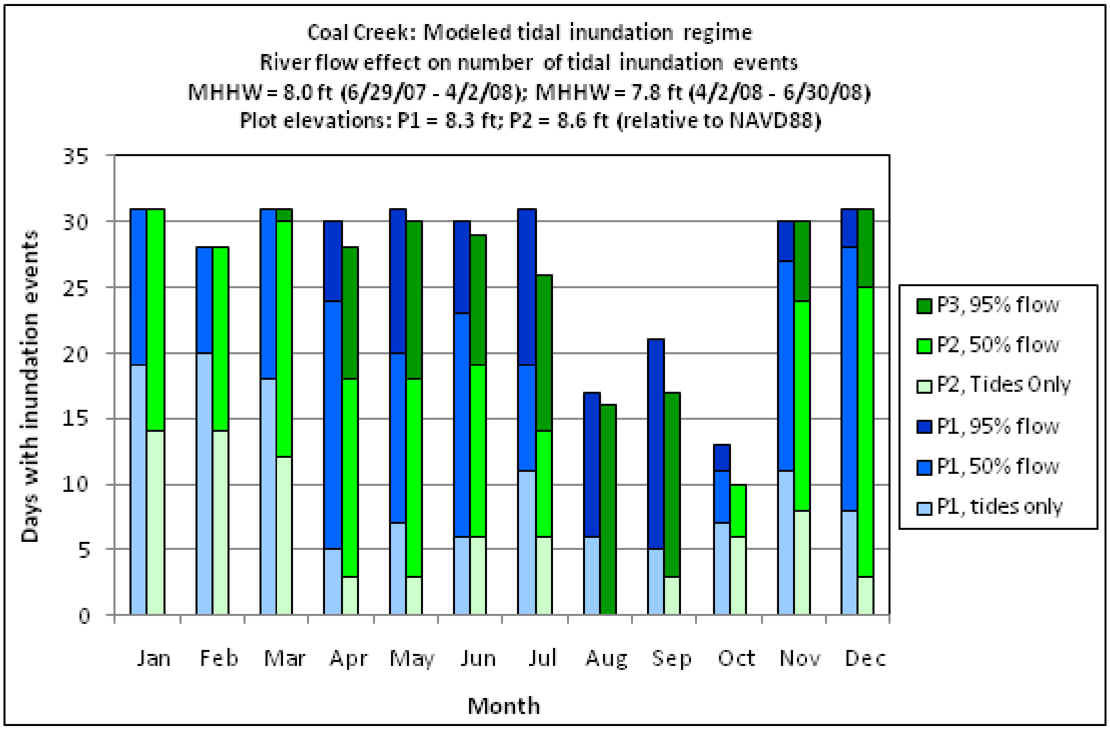


Figure 18. Coal Creek: Effect of river flows on tidal inundation frequency. Note that inundation in August through October is artificially low due to missing data.

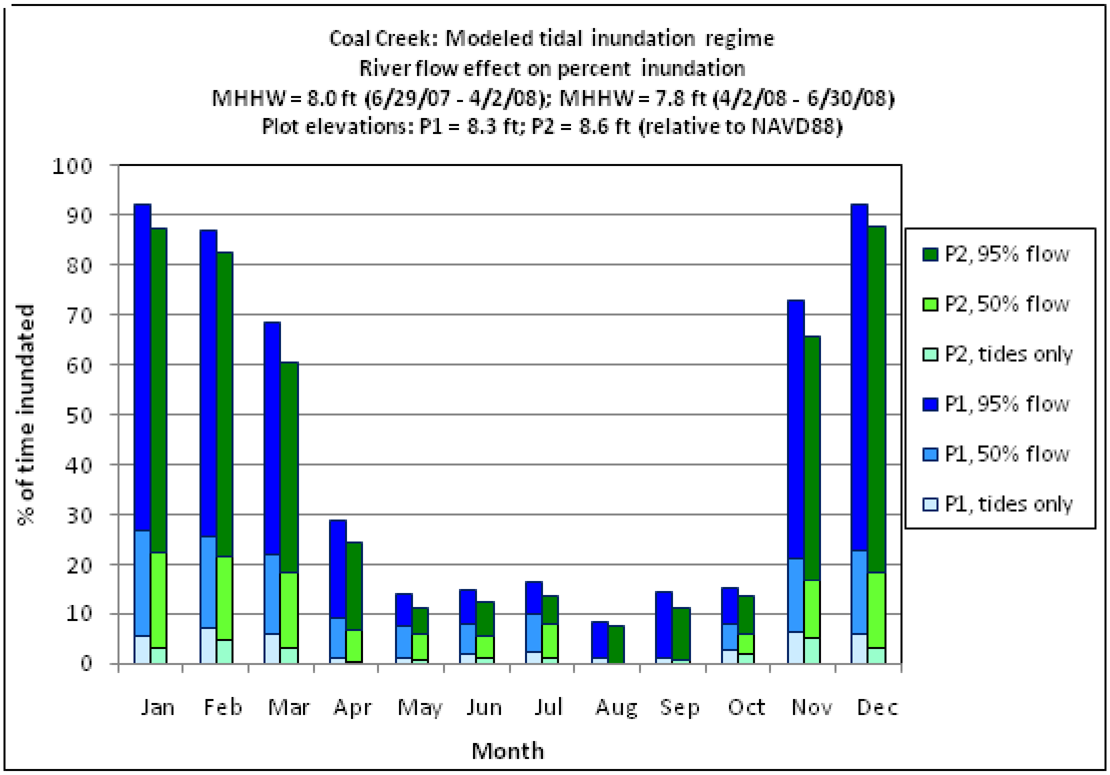


Figure 19. Coal Creek: Effect of river flows on percent inundation. Note that inundation in August through October is artificially low due to missing data.

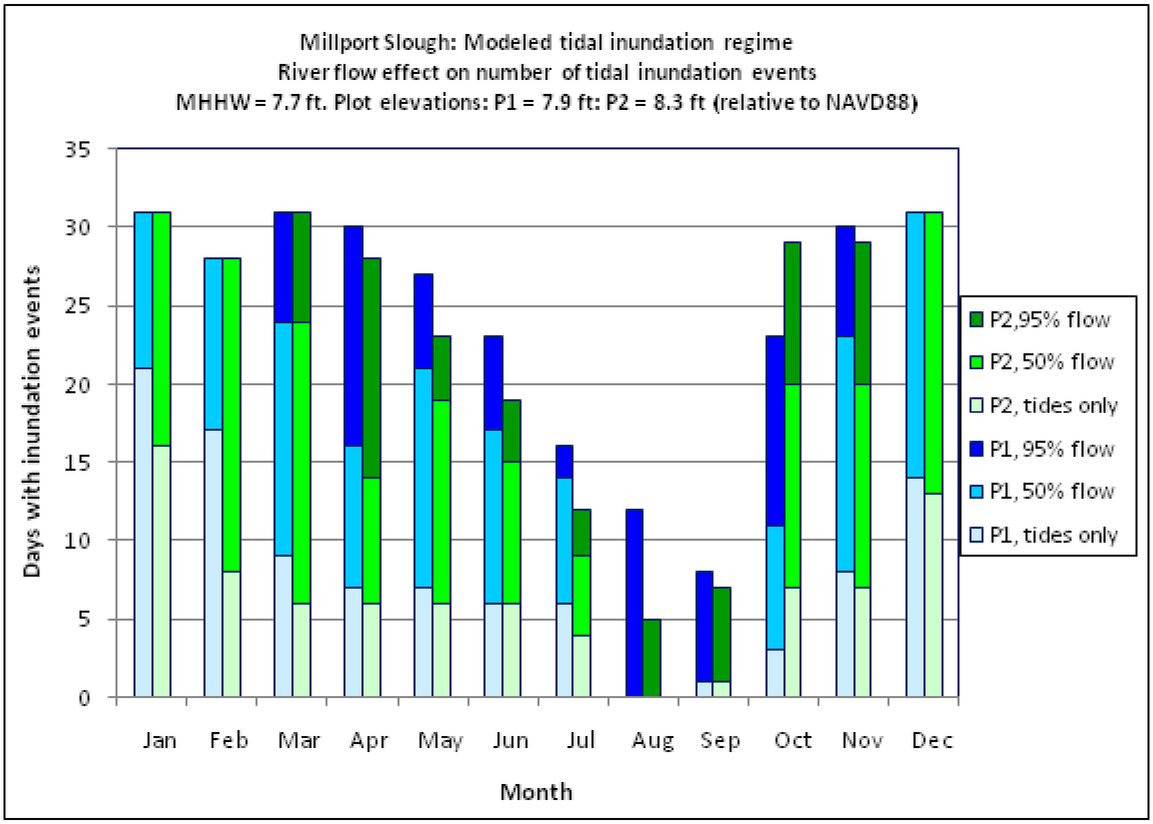


Figure 20. Millport Slough: Effect of river flows on tidal inundation frequency.

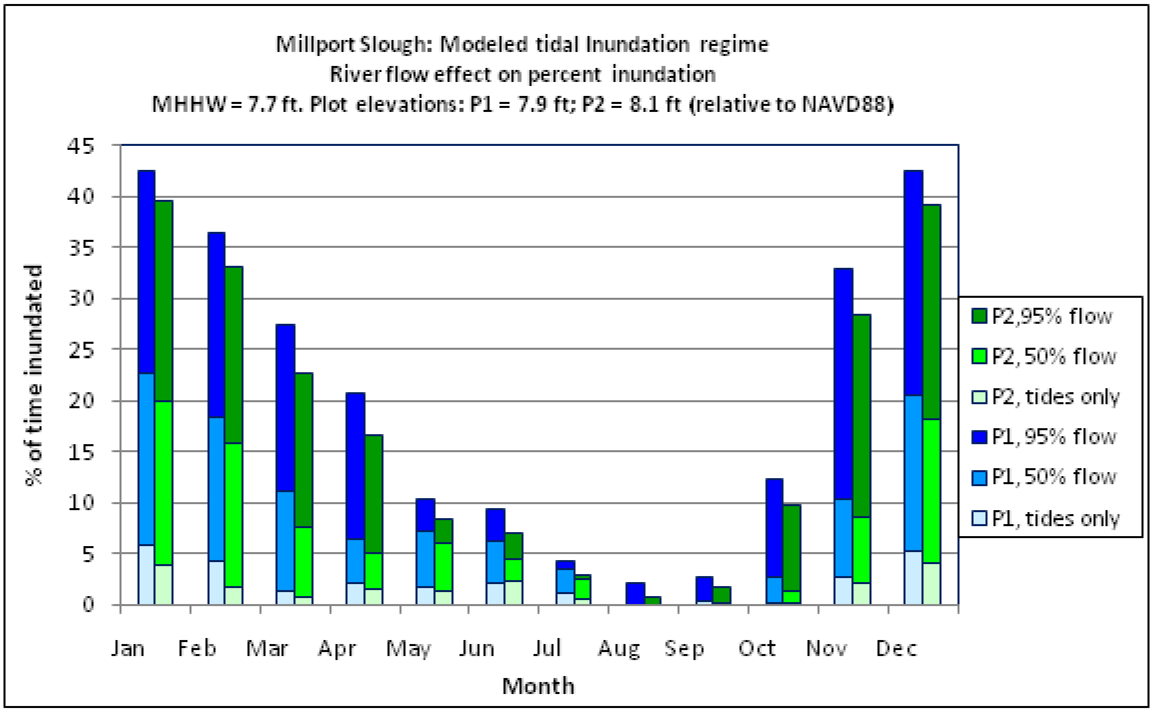


Figure 21. Millport Slough: Effect of river flows on percent inundation.

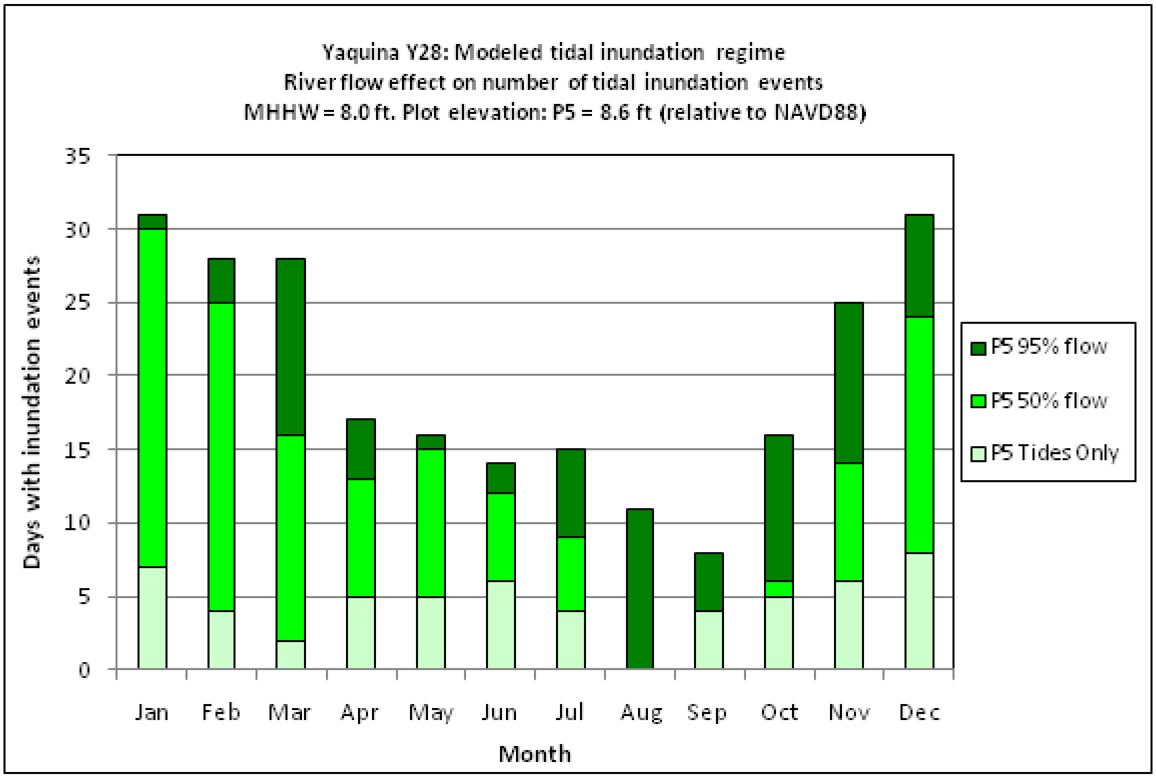


Figure 22. Yaquina Swamp (Site Y28): Effect of river flows on tidal inundation frequency.

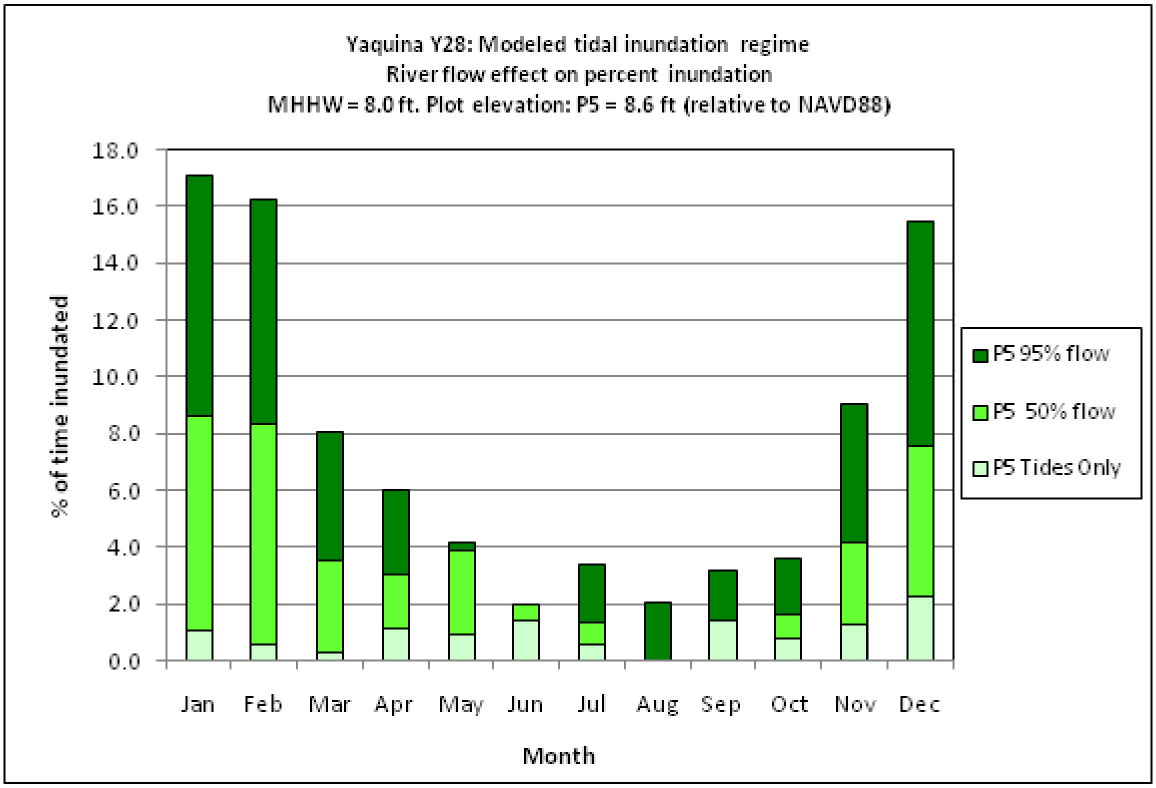


Figure 23. Yaquina Swamp (Site Y28): Effect of river flows on percent inundation.

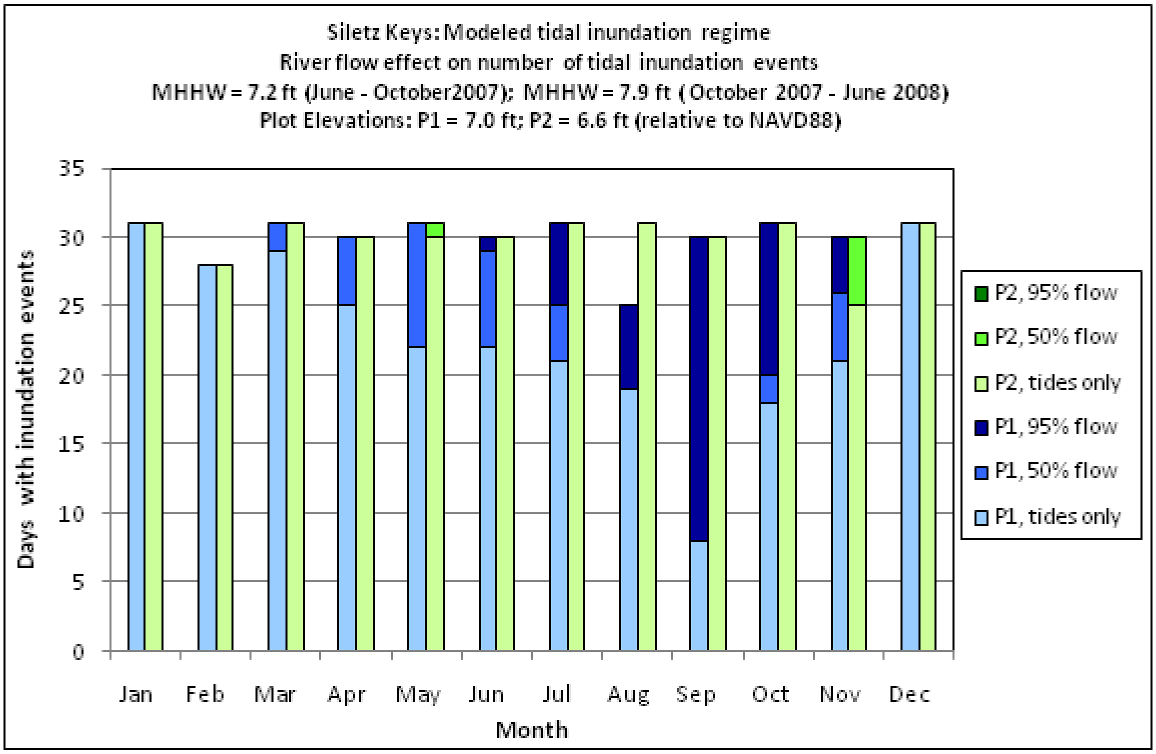


Figure 24. Siletz Keys: Effect of river flows on tidal inundation frequency.

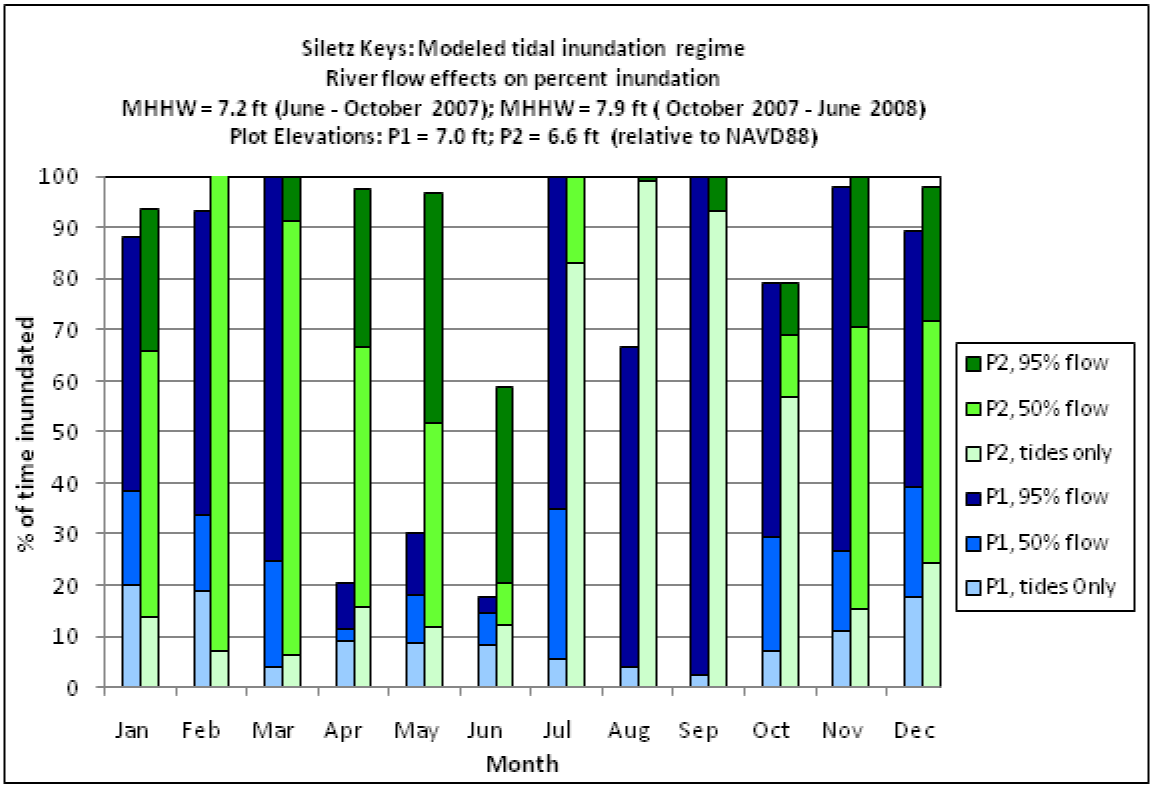


Figure 25. Siletz Keys: Effect of river flows on percent inundation.

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Appendix 10. Fluvial Effects on Coastal Flooding in the U.S. Pacific Northwest

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Fluvial Effects on Coastal Flooding in the U.S. Pacific Northwest

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Abstract: Tidal and fluvial forces can create compound flooding hazards in the U.S. Pacific Northwest because Pacific storms often result in large rainfalls. The total water level (TWL) of astronomical tides and fluvial-induced water levels is used to calculate long-term frequency and duration of inundation in the fluvial system. Our analysis indicates that there is a linear relationship between detided water level elevation and river discharge when river discharge is above a certain stage. By applying 70-year (1940 – 2010) discharge values to the linear relationship, the 70-year time series of TWL is constructed and analyzed. Long term sea-level trends, increased frequency and intensity of storms, variations in rainfall and decadal variations in sea level due to the El Nino Southern Oscillation (ENSO) can also be incorporated in the total water level to predict coastal inundation in similar geomorphologic settings in the Pacific Northwest.

INTRODUCTION

Tidal and fluvial forces can combine to increase flooding hazards in the U.S. Pacific Northwest (PNW), because Pacific storms often result in large rainfalls (Guidelines and Specifications for Flood Hazard Mapping Partners, FEMA, 2004). Inundations are among the more frequent, costly and deadly coastal hazards. In fact, coastal and riverine flooding, hurricanes and tropical storms are together responsible for almost 18% of natural-hazard-related deaths (Borden and Cutter, 2008). Ecological resources are also highly susceptible to inundation. Many coastal wetland plants can only survive within a narrow elevation band in the intertidal zone. This specialization make these species and the highly productive communities they support vulnerable to inundation. Increasing coastal inundation due to climate changes may lead to substantial socio-economic losses such as the loss of coastal structures, damage to buildings and settlements, dislocation of the population, and the loss of agricultural production.

Large amounts of rain and coastal flooding are generally associated with winter storms in the PNW. The most severe coastal impacts are likely to occur under a combination of storm-driven surges, extreme waves lasting for days, intense low-pressure autumn or winter storms, and high tides (Bromirski *et al.*, 2003). In fluvial inland areas, the effects of wave run-up diminish. Freshwater runoff, high tides and storm surge can combine to generate extreme water level elevations. Effective flood management in a lowland fluvial-tidal transitional area requires a method that addresses both fluvial and tidal processes while accommodating current and potentially higher future flood magnitudes and sea levels (Florsheim *et al.*, 2008).

This paper builds upon a method first developed by Burgette *et al*. (2009) and subsequently modified for use in the Siuslaw River estuary of Oregon (Dr. Ray Weldon, personal communication). The method assesses combined tidal and fluvial inundation in estuaries where river flow strongly influences inundation regime along the Oregon coast. The method was initially used in determining coastal uplift rates (Burgette *et al.*, 2009), but it has subsequently been used to guide wetland restoration planning and evaluate restoration results (Brophy, 2009). The methodology can also be extended to inundation risk assessment and coastal zone management. We use a modification of the method in this study, applying the total water level (TWL) of astronomical tides and fluvial-induced water levels to estimate the frequency and duration of inundation over 70 years (1940 – 2010). By understanding the present inundation regime and incorporating the various impacts of climate change, information on future inundation can be obtained for coastal hazards assessment and mitigation.

METHODOLOGY

The current project was funded by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), with collaboration from NOAA/National Geodetic Survey (NGS) for elevation survey and NOAA/Center for Operational Oceanographic Products and Services (CO-OPS) for water level modeling (Brophy *et al.* 2009, 2011). The study gathered reference data on key physical and biological attributes at six least-disturbed wetland sites to guide restoration planning. Data on these physical and biological attributes are sparse for tidal wetland habitats in Oregon, and nearly nonexistent for "tidal swamps" (forested and scrub-shrub tidal wetlands) (Brophy, 2009). In the PNW, tidal swamps are found in landscape settings where river flow has a major influence on inundation regime. Therefore, incorporating river effects into the inundation analysis will be particularly important for developing accurate reference data for PNW tidal swamps.

To analyze the fluvial effects on water level elevation, five Onset HOBO U20 water level loggers were installed at Blind Slough, Coal Creek, Millport, Yaquina and

Siletz Keys to measure water levels between June 28, 2007 and June 27, 2008. This paper focuses on the Coal Creek data as an example. Coal Creek is an estuarine forested wetland located in the upper Nehalem River estuary of Oregon USA (Figure 1). The site is fully characterized in the CICEET project report (Brophy *et al.*, 2011).

HOBO loggers measure pressure, so when they are inundated with water, pressure on the sensor increases. After compensation for barometric pressure, the pressure readings can then be converted to water depth. The HOBO water level gauges at all sites were out of water at low tide; therefore the data show a flat "baseline" between high tides. The project areas have a very strong seasonal inundation pattern, with high winter rainfall and low precipitation during summer months.

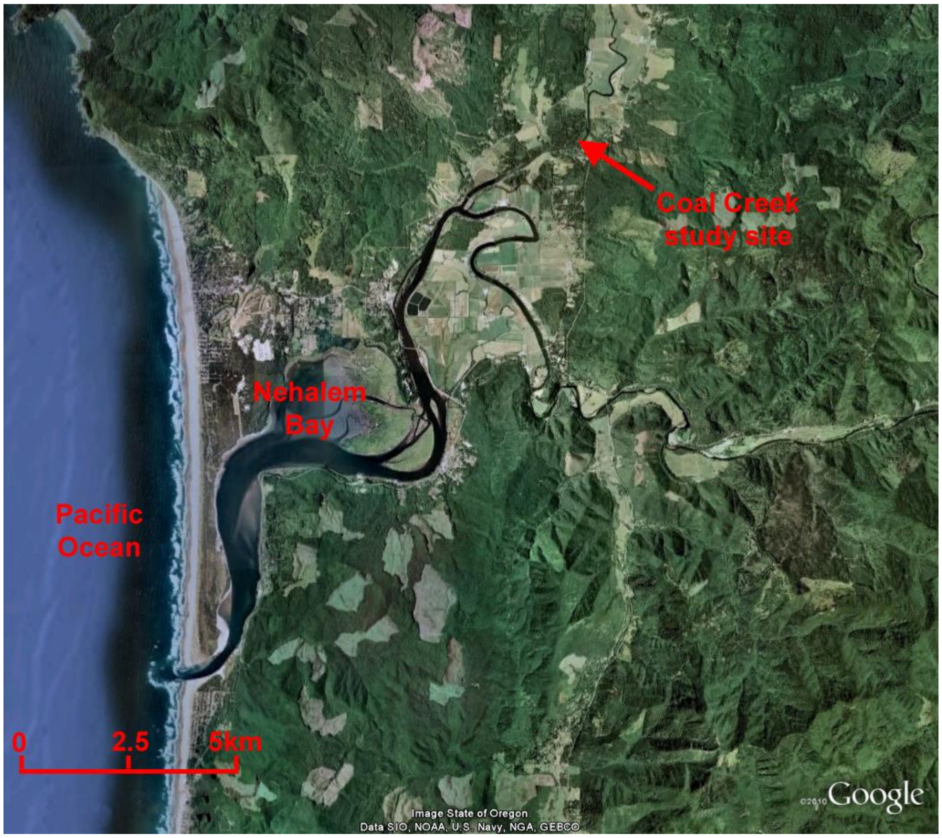

Figure 1. Coal Creek study site, Nehalem River estuary, Oregon USA

Tides in the project areas are mixed, mainly semidiurnal with a large diurnal inequality in higher high and lower high waters and/or higher low and lower low waters. The Great Diurnal Range (GT) is about 2.5 m. GT is the difference in height between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW). The water level sensors were leveled to reference points with known elevations of North America Vertical Datum of 1988 (NAVD88) and thus sensor "zeros" can be related to NAVD88 at each location. Tidal datums at the 5 stations were calculated by simultaneous comparison with the long-term stations operated and maintained by CO-OPS to get the equivalent 19-year National Tidal Datum Epoch (NTDE) datum (NOAA, 2003). The CO-OPS station at Astoria 943-9040 was used to control Blind

Slough, Garibaldi 943-7540 to control Coal Creek and South Beach 943-5380 to control Yaquina, Millport and Siletz Key. MHHW datum was used as the reference datum to analyze the frequency and duration of inundation.

In order to study the effects of lower frequency phenomena on tidal records, it is advantageous to first filter out the energy at tidal frequencies. A Doodson 39-hour Filter method was used to eliminate tidal energy from observed water level data. The Doodson Filter is one of the earliest and most commonly applied tidal filters, used to eliminate tidal energy from observed water level data (Parker, 2007). The Doodson Filter eliminates 99.94% of the tidal energy at the semidiurnal frequencies, 99.79% of the tidal energy at the diurnal frequencies and 99.38 % of the tidal energy at the overtide frequencies (Grove, 1955). The residual water level data only contains non-tidal energy such as wind and river runoff. During the Great Coastal Gale of December 2007, the maximum observed water level was 4.330 m above NAVD88 and 1.889 m above MHHW and the corresponding detided water level elevation was 3.947 m above NAVD88 and 1.506 m above MHHW (Figure 2) at Coal Creek.

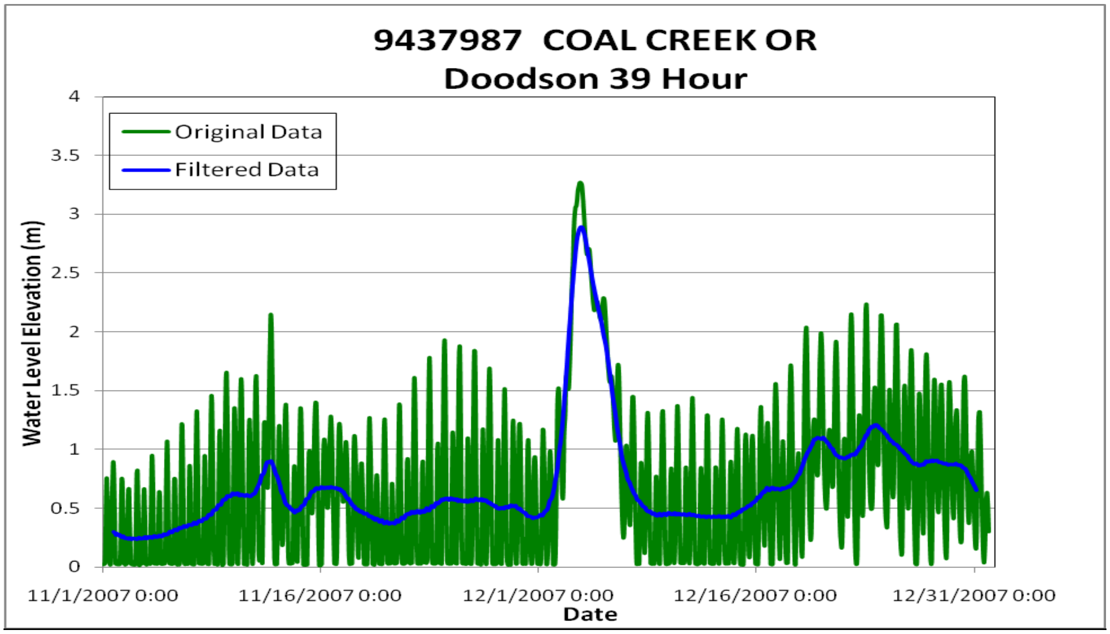

Figure 2. The measured water level data and the filtered (detided) data at Coal Creek. The baseline (sensor elevation) is 1.076 m above NAVD88

As illustrated in Figure 2, the river flow effect on the inundation regime is prominent at Coal Creek, and this is observed in many Oregon estuaries. Therefore, it is important to determine the fluvial contribution to water level elevation. To determine the fluvial contribution, the daily mean river discharge data (cubic feet) was obtained from U.S. Geological Survey (USGS) river gauge 14301000 on the Nehalem River near Foss, OR, which is located above head of tide (Figure 3). Comparison of the detided water level measured by tide gauge at Coal Creek (Figure 2) and the Nehalem River discharge at the USGS gauge near Foss (Figure 3) shows a strong relationship between the two datasets.

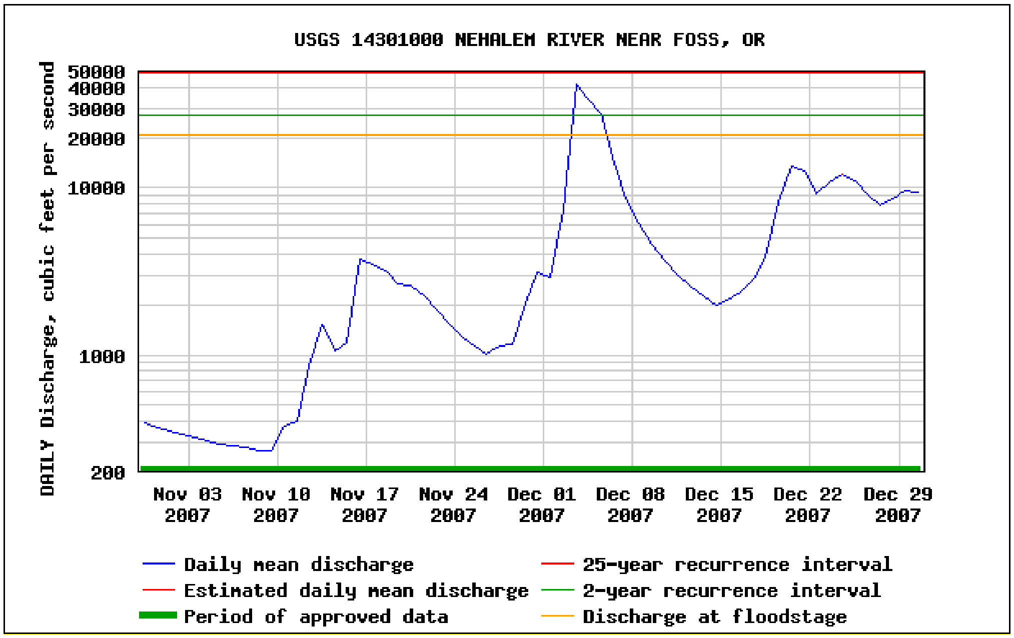

Figure 3. Daily mean river discharge at USGS gauge 14301000 (Nehalem River near Foss, OR) between November 1 and December 31 , 2007

The detided data was then plotted against normalized, log10-transformed river discharge data for the period of observation. “Normalized” means discharge relative to average summer low discharge, that is, summer low discharge is subtracted from each flow value to get the normalized discharge value (Brophy, 2009). As shown in the scatter plot, there was a linear relationship between detided water level elevation and river discharge at river discharges above 3.5 lg(ft^3) or 3,610 ft^3 at Coal Creek (Figure 4). A similar pattern was present at Millport Slough, Yaquina Swamp, and Siletz Keys. (The scatter plot at Blind Slough, however, did not show a linear relationship, probably due to the large river and watershed system). The linear equation at Coal Creek is:

$$y = 1.40x - 4.50 \qquad (1)$$

Where x is the daily mean river discharge (for discharge values above 3,610 ft^3), and y is the detided water level elevation. R^2 equals to 0.73. Based on this equation, the water level elevation due to river discharge can be calculated.

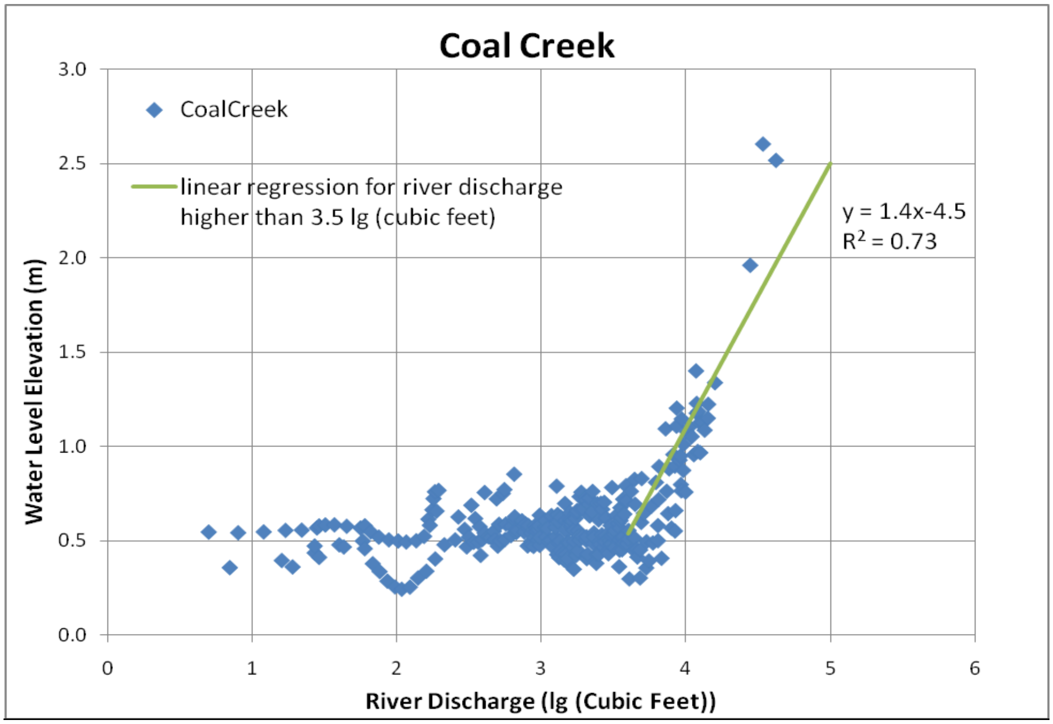

Figure 4. Detided water level elevation plot against normalized, log10-transformed river discharge at Coal Creek

The relationships established in equation (1) using one year of data were then used to estimate the relationship for the desired longer 70-year period. A 70-year (1940 – 2010) series of astronomical tides at Coal Creek, OR was generated using harmonic consituents at the CO-OPS station at Garibaldi, OR. Daily mean river discharge values in cubic feet for the same 70-year period were retrieved from USGS gauge 14301000 (Nehalem River near Foss, OR). The corresponding water level elevations were calculated according to equation (1). The 70-year time series of TWL was contructed by adding the water level elevations derived from river discharge to the astronomical tides. Comparison of the modeled TWL for 2007 - 2008 and observations during that period shows a good match between the two datasets (Figure 5). Figure 6 shows a one-year (2009 ~ 2010) time series of modeled astronomical tides, water level elevations from river discharge, and TWL at Coal Creek.

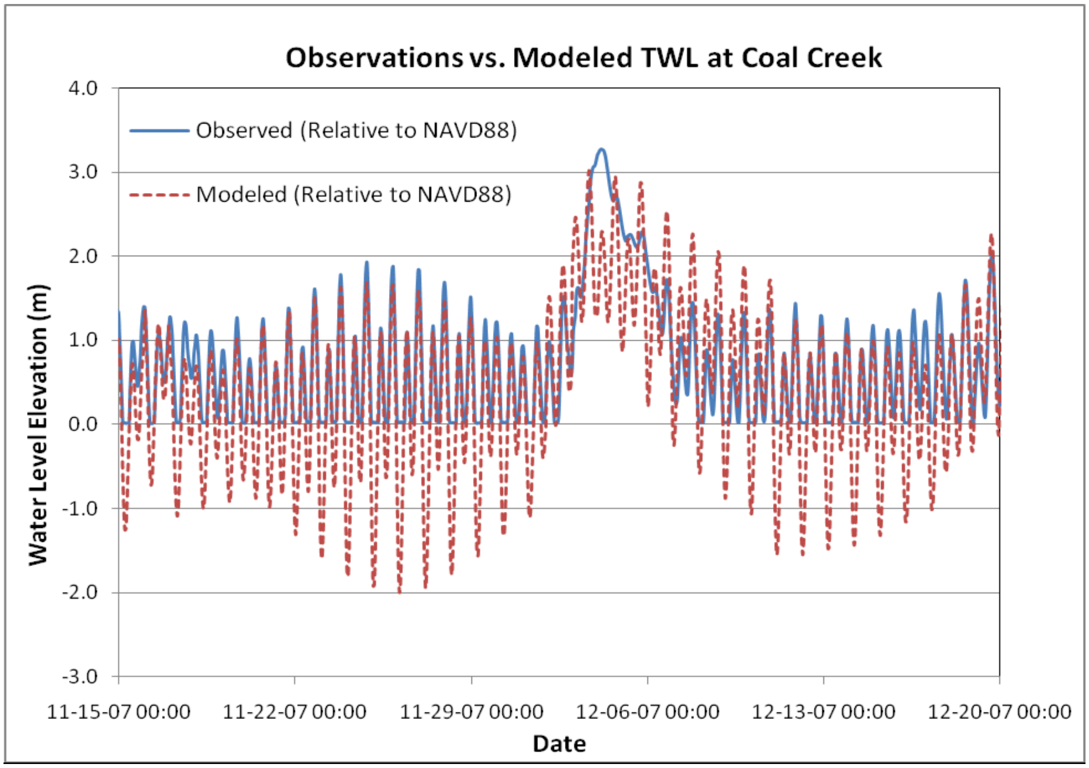

Figure 5. Comparison of the modeled TWL and observations between 2007 and 2008

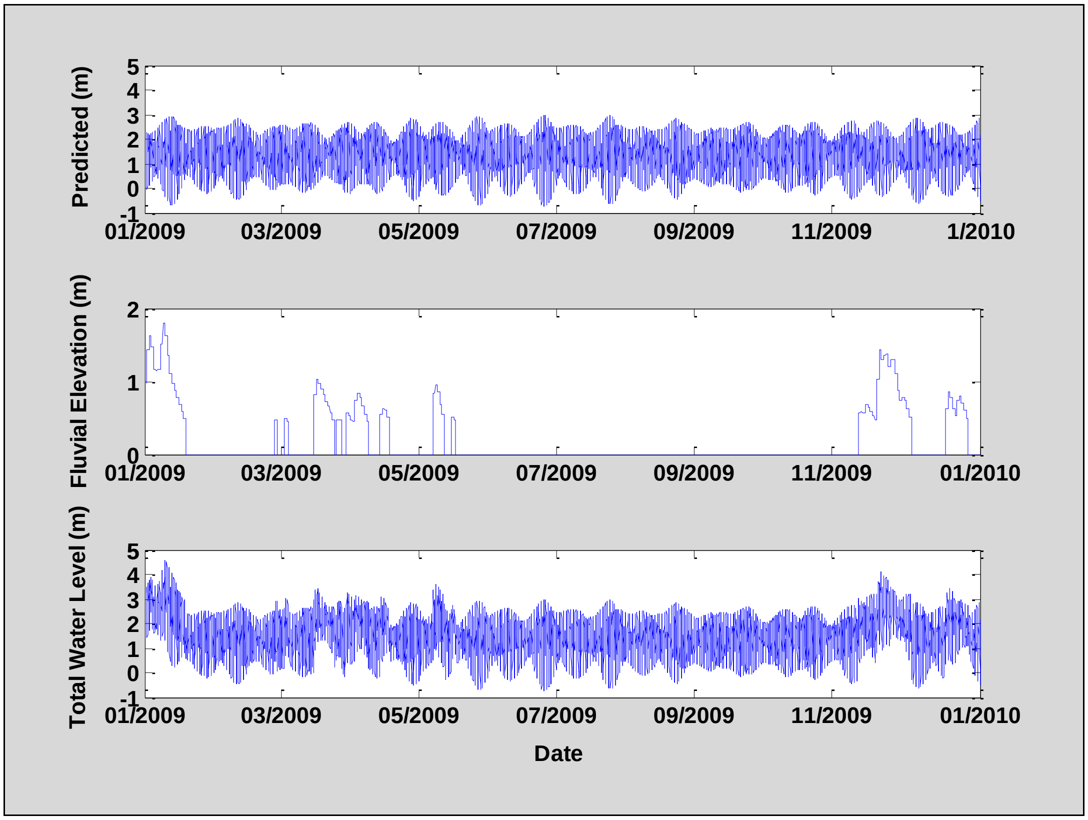

Figure 6. One-year (2009~2010) time series of modeled astronomical tides, fluvial water level elevations, and total water level at Coal Creek

RESULTS

The frequency and duration of inundation events above critical elevations are important to assess the impacts caused by inundation. For this analysis, MHHW was used as the critical elevation. The NOAA frequency and duration of inundation algorithm examines tabulated water level data relative to a user-specified datum (tidal, geodetic, or some specific vertical reference, such as a marsh surface or levee) to create a table of inundation events over a given period of time. The analysis results include frequency of inundation (defined as the number of times the tide rose above the critical elevation), duration of inundation (length of time that the water level remained above the critical elevation during each inundation event), and the relationship between duration and elevation of inundation. There were approximately 63,271 hourly TWL above MHHW over the 70 years being modeled. In the two figures below, Figure 7 shows the frequency of elevations above MHHW between 1940 and 2010. 90% of inundation elevations are within 1.0 m relative to MHHW, and 99% of inundation elevations are within 1.5 m relative to MHHW. Figure 8 is the plot for the same time period showing the distribution of duration for each inundation event above MHHW. 90% of these inundation events have durations under 6 hours, and 99% of these inundation events have durations under 8 hours.

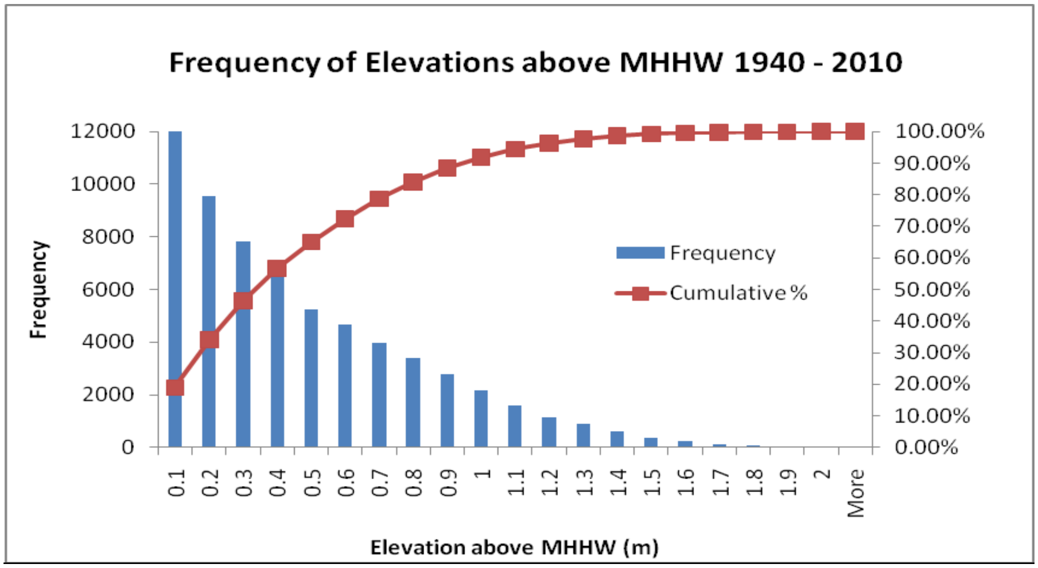

Figure 7. Modeled frequency of water level elevations above MHHW at Coal Creek between 1940 and 2010

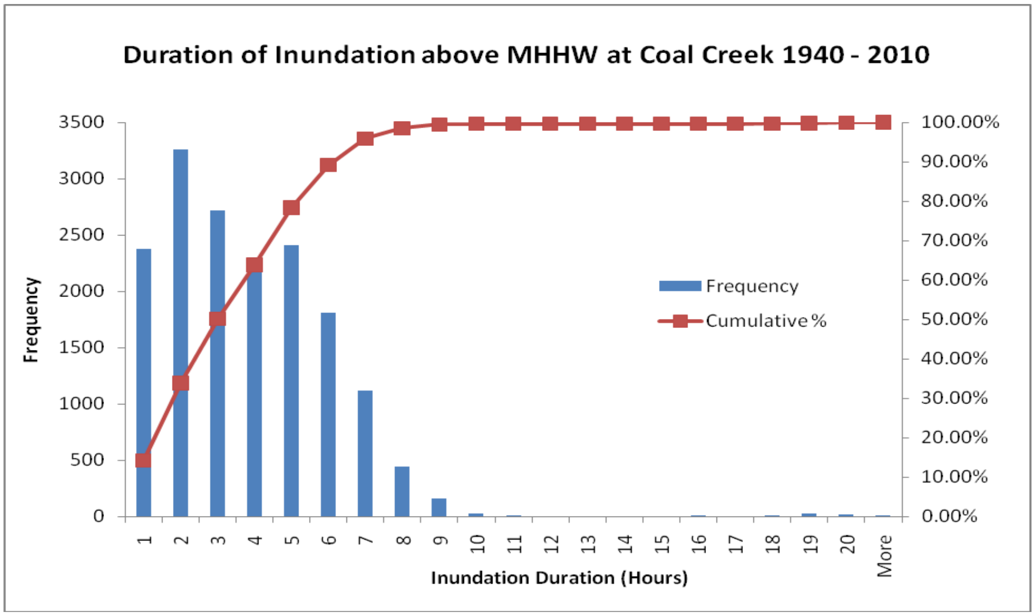

Figure 8. Modeled duration of water level inundation events above MHHW at Coal Creek between 1940 and 2010

As mentioned above, tidal and fluvial forces can combine to increase flooding hazards in the lowland fluvial-tidal transitional area. The modeled inundation frequency at Coal Creek (a lowland fluvial-tidal transitional area) was simultaneously compared with the observed inundation frequency at a NOAA coastal tide station (South Beach, OR). The observed water levels at the South Beach station, which is located at the entrance of Yaquina Bay, OR, represent tides along Oregon Coast. There were approximately 20,598 observed hourly heights above MHHW over the 44 years (February, 1967 – December, 2010) at South Beach and 38,275 hourly TWL above MHHW during the same time period at Coal Creek. Not only is the number of high waters above MHHW at Coal Creek much higher than at South Beach, but the water level elevations are also much higher (Figure 9). The blue (dotted) curve for Coal Creek shows over 40% of the inundation elevations higher than 0.45 m above MHHW. The green (solid) curve for South Beach shows only 10% of the inundation elevations higher than 0.45 m above MHHW.

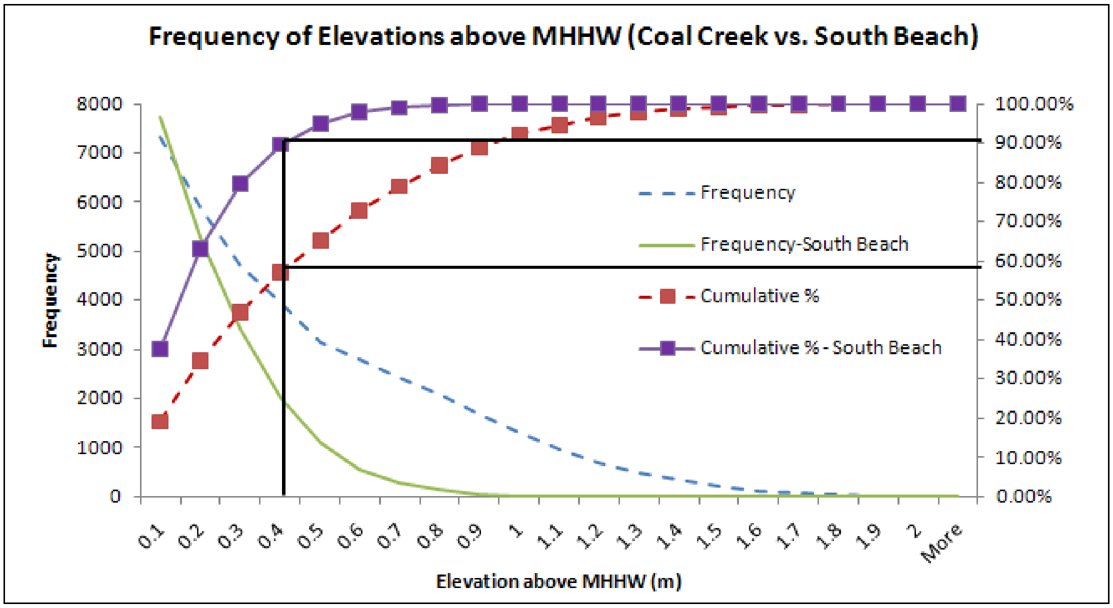

Figure 9. Distribution of inundation elevations above MHHW datum at Coal Creek (modeled) and South Beach (observed) for February 1967 – December 2010

DISCUSSION

This approach provides more thorough analysis of inundation in the lowland fluvial-tidal transitional area in the PNW, where both tides and river runoff can contribute to water level elevations. The results indicate that the lowland fluvial-tidal transitional area gets inundated more frequently, and with higher water level elevations, compared to the corresponding coastal area. We recommend validation of the linear relationship between river discharge and water level elevation when river discharge is above a certain stage in other estuaries with similar geomorphologic settings.

Long-term sea level rise and increasing storminess have the potential to exacerbate the frequency and duration of inundation in lowland fluvial-tidal transitional areas. In the last 10 years, many rivers in the PNW have experienced flooding levels at increased frequency and magnitude, most likely due to climate changes and variability associated with long tem sea-level rise, increased frequency and intensity of storms, variations in rainfall and decadal variations in sea level due to the El Nino Southern Oscillation (ENSO). Our model indicates that exteme inundation events (longer than 16 hours above MHHW) may have been more frequent in the past two decades (Figure 10).

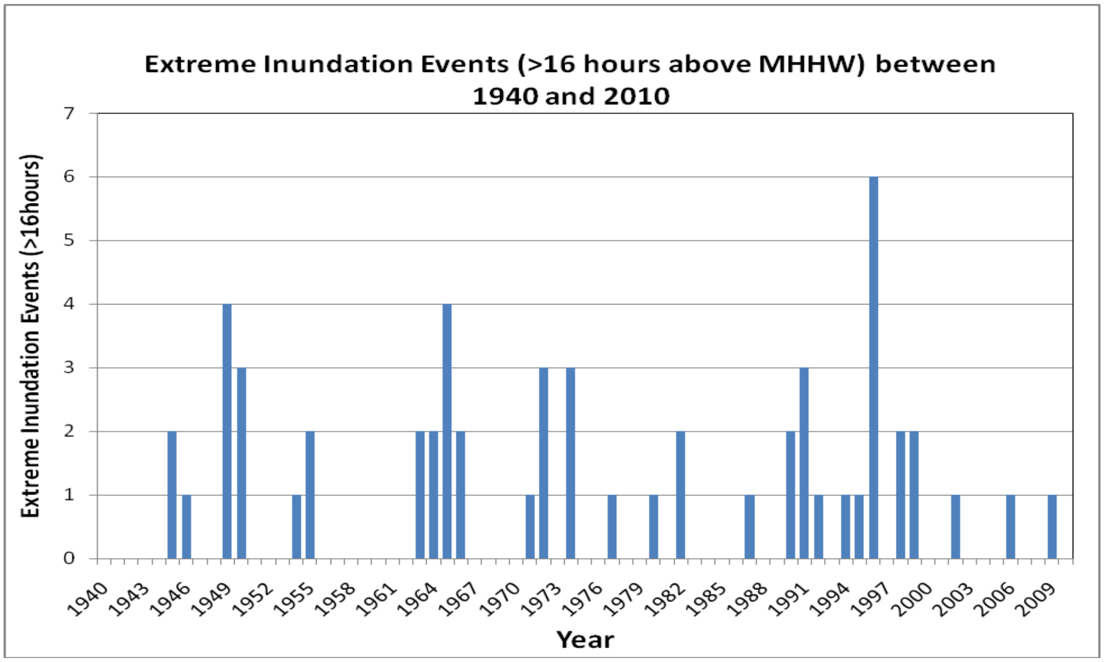

Figure 10. Modeled extreme inundation events (>16 hours above MHHW) at Coal Creek between 1940 and 2010

Using the above model, potential changes in TWL associated with climate change scenarios can be computed, along with corresponding inundation scenarios. For example, the relative sea level trend at Garibaldi is presently rising at a rate of 1.98 mm/year with a 95% confidence interval of +/- 1.82 mm/year, based on monthly mean data from 1970 to 2006 (Zervas, 2009). Long-range streamflow forecasts can also be incorporated in the linear relationship to predict TWL and potential flooding. The results may be useful to coastal resource managers and policymakers in decision-making relative to land use planning, flood control, wetland restoration, and other coastal zone actions.

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Appendix 11. Benthic Invertebrates at CICEET Study Sites

Prepared by Ayesha Gray, Cramer Fish Sciences

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Introduction

Macroinvertebrates have been used to characterize ecosystems and infer ecological health by comparing abundance, and taxonomic and functional composition between reference and restored conditions. Since invertebrates have a variety of physiological needs, their presence or absence reflects the condition of the surrounding environment, and for this reason they have been thought of as integrators of ecosystem variability and possible descriptors of ecosystem function. Biotic metrics have been used to assess the condition of freshwater aquatic environments (Karr and Chu 1999) and groups of indicator species, or assemblages, have been used to determine biotic integrity (Karr 1987). Invertebrates, as biotic indicators, represent popular "litmus" tests for determining ecosystem status and state, and have been widely applied with a variety of taxa in many different ecosystems (Carignan and Villard 2002). Dufrene and Legendre (1997) developed analysis techniques to determine wetland characteristics with invertebrate indicators. Invertebrates may make useful indicators of reference tidal wetland condition as they are strongly influenced by environmental variation and react mainly to disturbances on fine spatial scales (Carignan and Villard 2002). Invertebrate communities have often been used to compare conditions among disturbed, restored and reference wetland sites (Greenwood *et al*. 1991; Lerberg *et al*. 2000; Zajac and Whitlatch 2001; Craft *et al*. 2002). Single species and assemblages of a variety of insects have been used to determine environmental condition and change in habitats ranging from forests to grasslands to urban areas and mine sites (McGeoch 1998). Determining reference conditions in terms of invertebrate assemblage characteristics may help natural resource managers in the Pacific Northwest better understand restoration targets and success.

This study was a component of a larger project (Brophy *et al.* 2011) which tested innovative methods to measure key habitat drivers (elevation, inundation regime, salinity, groundwater level) and related those habitat conditions to physical and biological characteristics (soil characteristics, vegetation cover, woody stem density and basal area, and invertebrate assemblages) of the study sites. These datasets are of significant value, particularly for scrub-shrub and forested intertidal wetlands ("tidal swamps"), for which physical and biological data are almost completely lacking (Brophy 2009, Brophy *et al.* 2011). The tidal swamp data gap is a significant problem for restoration practitioners, since tidal swamps constitute important restoration targets due to their disproportionate loss to coastal development (Graves *et al*. 1995, Brophy 2005).

Interpretation of macroinvertebrate community composition and abundance depends on robust experimental design and careful statistical analysis, as these communities are known to have extreme spatial and temporal variability. This study of macroinvertebrates in least-disturbed tidal wetlands on the Oregon coast helped meet the larger project's objectives by determining relationships between key habitat drivers and biological structure at each site, and by contributing to a pilot reference conditions database for use by future restoration practitioners.

Methods

Experimental Design and Field Sampling

In July 2007, we collected 15 replicate samples (90 total) from four habitat types (low marsh, high marsh, scrub-shrub, and forested tidal wetlands) at the six CICEET study sites described in Brophy *et al*. (2011). One benthic invertebrate sampling module (10 X 10 m) was established within each habitat type at each site; sampling modules were located near permanent study plots. Our sampling procedures followed the Estuarine Habitat Assessment Protocol (Simenstad *et al.* 1991) for benthic invertebrates. Benthic invertebrates were sampled from dewatered channel sediments using a 6.35-cm diameter plastic corer. Cores were taken to a depth of 5 cm for a total volume of 160.8 cm^3. Exact sampling location was randomized within the module boundaries using a random number table and grid, and location of the grid was recorded using a Trimble ProXR GPS. We retained samples in labeled sample jars, and fixed them in the field with a 10% solution of buffered formalin. We analyzed the number of taxonomic groups represented in our replicated samples following methods described in Hurtubia (1973) to determine the optimum number of samples for each site. In July 2008, we collected 12 replicate samples (72 total) from 5 of the 6 sites sampled in 2007, using the same methods as in 2007. The 2008 sampling omitted the Blind Slough scrub-shrub wetland since the nature of the substrate (dense root fibers) made it impossible to find appropriate substrate from which to collect core samples.

Laboratory Setup and Processing

In September 2007, two experienced laboratory technicians were given a 1 ½ day refresher course conducted by Ayesha Gray (Cramer Fish Sciences) at the South Slough NERR Estuarine and Coastal Lab in Charleston, OR. Training included proper handling of samples, identification of invertebrates, microscope photography and graphic file exchange (to verify identification), and database development. In the laboratory, sample contents were washed through a 0.5 mm sieve to remove fine particulates and retain macrofauna. Samples were then be transferred to water or isopropanol (depending on length of time until organism identification), and stained with Rose Bengal (a biological dye). After 24 hours in dye, using a light dissecting scope, all organisms were counted and identified to the finest taxonomic resolution possible without dissection, generally family or species identification for most common estuarine invertebrates. Unknown organisms were photographed and identified by Cramer Fish Sciences personnel or Jeff Cordell (University of Washington) from images and voucher specimens.

Statistical Analysis

In total 162 samples were processed (90 from 2007 and 72 from 2008). Data were collated and stored in a Microsoft Access database and analyzed as described below. Statistical analysis focused on characterizing total abundance, taxonomic richness, percent composition, assemblage structure and presence of indicator taxonomic groups. Abundance results were determined as the number of invertebrates per sample, and taxonomic richness was measured as the total number of taxonomic groups (separating life stages) per sample. Invertebrate assemblage characteristics were explored using multivariate statistics: nonmetric multidimensional scaling (NMDS) and analysis of similarity (ANOSIM) using PRIMER 6.0 (Clarke and Gorley 2006). Among multivariate statistics, NMDS is an especially powerful technique for determining assemblage differences among ecological data. Data are log transformed and taxonomic groups accounting for less than 3% of any sample are discounted. NMDS graphically plots differences in invertebrate assemblages in ordination space (axes with no scale) based on the Bray-Curtis similarity matrix.

ANOSIM ("analysis of similarities") looks for differences between groups of community samples (defined *a priori*), using permutation/randomization methods. ANOSIM is a statistical test to determine significant differences among groupings delivered by NMDS, and returns a p-value (similar to ANOVA); $p < 0.10$ represents significance at the 90% confidence level. An R value, scaled between -1 and +1, is also reported, with 0 representing no difference and a value of 1 representing biological difference among samples. Following standard practice, we considered comparisons with R values over 0.4 and p-values < = 0.1 to be significantly different, and those with R values under 0.4 and p-values < = 0.1 were considered to have no significant difference. Indicator analysis (INDVAL) developed by Dufrene and Legendre (1997) was used to identify “indicator species” using PC-ORD software (McCune *et al*. 2002). Indicators can be compared among sites and with indicators of ecosystem state as identified in Gray (2005). Specific indicators may provide information on site characteristics in terms of invertebrates.

Results

Based on data obtained from 162 processed samples, we have evaluated total abundance, taxonomic richness, percent composition, invertebrate assemblage patterns, and indicator species. Total abundance, taxonomic richness, and percent composition were summarized by year and site (Figures 1 and 2). Total abundance was highest at Hidden Creek Low Marsh in both sampling years, and lowest in the shrub and forested wetlands. Taxonomic richness was also highest in the Hidden Creek Low Marsh, but comparable with all other sites except Coal Creek Forested Wetland, where taxonomic richness was lower. Taxonomic richness at the Coal Creek site was low due to the predominance of New Zealand mudsnails (*Potamopyrgus antipodarum;* non-native, invasive). New Zealand mudsnails made up over 50% of the sample in 2007, and over 90% in 2008 (Figure 2).

A statistical comparison of percent composition is provided by the multivariate statistics and NMDS plots for both years (Figure 3). NMDS plots showed that assemblage structure was similar for high and low marshes, while the shrub and forested wetlands were significantly different from each other and from the high and low marshes. Based on ANOSIM (Table 1), most pair-wise site comparisons showed significant differences in invertebrate assemblages. Non-significant comparisons were the Hidden Creek High Marsh compared with the Millport Slough High Marsh and Siletz Keys Low Marsh, the Millport and Siletz Keys sites compared to each other, and the Blind Slough shrub wetland compared with the Blind Slough forested wetland.

The INDVAL analysis provided repeatable indicators across the two sample years at all sites, except for Siletz Keys Low Marsh (Table 2). New Zealand mudsnails were identified as the only indicator at the Coal Creek site in both years. Indicators at Blind Slough Plot 1 (forested wetland) included the common bivalve, *Macoma* spp., and the brackish-water isopod, *Caecidotea* spp. Indicators at the two high marsh sites were different with Hidden Creek having isopods and the non-native amphipod *Grandidierella japonica*, and Millport Slough having flatworms and polychaetes. Several indicators were identified in the Hidden Creek Low Marsh sites, including nematodes, the free-living estuarine anemone, and diptera larvae. Only the ostracod was identified as an indicator (2008) at the Siletz Keys Low Marsh sites. No indicators were found in 2007 at the scrub-shrub Blind Slough Plot 2 (scrub-shrub wetland), and this wetland was not sampled in 2008.

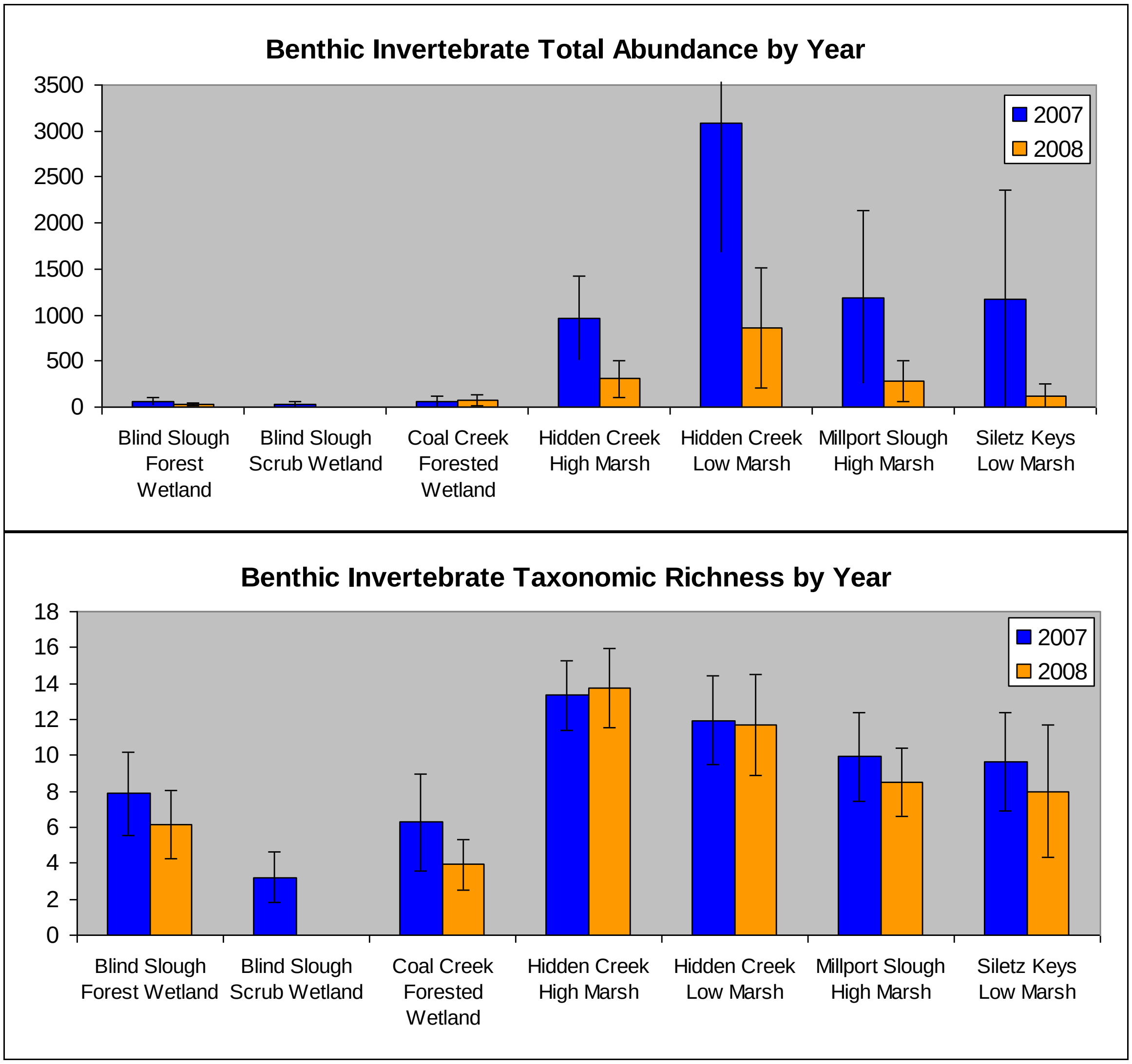

Figure 1. Total abundance (above) and taxonomic richness (below) in each sampling year. Note: Blind Slough Plot 2 (scrub-shrub wetland) was not sampled in 2008.

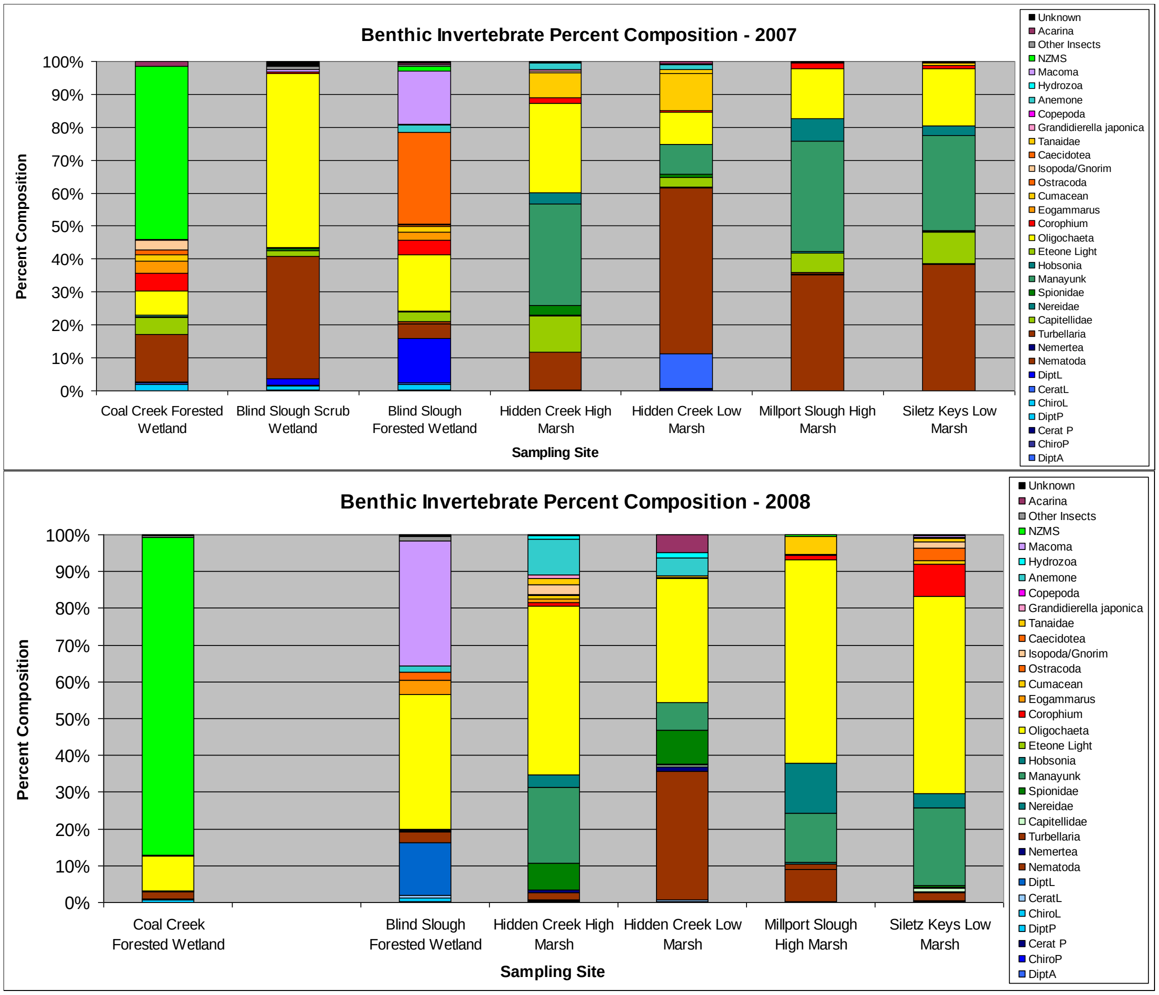

Figure 2. Average percent composition of benthic invertebrate samples from 2007 and 2008. Note: Blind Slough Plot 2 (scrub-shrub wetland) was not sampled in 2008.

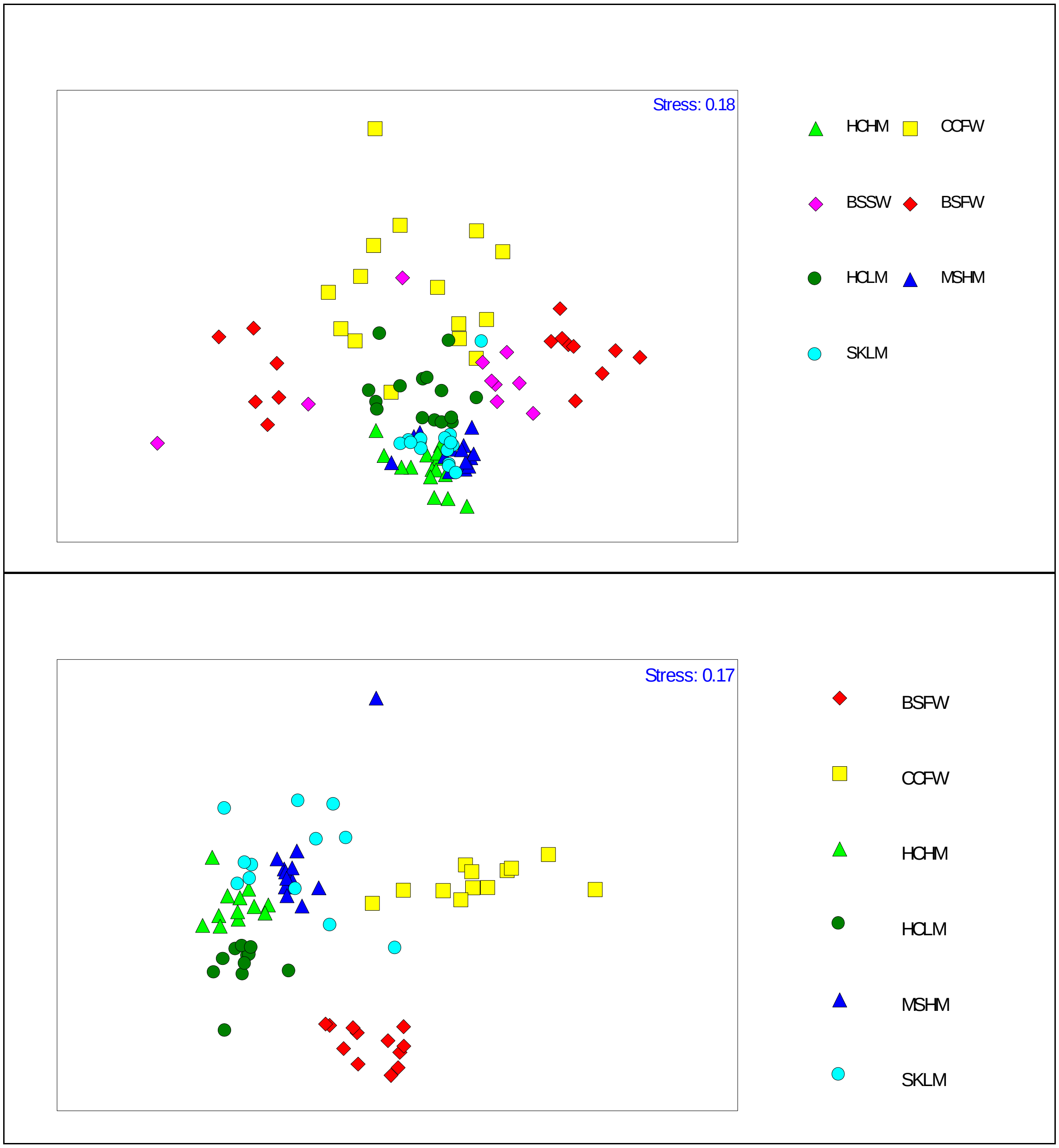

Figure 3. NMDS multivariate analysis plots the relative position (in terms of abundance and composition of taxonomic groups) of each sample in 2007 (above) and 2008 (below). Site abbreviations: Hidden Creek High Marsh (P3 and P4)=HCHM; Hidden Creek Low Marsh (P1 and P2)=HCLM; Millport Slough High Marsh=MSHM; Siletz Keys Low Marsh=SKLM; Blind Slough Scrub Wetland (P2)=BSSW; Blind Slough Forested Wetland (P1)=BSFW; and Coal Creek Forested Wetland=CCFW.

Table 1. ANOSIM results for NDMS analysis. Bold type indicates pairwise comparisons that are not significantly different. Abbreviations: Hidden Creek High Marsh (HCHM); Hidden Creek Low Marsh (HCLM); Millport Slough High Marsh (MSHM); Siletz Keys Low Marsh (SKLM); Blind Slough Scrub-shrub Wetland (BSSW); Blind Slough Forested Wetland (BSFW); and Coal Creek Forested Wetland (CCFW).

	2007		2008	
Groups	**R value**	**P value**	**R value**	**P value**
HCHM, CCFW	0.819	0.1	0.994	0.1
HCHM, BSSW	0.814	0.1		
HCHM, BSFW	0.555	0.1	0.997	0.1
HCHM, HCLM	0.699	0.1	0.769	0.1
HCHM, MSHM	**0.291**	**0.1**	0.731	0.1
HCHM, SKLM	**0.225**	**0.1**	0.477	0.1
CCFW, BSSW	0.526	0.1		
CCFW, BSFW	0.507	0.1	0.996	0.1
CCFW, HCLM	0.763	0.1	0.981	0.1
CCFW, MSHM	0.812	0.1	0.925	0.1
CCFW, SKLM	0.746	0.1	0.939	0.1
BSSW, BSFW	**0.319**	**0.6**		
BSSW, HCLM	0.651	0.1		
BSSW, MSHM	0.756	0.1		
BSSW, SKLM	0.631	0.1		
BSFW, HCLM	0.536	0.1	0.996	0.1
BSFW, MSHM	0.559	0.1	0.941	0.1
BSFW, SKLM	0.530	0.1	0.888	0.1
HCLM, MSHM	0.775	0.1	0.841	0.1
HCLM, SKLM	0.618	0.1	0.766	0.1
MSHM, SKLM	**0.069**	**7.7**	**0.330**	**0.1**

Table 2. INDVAL indicators identified at each sampling site, highlighted names were consistent indicators between years.

2007 INDVAL Indicators (value >40%)

Coal Creek Forested Wetland	Blind Slough Forested Wetland	Hidden Creek High Marsh	Hidden Creek Low Marsh	Millport Slough High Marsh	Siletz Keys Low Marsh
NZMS	*Macoma* spp.	Polychaeta: Spionidae	Nematoda	Turbellaria	
	Isopoda: *Caecidotea* spp.	Isopoda	Anemone	Polychaeta: Nereidae	
		Amphipoda: *Grandidierella japonica*	Tanaidae	Polychaeta: *Hobsonia florida*	
			Diptera: Ceratopogonidae Pupae		
			Diptera: Ceratopogonidae Larvae		
			Acarina		
			Hydrozoa		

2008 INDVAL Indicators (value >40%)

Coal Creek Forested Wetland	Blind Slough Forested Wetland	Hidden Creek High Marsh	Hidden Creek Low Marsh	Millport Slough High Marsh	Siletz Keys Low Marsh
NZMS	*Macoma* spp.	Amphipoda: *Eogammarus* spp.	Nematoda	Turbellaria	Ostracoda
	Isopoda: Caecidotea	Isopoda	Polychaeta: Capitellidae	Polychaeta: Nereidae	
	Diptera: Ptychopteridae	Amphipoda: *Grandidierella japonica*	Polychaeta: Spionidae	Polychaeta: *Hobsonia florida*	
	Diptera: *Bittacomorphella* spp.		Anemone	Cumacea	
			Diptera: Ceratopogonidae Larvae		
			Acarina		
			Nemertea		
			Hydrozoa		

Discussion

This study used macroinvertebrate assemblages to describe ecosystem structure, contributing to the larger study's use of innovative methods to assess key habitat drivers (Brophy *et al*. 2011). Results from this two-year study indicated differences in assemblage structure at reference tidal wetlands and identified repeatable indicators for each site which may be useful in characterizing reference wetland conditions (Dufrene and Legendre 1997). Better understanding of reference conditions may help restoration practitioners interested in recovering habitat function of degraded or impacted tidal wetlands in the Pacific Northwest. While the results are promising, much additional study is needed to conduct a robust characterization of these tidal wetland habitats in terms of macroinvertebrates.

While univariate measures such as total abundance and taxonomic richness demonstrated some differences among sites, i.e. higher abundance and taxonomic richness in emergent tidal marshes versus forested and scrub-shrub wetlands; the multivariate statistical techniques were more powerful at detecting differences in biological structure among sites with similar physical structure. For example, NMDS was able to detect differences among high marsh habitats with similar physical structure in two geographic locations. By looking at overall patterns in assemblage composition a better characterization of habitats may be accomplished and it may be more instructive in determining site-specific environmental differences than univariate measures (Heino 2003). INDVAL was also a useful metric for characterizing biological structure, as it identified specific taxa (indicators) responsible for community level differences. Repeatable indicators determined using this statistical method provided a simple metric for characterizing reference sites and a target for those interested in restoring ecosystem structure, as the procedure can be used to assess restored sites and make comparisons with reference conditions.

Several ecological assessment protocols evaluate macroinvertebrate response to restoration in estuarine marsh environments as they are sensitive indicators of wetland condition (Simenstad *et al.* 1991; Zedler 2001). Similarities in macroinvertebrates have been found by some studies at restored and reference sites, although differences in other organisms such as fish still exist (Moy and Levin 1991). Some species of macroinvertebrates recover in a relatively short time frame (< 5 years), but others (e.g., the snail *Melampus*) may require decades to reach reference densities (Warren *et al*. 2002). Warren *et al.* (2002) determined that invertebrate populations recover at different rates depending on the individual marsh, and that recovery rates are not necessarily related to changes in vegetation. Indicators have been useful in detecting conditions in wetland environments in restored and reference sites (Dufrene and Legendre 1997; Gray 2005). Using studies of macroinvertebrates enables researchers to assess and pinpoint mechanisms of assemblage change when studies are conducted over long periods of time. Few studies have attempted to characterize reference condition of tidal marshes, even though important information on ecosystem condition may be available with detailed study.

Using the indicator assemblage to assess reference wetlands revealed specific characteristics undetected by other methods of evaluation. Coal Creek Forested Wetland was dominated by New Zealand mudsnails in both years of the study; this invasion by a non-native species may have a significant effect on ecosystem function. Kelley (2008) found that mudsnails serve as prey for benthic feeders such as sculpins, but Bersine *et al*. (2008) found that Chinook salmon consumed only very low numbers of mudsnails in the Columbia River estuary. Indicators from the other forested wetland site (i.e., Blind Slough) thought to be unaffected by New Zealand mudsnail invasion were unique from the other sites and may represent more natural condition for these habitat types. Non-native species (i.e., *Grandidierella japonica*) were also detected as indicators at the Hidden Creek High Marsh distinguishing it from the conditions found at the Millport Slough High Marsh (two sites nearly identical in physical structure). However, the impact of invasion from this species may not be as high, because *Grandidierella* function as a prey resource for fish, similar to *Corophium* spp., the native equivalent. Millport Slough High Marsh indicators included polychaetes and flat worms. Indicators at the Hidden Creek Low Marsh also differed from the adjacent high marsh revealing the power of the INDVAL analysis to detect minute differences in biological structure between neighboring sites. No repeatable indicators were detected at the Siletz Keys Low Marsh, indicating more study may be needed to characterize differences in low marsh macroinvertebrate communities.

To inform restoration, a better understanding of reference conditions for tidal marshes is needed. Although many resource managers, funding agencies, policy-makers and scientists often view restoration ecology as more an art than a science -- relying on intuition rather than well-documented knowledge (Michener 1997) -- baseline data will provide information on target conditions for recovery actions and thus improve efforts to restore ecosystem function. Establishing data on reference conditions in tidal marshes is important and requires detailed, robust studies. Macroinvertebrates may be especially difficult to characterize due to their inherent variability and the need for sufficient replication to obtain statistically significant results; however information on community structure in invertebrates may provide a more sensitive descriptor of biological structure and give better inferences on ecosystem function. Ecology-based management of wetland habitats will require long-term monitoring efforts, replicated controls and treatments, and projects designed with definable questions, specific hypotheses, and robust and repeatable measurements (Simenstad *et al*. 2000). An investment in innovative techniques for habitat characterization is important to achieve these goals, and this project provides some pilot information on how analyses of macroinvertebrate community structure may aid restoration practitioners aiming to better understand reference conditions. These methodically collected and analyzed data represent the continuing development of new approaches that can be used to discover useful patterns and links among abiotic and biotic environmental factors.

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Appendix 12. Restoration Practitioner Survey

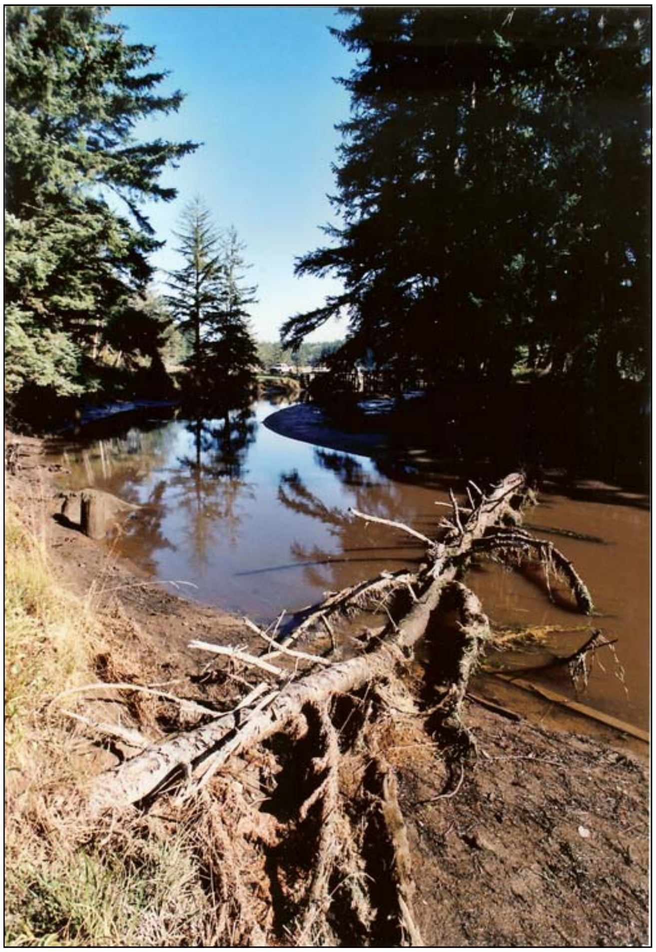
Citation: South Slough National Estuarine Research Reserve (SSNERR). 2007. Pacific Northwest Estuarine Wetland Restoration Information Gaps Survey. Charleston, Oregon. 31pp.

The following report contains summaries and analysis of the results of the Restoration Practitioner Survey conducted by South Slough NERR in September 2007. The following message was sent with the survey link:

> *Dear Restoration Scientists and Practitioners:*
>
> *This is an invitation to participate in a simple, relatively painless on-line survey about a subject near and dear to your hearts: Restoration of estuarine wetland habitats.*
>
> *With your experience conducting, managing, and/or funding habitat restoration planning, design, construction, monitoring and research, you're particularly qualified to help identify information gaps in the science and practice of estuarine wetland restoration and monitoring. With this in mind, we have created a simple on-line survey (see survey link below) designed to identify the information gaps that confound effective project site selection, design, and evaluation. We also want to know about your use of reference sites, what estuarine wetland habitat types are most commonly the focus of habitat restoration and mitigation projects, and what habitat types are in need of more attention (as well as some other things).*
>
> *The results of this survey will be shared widely and used as a resource for recommending new, or refining existing research priorities for regional habitat restoration programs and for helping direct the focus of regional restoration science initiatives. The goal is to improve the effectiveness of habitat restoration and monitoring efforts in the Pacific Northwest. Thanks in advance for completing the survey (estimated time to completion: 20-25 minutes).*
>
> *** *The address list on this e-mail is by no means all-inclusive. Please forward this survey to any groups or individuals you feel should contribute their thoughts to this effort.*
>
> *Thanks!*

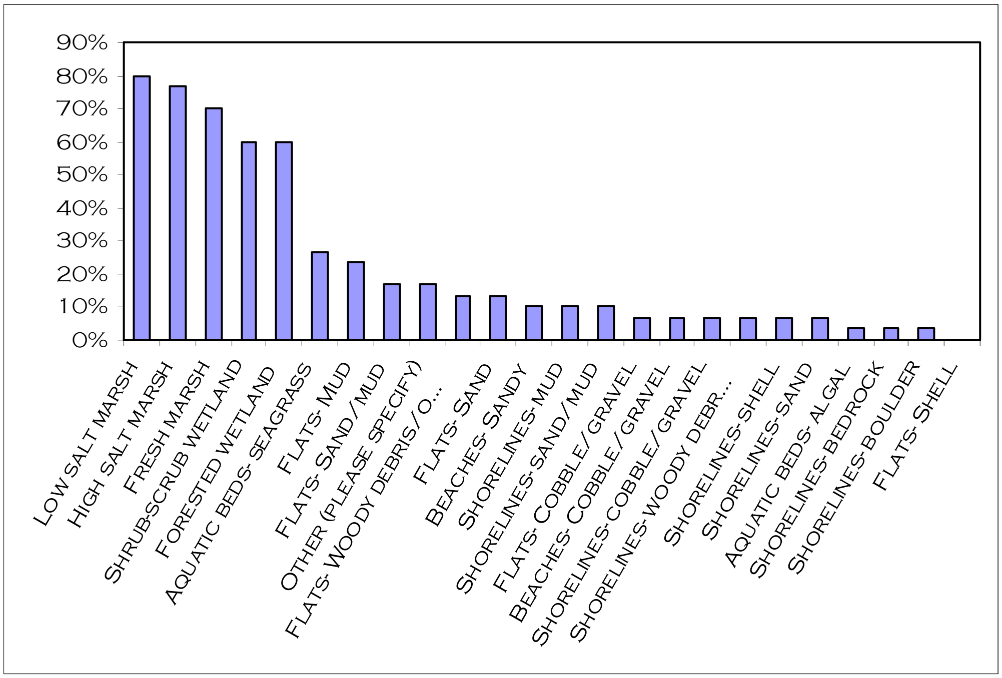
South Slough
National Estuarine Research Reserve

Pacific Northwest Estuarine Wetland Restoration Information Gaps Survey



Restoration Advisory Group meeting
July 10-12, 2007
South Slough Interpretive Center
Charleston Oregon

1) What habitat types are the focus of the habitat restoration activities with which you've been involved?



Low salt marsh	80.00%	24
High salt marsh	76.67%	23
Fresh marsh	70.00%	21
Shrub-scrub wetland	60.00%	18
Forested wetland	60.00%	18
Aquatic beds- seagrass	26.67%	8
Flats- Mud	23.33%	7
Flats- Sand/mud	16.67%	5
Other (please specify)	16.67%	5
Flats- Woody debris/org	13.33%	4
Flats- Sand	13.33%	4
Beaches- Sandy	10.00%	3
Shorelines- mud	10.00%	3
Shorelines- sand/mud	10.00%	3
Flats- Cobble/gravel	6.67%	2
Beaches- Cobble/gravel	6.67%	2
Shorelines- cobble/gravel	6.67%	2
Shorelines- woody debris/org	6.67%	2
Shorelines- shell	6.67%	2
Shorelines- sand	6.67%	2
Aquatic beds- algal	3.33%	1
Shorelines- bedrock	3.33%	1
Shorelines- boulder	3.33%	1
Flats- Shell	0.00%	0

Other (please specify)

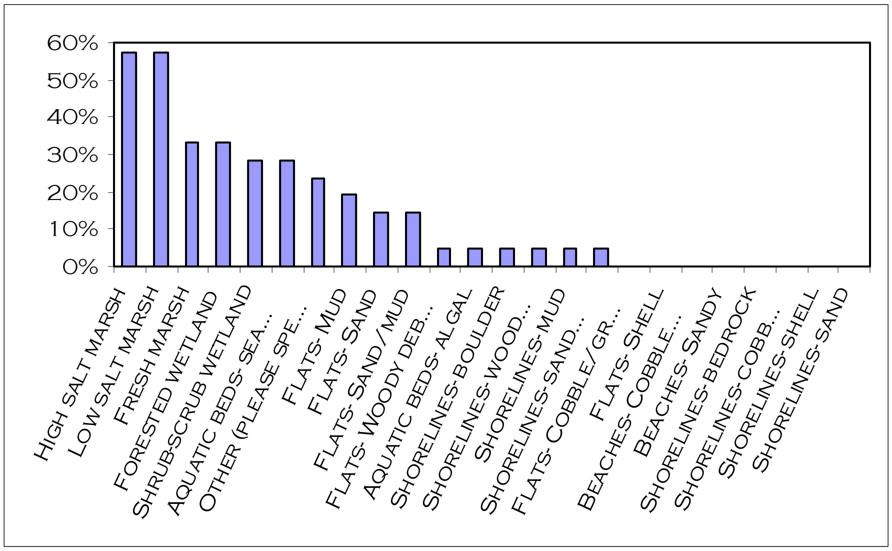
- Freshwater & tidal streams
- all of the above
- -shallow subtidal -tidal channel -pannes and ponds
- slough channels
- tidally influenced streams and river channels. Tide gate replacement

Answered	30
Skipped	1

2) Why have these these habitat types been the focus of your habitat restoration activities?

- My work has recently focused on scrub-shrub and forested wetlands (tidal swamps) because these types have been disproportionately impacted by agricultural activities and they are a "missing link" in the chain of habitats from ocean to headwaters. Also, tidal swamps are not often the target of restoration, because they are not widely recognized (either as part of the original system, or as restorable sites). My work also includes tidal marshes because they the most widely recognized tidal wetland habitats, and they constitute a large part of the estuarine wetland landscape. When organizations want to do a tidal wetland restoration project, they usually focus on a former tidal marsh, because these sites are easily recognized as restorable (due to obvious diking, tide gates, etc.).
- There are clear and expedient actions that reestablish these systems that result in increased goods and services to NOAA trust species. These systems have been destroyed or degraded in a way that is apparent and easy to assess. NOAA Restoration Center supports Olympia Oyster restoration in Puget Sound
- These are the estuarine wetland habitats that were most significantly altered where we work
- We have been working in the Salmon River estuary for a number of years, which is part of the Cascade Head Scenic Research Area. The management plan calls for restoring the salt marsh.
- Importance for spawning and rearing habitats for salmonids
- our organization works on biodiversity conservation, and we are doing an analysis to establish a framework for prioritizing coastal biodiversity conservation work as well as guiding monitoring of strategies (including habitat restoration)
- As in-kind mitigation for impacted wetlands.
- 1. these types are identified as having been degraded or lost at sites compared to historic condition. 2. these are the kinds of projects that proponents have brought in for funding.
- Opportunity and institutional interest associated with mitigation.
- Opportunities for restoration, due primarily to landowner willingness, but also valuable location of the sites.
- Land of interest to local community
- Wetland permitting requirements; some for land management efforts to improve habitat quality
- consulting on: 1.restoration of estuarine ecosystem processes 2 shoreline management issues e.g. erosion, coastal flooding
- The greatest opportunity for projects occurs in these areas.
- Because they are easier to tackle and my focus is freshwater fisheries.
- Opportunities for restoration are most frequent, and these systems have been damaged
- Important and degraded habitats that require the most urgent need.
- Known as juvenile salmon habitat
- These habitat types reflect the kinds of habitats that are adversely affected by development actions in western Oregon and that have suffered chronic degradation over time. Therefore, they often become goals in mitigation and restoration actions.
- Research opportunities related to my long-term interest in wetland systems, their development and functioning.
- funding availability
- Restoration has focused on restoring species that occupies intertidal eelgrass habitat.
- Ownership. Partnered projects with watershed councils / landowners.
- They are the habitat types we own.
- The marsh habitats have experienced significant historical losses and are a priority for the recovery of salmon and water birds. The flats have been invaded by Spartina anglica, and we want to control/eradicate the infestation.
- Focus of restoring tidal wetland mosaics, that are particularly important for estuarine rearing of juvenile Pacific salmon.
- Because they are present on the site.
- Willing Landowners
- Due to losses related to anthropogenic stressors and subsequent interest among NGOs and agencies to restore.
- These areas prioritized for restoration within urbanized areas.

3) What habitat types are the focus of compensatory mitigation activities with which you've been involved?



High salt marsh	57.14%	12
Low salt marsh	57.14%	12
Fresh marsh	33.33%	7
Forested wetland	33.33%	7
Shrub-scrub wetland	28.57%	6
Aquatic beds- seagrass	28.57%	6
Other (please specify)	23.81%	5
Flats- Mud	19.05%	4
Flats- Sand	14.29%	3
Flats- Sand/mud	14.29%	3
Flats- Woody debris/organic	4.76%	1
Aquatic beds- algal	4.76%	1
Shorelines- boulder	4.76%	1
Shorelines- woody debris/organic	4.76%	1
Shorelines- mud	4.76%	1
Shorelines- sand/mud	4.76%	1
Flats- Cobble/gravel	0.00%	0
Flats- Shell	0.00%	0
Beaches- Cobble/gravel	0.00%	0
Beaches- Sandy	0.00%	0
Shorelines- bedrock	0.00%	0
Shorelines- cobble/gravel	0.00%	0
Shorelines- shell	0.00%	0
Shorelines- sand	0.00%	0

Other (please specify)
Do not work on mitigation projects

These habitat types reflect the kinds of habitats that are adversely affected by development actions in western Oregon and that have suffered chronic degradation over time. Therefore, they often become goals in mitigation and restoration actions.

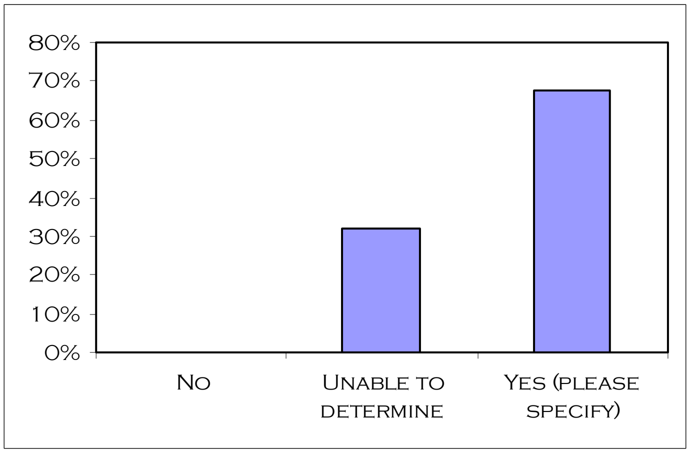
Answered	21
Skipped	10

4) Why have these habitat types been the focus of your compensatory mitigation activities?

- Same reasons as #2 above.
- My mitigation activities are primarily in major ports. These habitats are the component of the historic habitat structure that are missing, and whose replacement will hypothetically achieve the highest restoration of function.
- These seemed to be the habitats that were the easiest for the "mitigator" to create
- In-kind for impacted lands.
- Opportunity and institutional interest associated with mitigation.
- They were common areas for development and associated impacts.
- as 2
- Project opportunity again.
- Because they are smaller, easier projects to tackle. The methods are more tested and easier to justify funding with. There is more of a history of these types of projects and examples of some successful ones.
- Often affected by development activities
- They represent key habitat elements necessary to maintain hydrogeomorphic and ecological processes that sustain native biota in estuaries.
- N/A
- Because these types are either impacted by removal-fill activities and require "in-kind" compensatory mitigation, or they are restored or enhanced for "out-of-kind", i.e., freshwater impacts mitigated by restoration or enhancement of estuarine (brackish or freshwater), compensatory wetland mitigation purposes.
- N/A
- [We are typically not involved in compensatory mitigation activities]
- Because it's all DSL was interested in.
- Willing Landowners
- Due to ongoing pressures from public transportation systems including docks and ferries on nearshore eelgrass beds.
- They were the types that were damaged by ODOT and WSDOT activities.

Answered	19
Skipped	12

5) Are there habitat types not being restored that should be? If so, what are they?



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- Small creek mouths are often overlooked. Management of sediment supply through bulkhead removal and conservation is critical to beach function.
- Forested intertidal wetlands- e.g., spruce swamps
- Breached dike mitigation/compensation wetlands.
- Non-tidal riverine sand and mud flats
- tidal channel systems -especially high order deep tidal channels within marshes deltaic distributary channels
- We need a greater focus on scrub-shrub, forested, tidally-influenced freshwater floodplains, and floodplains generally. We also need some additional effort in pocket estuaries.
- kelp tidal forested swamps
- forested tidal wetlands
- Tidal swamp has been given too little attention as is one of the estuarine habitat types that has suffered most historically.
- I believe that most efforts in compensatory mitigation are either mis-directed or inadequate and few cover the many types of systems listed.
- expanded juvenile coho salmon habitat in estuarine areas is critically needed and provides immediate benefits
- Nearly all estuarine habitat types have sustained habitat degradation and loss and thus would qualify for restoration.
- Scrub-shrub and forested tidal wetlands.
- Freshwater tidal forested communities.
- tidal scrub shrub tidal forest swamp non-tidal river delta floodplain
- Scrub-shrub and forested wetlands.
- ANY of the non-vegetated flats!
- flats!
- Spruce Swamps
- More nearshore beach restoration is needed to reduce erosion, provide vegetation, shade, organic matter.

Answered	28
Skipped	3

6) Why do you think these habitats are being overlooked?

- As described in #2 above, tidal swamps are not often the target of restoration, because they are not widely recognized (either as part of the original system, or as restorable sites). The low awareness of these habitat types is partly due to the fact that they were heavily modified in the early history of settlement. Trees were removed early due to easy log transport opportunities along the adjacent rivers. The sites are high enough that only minimal diking (or no diking) was necessary to nearly eliminate tidal influence, so clear indicators of hydrologic modification are absent. Drainage ditches were dug and restrictive culverts placed early on, eliminating tidal exchange and radically altering channel morphology. Most tidal swamps were probably gone by the early 1900's, though some tidal swamps continued to be cleared, drained and culverted through the mid-1900s. To locate actual intact tidal swamps or restorable tidal swamps, onsite observation is needed. The field work has to occur at specific times (e.g. a wintertime spring tide series and possibly also during a summer minus tide), to confirm that these sites are tidally influenced and to determine the nature of the hydrologic modifications. It takes good elevation survey work and tide gauging to estimate the potential tidal inundation regime after restoration at these sites, so it's harder to prove that they're suitable restoration targets.

6) (Continued from previous page)

- Small parcel property ownership combined with conflicting human-centered uses makes small creek and bluff-to-beach restoration difficult. Assessments of bluff function are just coming on line to prioritize work.
- There are so few left that I don't think there's much common awareness of their original extent and function
- Mitigation/compensation credit sufficient for simple dike breaching, but maximization of functional condition is possible, but no added incentive for mitigation sponsor.
- Large rivers probably have been too altered hydrologically to make this feasible without major infrastructure change.
- Some habitat types are rarer (e.g. forested wetlands) and therefore more difficult to find opportunities to restore. However, I am not aware of any specifics habitat types that are necessarily being overlook.
- these are 'forgotten landscapes' largely obliterated 100-150 years ago
- Practical difficulties in developing projects. Multiple landowners, political obstacles.
- kelp is not a high priority. TFS are too difficult and largely privately owned
- almost none are left in the region
- The time frame in which it takes to recover and the processes that are required to initiate are daunting. But we have seen ample evidence where large wood placed in high marsh provides a nurse log for hemlock, cedar, and spruce to establish as they did historically from old growth blow downs that fell out onto the open tideland.
- Basic lack of knowledge of their value and functions as well as their distribution and condition.
- only recently has the significance of such areas to juvenile coho rearing become widely appreciated
- Restoration techniques in estuaries are not completely understood beyond the removal of tide control structures, there has been too little importance placed on estuaries in general, and most coastal restoration has focused on upriver salmon function, not estuaries.
- It may not be that they are overlooked, but it may be that restoring forested plant communities has a higher risk (or lower likelihood of success) or takes a longer time for success-however defined-than, for instance, breaching a berm/dike to restore tidal influences (thus natural processes). Having said that, I just worked on restoration of a forested community in freshwater tidal habitat in the N. Fork Siuslaw.
- N/A
- largely missing from landscape so few reference sites and little record of their function, size or role. They have unique geomorphic characteristics that are generally destroyed when converted to ag lands so active restoration would require knowing how to recreate those geomorphic features. Passive restoration will require decades or centuries to recreate the geomorphology.
- They are considered less productive than emergent wetlands, there's no preference among types of wetlands, and lack of restoration opportunity.
- Not perceived as being as functional and publicly valuable as vegetated ecosystems.
- Continued Cattle and Hay production
- They may not have been prioritized as major habitats, they may be under private ownership.

Answered	21
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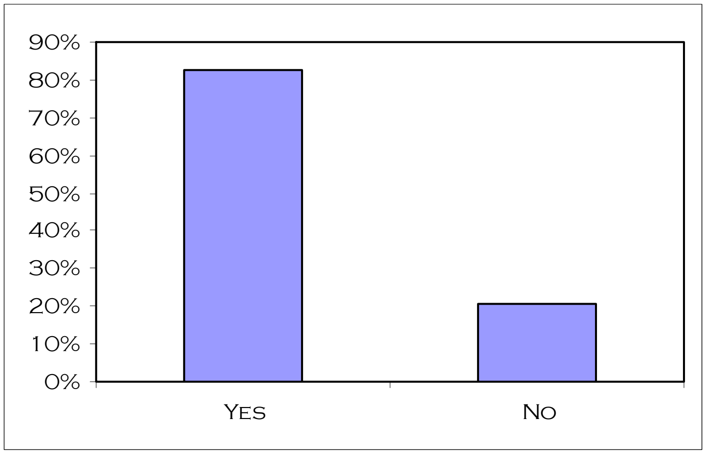
7) Do you collect data from your estuarine wetland restoration project sites) to determine whether project goals are being met (effectiveness monitoring)?



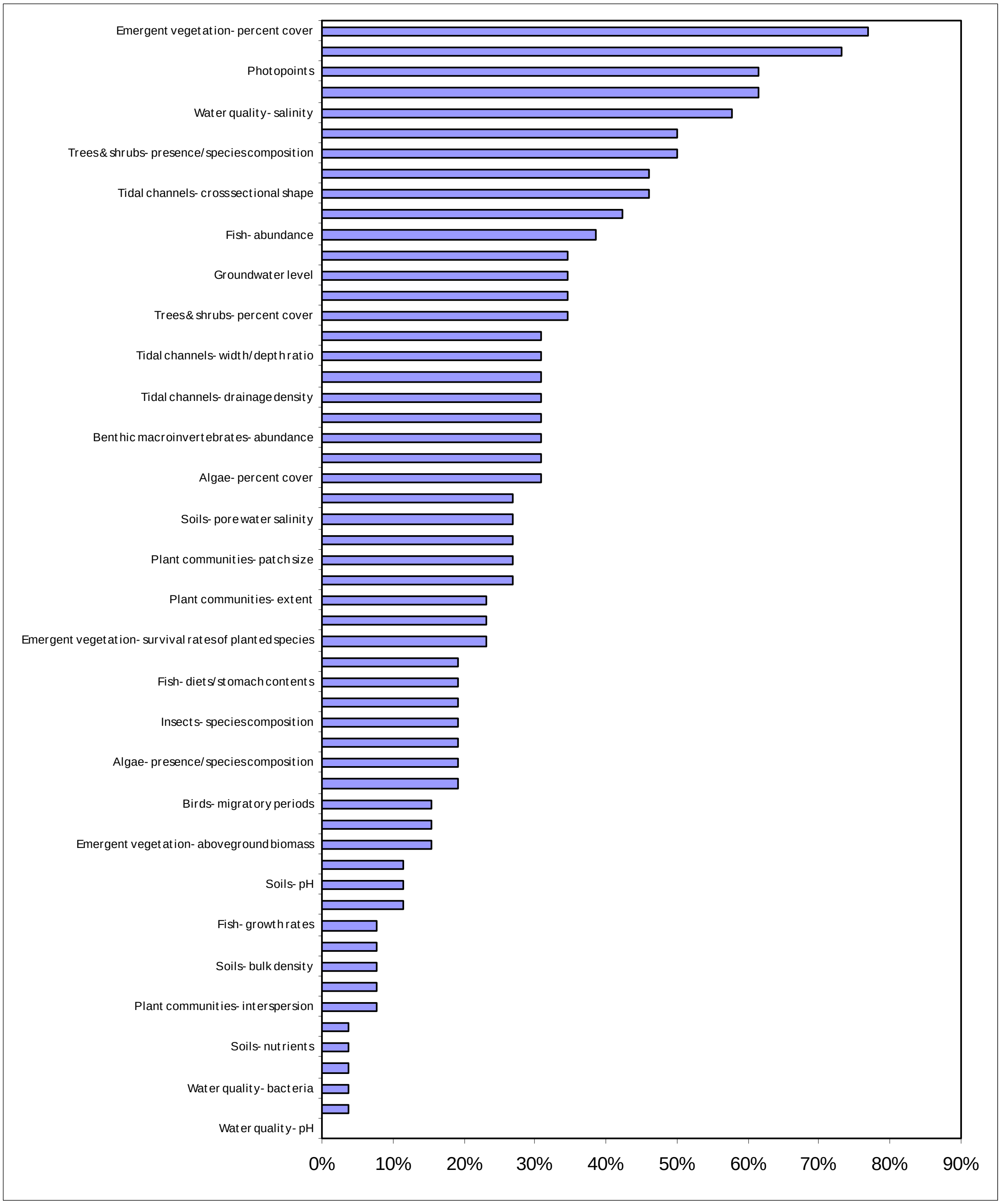
Answered	29
Skipped	2

8) If you do collect effectiveness monitoring data at your project sites, what monitoring parameters do you typically use? (Please refer to the information below and the graph on the following page)

Other (please specify)

- Amphibians
- Seasonal bird (species, sex, age) use behavior(breeding, feeding, migration, etc.) by habitat type (forest, scrub-shrub, emergent, mudflat).
- eelgrass bed cover, Olympia oyster growth and survival rates
- Not all of these parameters are collected at every site. Vegetation is always included but tidal channel measurements, water temperature, and soil parameters are not always included.
- This question could really be broken out per specific compensatory wetland mitigation types or concepts. The monitoring parameters are very project specific. For instance, restoring a forested plant community has, generally for our purposes, distinct success criterion or monitoring parameters than breaching a dike (one obviously requires specific vegetation success criteria, the other requires tidal influence/acre-but not necessarily vegetation monitoring). We have, in general(!), tended to focus on restoring natural processes rather than to speculate on what the future site condition, i.e., %cover of vascular plants, etc., will look like.
- Most data collected by project partners
- large wood abundance and characteristics
- Submerged Aquatic Vegetation - stem height/density
- Submerged Aquatic Vegetation - percent cover

8) If you do collect effectiveness monitoring data at your project sites, what monitoring parameters do you typically use?



Answered	26
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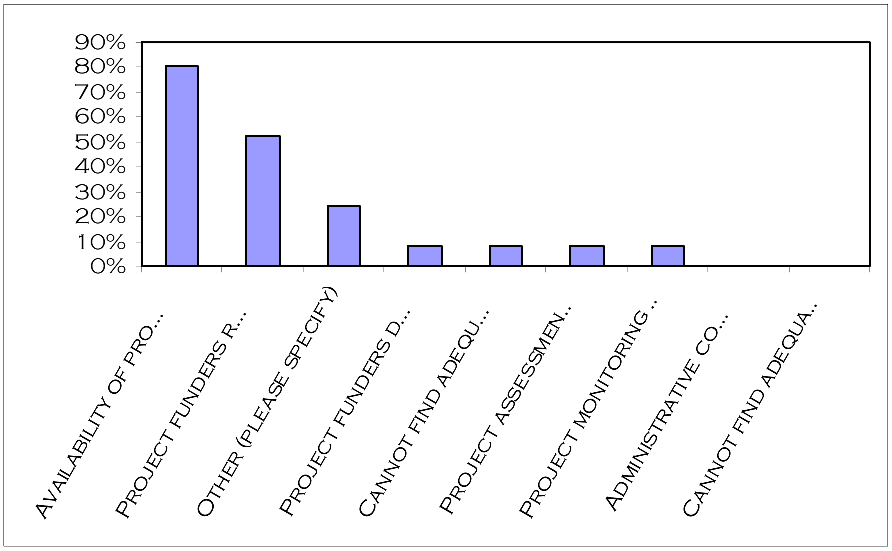
8) (Continued from previous page)

Emergent vegetation- percent cover	76.92%	20
Emergent vegetation- presence/species composition	73.08%	19
Wetland surface- elevation	61.54%	16
Photopoints	61.54%	16
Water quality- salinity	57.69%	15
Trees & shrubs- presence/species composition	50.00%	13
Tidal channels- length	50.00%	13
Tidal channels- cross sectional shape	46.15%	12
Fish- species composition	46.15%	12
Wetland surface- frequency of tidal flooding	42.31%	11
Fish- abundance	38.46%	10
Trees & shrubs- percent cover	34.62%	9
Trees & shrubs- survival rate of planted species	34.62%	9
Groundwater level	34.62%	9
Water quality- temperature	34.62%	9
Algae- percent cover	30.77%	8
Wetland surface- sediment accretion/erosion	30.77%	8
Benthic macroinvertebrates- abundance	30.77%	8
Benthic macroinvertebrates- species composition	30.77%	8
Tidal channels- drainage density	30.77%	8
Tidal channels- sinuosity	30.77%	8
Tidal channels- width/depth ratio	30.77%	8
Other (please specify)	30.77%	8
Trees & shrubs- basal area	26.92%	7
Plant communities- patch size	26.92%	7
Soils- organic matter	26.92%	7
Soils- pore water salinity	26.92%	7
Tidal channels- order	26.92%	7
Emergent vegetation- survival rates of planted species	23.08%	6
Trees & shrubs- stem density	23.08%	6
Plant communities- extent	23.08%	6
Emergent vegetation- stem height/density	19.23%	5
Algae- presence/species composition	19.23%	5
Soils- texture	19.23%	5
Insects- species composition	19.23%	5
Tidal channels- flow rates	19.23%	5
Fish- diets/stomach contents	19.23%	5
Fish- habitat use	19.23%	5
Emergent vegetation- aboveground biomass	15.38%	4
Insects- abundance	15.38%	4
Birds- migratory periods	15.38%	4
Water quality- dissolved oxygen	11.54%	3
Soils- pH	11.54%	3
Fish- residence times	11.54%	3
Plant communities- interspersion	7.69%	2
Water quality- turbidity	7.69%	2
Soils- bulk density	7.69%	2
Tidal channels- bifurcation ratio	7.69%	2
Fish- growth rates	7.69%	2
Water quality- nutrients	3.85%	1
Water quality- bacteria	3.85%	1
Soils- redox potential	3.85%	1
Soils- nutrients	3.85%	1
Birds- nesting/fledging	3.85%	1

9) If you do not collect effectiveness monitoring data at your project sites, or are unable to collect as much data as you feel should be collected, please indicate why.



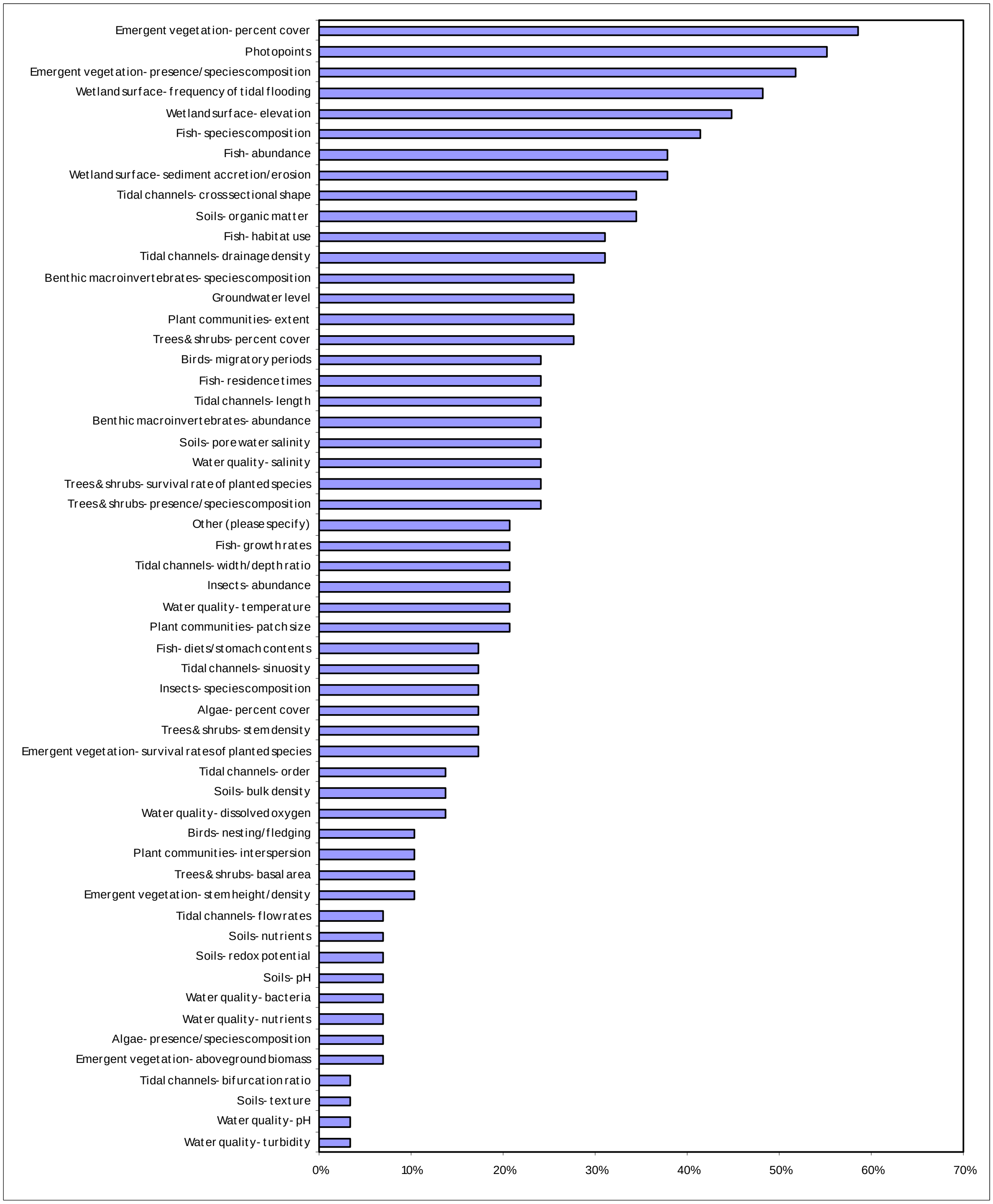
Answered	25
Skipped	6

Program or grant funds are insufficient	80.00%	20
Funders require monitoring but do not provide adequate funding	52.00%	13
Other (please specify)	24.00%	6
Project funders do not require project monitoring	8.00%	2
Cannot find adequately trained monitoring personnel	8.00%	2
Project assessments are based on best professional judgement	8.00%	2
Project monitoring is not a high priority for our organization	8.00%	2
Administrative constraints on hiring monitoring personnel	0.00%	0
Cannot find adequate guidance for project monitoring	0.00%	0

Other (please specify)

- Restoration project not yet approved -- planning stage only now.
- My work has a research focus and isn't associated with particular projects.
- lack of archival institution that can make use of long term monitoring data to advance restoration practice
- Inadequacy of my own knowledge
- Some compensatory mitigation sites require effectiveness monitoring, some only require implementation monitoring. For instance, transplanting of eelgrass requires effectiveness monitoring, breaching a berm may not require effectiveness monitoring-it really depends on the project objectives.
- In projects I have been involved with, it has not been possible to monitor all the variables that would be useful to understand why vegetation structure changes (usually, vegetation is monitored). Sediment/soil characteristics, even visual assessment of these characteristics would be helpful but we have been limited in the number of people who have experience reading sediments - especially in brackish areas.

10) What are the top five to ten monitoring parameters you think should routinely be used for project effectiveness monitoring?



10) (Continued from previous page)

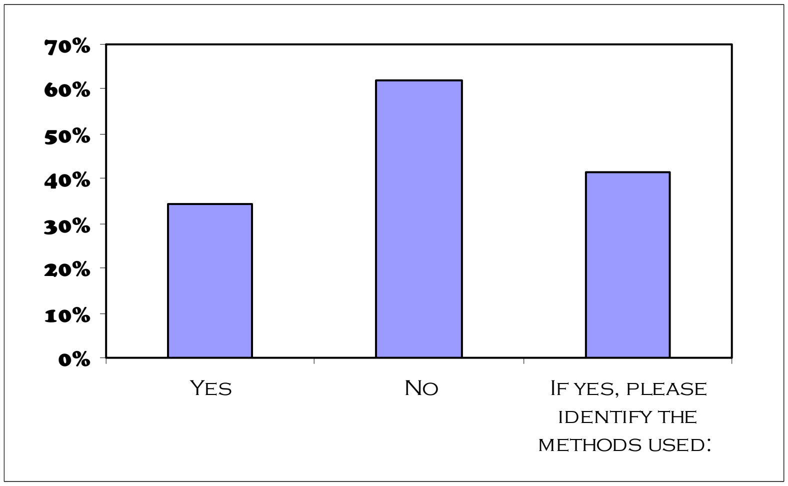
Emergent vegetation- percent cover	58.62%	17
Photopoints	55.17%	16
Emergent vegetation- presence/species composition	51.72%	15
Wetland surface- frequency of tidal flooding	48.28%	14
Wetland surface- elevation	44.83%	13
Fish- species composition	41.38%	12
Wetland surface- sediment accretion/erosion	37.93%	11
Fish- abundance	37.93%	11
Soils- organic matter	34.48%	10
Tidal channels- cross sectional shape	34.48%	10
Tidal channels- drainage density	31.03%	9
Fish- habitat use	31.03%	9
Trees & shrubs- percent cover	27.59%	8
Plant communities- extent	27.59%	8
Groundwater level	27.59%	8
Benthic macroinvertebrates- species composition	27.59%	8
Trees & shrubs- presence/species composition	24.14%	7
Trees & shrubs- survival rate of planted species	24.14%	7
Water quality- salinity	24.14%	7
Soils- pore water salinity	24.14%	7
Benthic macroinvertebrates- abundance	24.14%	7
Tidal channels- length	24.14%	7
Fish- residence times	24.14%	7
Birds- migratory periods	24.14%	7
Plant communities- patch size	20.69%	6
Water quality- temperature	20.69%	6
Insects- abundance	20.69%	6
Tidal channels- width/depth ratio	20.69%	6
Fish- growth rates	20.69%	6
Other (please specify)	20.69%	6
Emergent vegetation- survival rates of planted species	17.24%	5
Trees & shrubs- stem density	17.24%	5
Algae- percent cover	17.24%	5
Insects- species composition	17.24%	5
Tidal channels- sinuosity	17.24%	5
Fish- diets/stomach contents	17.24%	5
Water quality- dissolved oxygen	13.79%	4
Soils- bulk density	13.79%	4
Tidal channels- order	13.79%	4
Emergent vegetation- stem height/density	10.34%	3
Trees & shrubs- basal area	10.34%	3
Plant communities- interspersion	10.34%	3
Birds- nesting/fledging	10.34%	3
Emergent vegetation- aboveground biomass	6.90%	2
Algae- presence/species composition	6.90%	2
Water quality- nutrients	6.90%	2
Water quality- bacteria	6.90%	2
Soils- pH	6.90%	2
Soils- redox potential	6.90%	2
Soils- nutrients	6.90%	2
Tidal channels- flow rates	6.90%	2
Water quality- turbidity	3.45%	1
Water quality- pH	3.45%	1
Soils- texture	3.45%	1
Tidal channels- bifurcation ratio	3.45%	1

10) (Continued from previous page)

Other (please specify)

- Tidal channel planform geometry generally (from high resolution air photos) Winter waterfowl habitat use
- Specific parameters should coincide with the goals for the project.
- Seasonality of tidal inundation is an important parameter -- but not a direct measurement. It's derived from either longterm tide gauging or modeling ot tide levels, combined with site elevation survey. This is a comment, not another parameter... To keep the number of parameters down to 10, I'm relying on the fact that data on vegetation percent cover automatically generates data on species presence and species composition; data on channel cross-sectional shape can be used to calculate width:depth ratio; and data on frequency of flooding can't be obtained without elevation survey (so the latter incorporates the former).
- Too general a question depends upon project.
- THe monitoring needed depends on the purpose of the restoration project. To understand the full impact of the restoration project, however, other variables outside those that were the focus of the restoration should be monitored so that information needed for adaptive management is available.
- THIS QUESTION CANNOT BE ANSWERED WITHOUT REFERENCE TO A SPECIFIC HABITAT TYPE (E.G. CAN'T SPECIFY EMERGENT OR FORESTED....)

11) Do you use established wetland functional assessment protocols (e.g., Hydrogeomorphic Method) to guide restoration planning or to evaluate project effectiveness?



If yes, please identify the methods used:

- We helped develop the Coastal Oregon Tidal Fringe Wetlands Regional Guide.
- HGM Guidebook for Oregon Tidal Wetlands
- Used OWEB funds for training and development of protocal.
- Puget Sound Habitat Monitoring Protocols (modified) Columbia River EstuaryHAbitat Restoration Protocols (draft)
- hydrodynamic modeling
- estuarine habitat assessment protocol
- Somewhat use HGM, Johnson-O'Neil, HEP, etc. but rely mostly on performance standards.
- I do not use them as I consider them ineffective in meaningful assesment
- We are trying to restore the estuary primarily by removing dikes and infrastructure.
- I do not believe that HGM provides adequate quantitative data that is required to determine success. It can be used for an interesting comparison, but I would not use it to determine successs of a compensatory mitigation project.
- HGM
- Roegner et al. Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary

Answered	29
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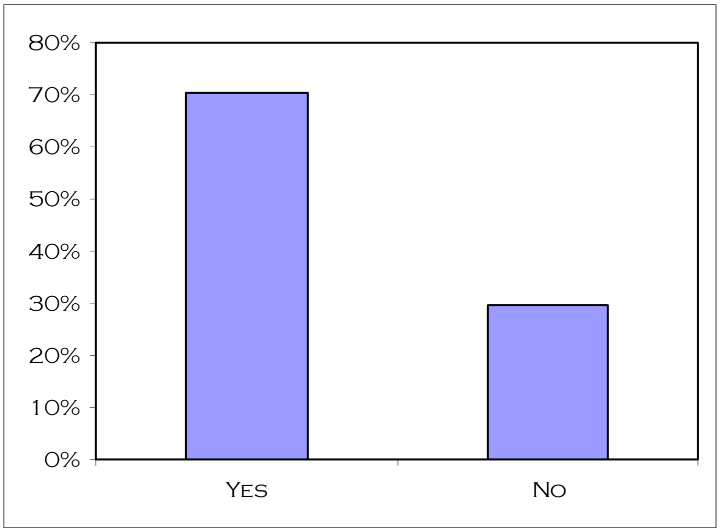
12) Do you collect data at project sites for reasons other than to determine whether project goals are being met?



Answered	27
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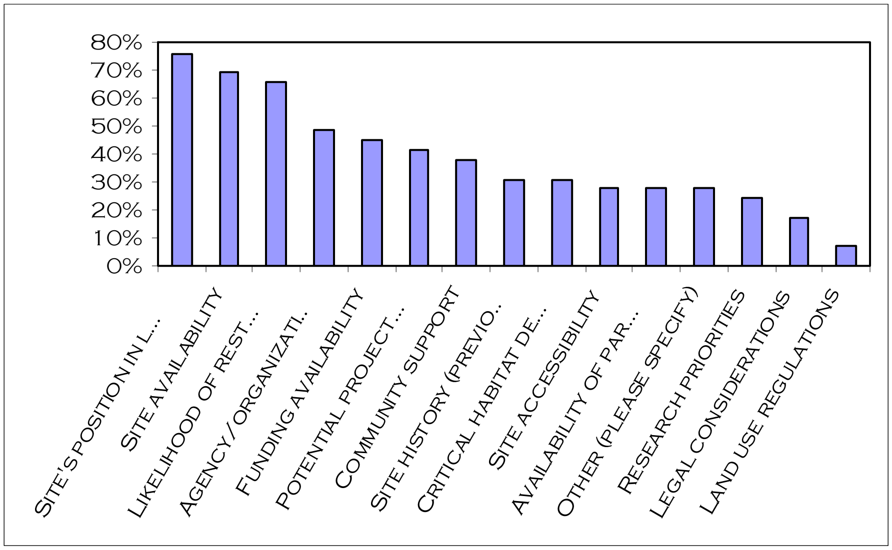
If yes, please specify the type of monitoring and what questions/hypotheses are being addressed.

- Restoration science: methods for addressing diked tidal wetland subsidence; tidal channel creation, restoration and enhancement; non-tidal channel creation/restoration; fish habitat restoration
- Vegetation monitoring to monitor the potential impacts of groundwater withdrawals on wetland/ upland morphology near sand dune lakes.
- to determine the outcome of specific restoration treatments, and identify variability of outcome accross site gradients. We are increasing collecting qualitative 'data' to track observations and work of multiple 'stewards'.
- We use monitoring as a tool for local education and community involvement
- I prefer measures of wetland condition rather than function. I feel that the information is more easily communicated and compared among systems.
- see list of questions in SF Bay tidal wetland restoration design guidelines document
- Basic research on marsh geomorphology, controls on vegetation distribution, methods to control exotic vegetation, effects of sea-level rise on vegetation communities.
- Examining cumulative effects of multiple projects on an ecosystem Adaptive management
- We collect habitat use by wildlife data but do not measure the data against performance standards.
- What is the rate of recovery
- To incorporate into larger research databases of similar type projects.
- for refining future designs
- I also conduct research into tidal wetland ecology which involves monitoring many of the same parameters listed above. I do it for several purposes: To increase scientific understanding of the relationships between structural and biological characteristics of tidal wetlands; to refine my monitoring recommendations by confirming what monitoring parameters best reflect the trajectory of restoration; and to help improve future restoration design.
- experimental projects are testing alternative treatments. Currently invasive plant and large wood experiments in progress.
- baseline landscape-scale monitoring--what are the locations and extents of estuarine habitats and what are their characteristics in different locations?
- Research that addresses causal mechanisms behind basic monitoring metrics.
- Project goals have been very vague on the projects I have worked on. For the most part, any remote monitoring such as aeiral photography or sidescan sonar has been considered extra, but I consider it primary.
- 1) Cumulative effects of multiple restoration projects. 2) Effects of overwater structures on eelgrass growth/density.

13) In prioritizing sites for estuarine wetland restoration actions, what selection criteria other than habitat type do you use?



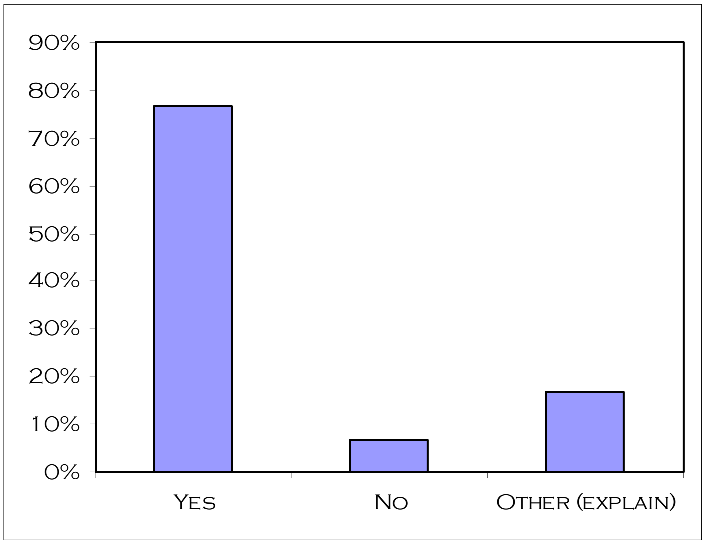
Answered	29
Skipped	2

Other (please specify)

- NOAA has criteria of evaluation that include community participation, future protection of restoration investment, capabilities of project proponent, visibility of the restoration action, and further defines restoration success by preferring actions that result in self-sustaining ecological benefits, and projects which support a diversity of species.
- Meeting multiple biodiversity objectives
- integrity of natural processes that support development of habitat functions.
- Likelihood of being able to restore habitat forming and sustaining processes, e.g., completely removing dikes to allow tidal and riverine flooding.
- level of distrubance, probablility of success, degree in change in function and area
- In my work, initial prioritization has generally been based on ecological criteria (some of which are marked above -- see my estuary assessment chapter for the full process). Choice of specific action sites is then informed by the other criteria you list above.
- Size of site and connectivity to other high-priority sites, preferably following a regional or local wetland conservation plan.
- I am not usually involved in selecting restoration sites.

Site's position in landscape	75.86%	22
Site availability	68.97%	20
Likelihood of restoration success	65.52%	19
Agency/organization priorities	48.28%	14
Funding availability	44.83%	13
Potential project cost	41.38%	12
Community support	37.93%	11
Site history (previous land uses)	31.03%	9
Critical habitat designations/ESA	31.03%	9
Site accessibility	27.59%	8
Availability of partners	27.59%	8
Other (please specify)	27.59%	8
Research priorities	24.14%	7
Legal considerations	17.24%	5
Land use regulations	6.90%	2

14) Do you routinely use reference sites in restoration project planning and/or evaluation?



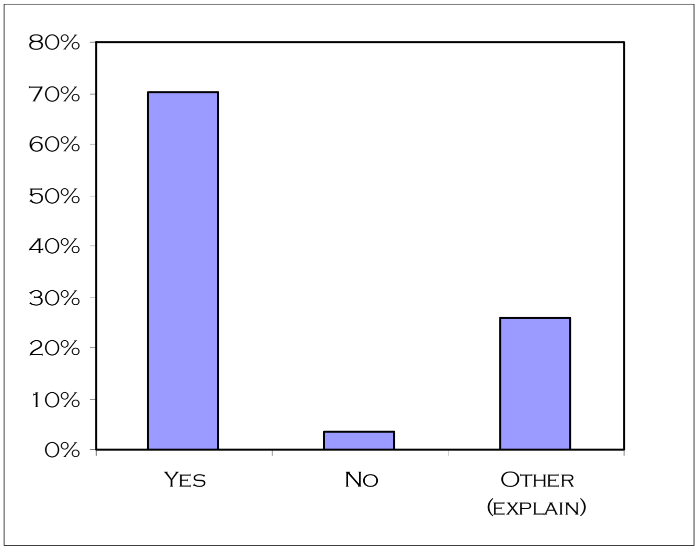
Yes	76.67%	23
No	6.67%	2
Other (explain)	16.67%	5

Answered	30
Skipped	1

Other (explain)

- I would if I knew where to find appropriate sites.
- Not individually paired sites, but rather the series of dozens of reference sites from which data were collected for the Oregon HGM Tidal Guidebook
- sometimes look at reference sites. Not very systimatic.
- We use estimations of reference conditions.
- Don't use reference sites routinely, but whenver possible. It is often difficult to find valid reference sites, especially along an estuarine gradient, and, of course, money to monitor reference sites is scarce.

15) If you use reference sites, are you able to find sites from which you can collect useful data?

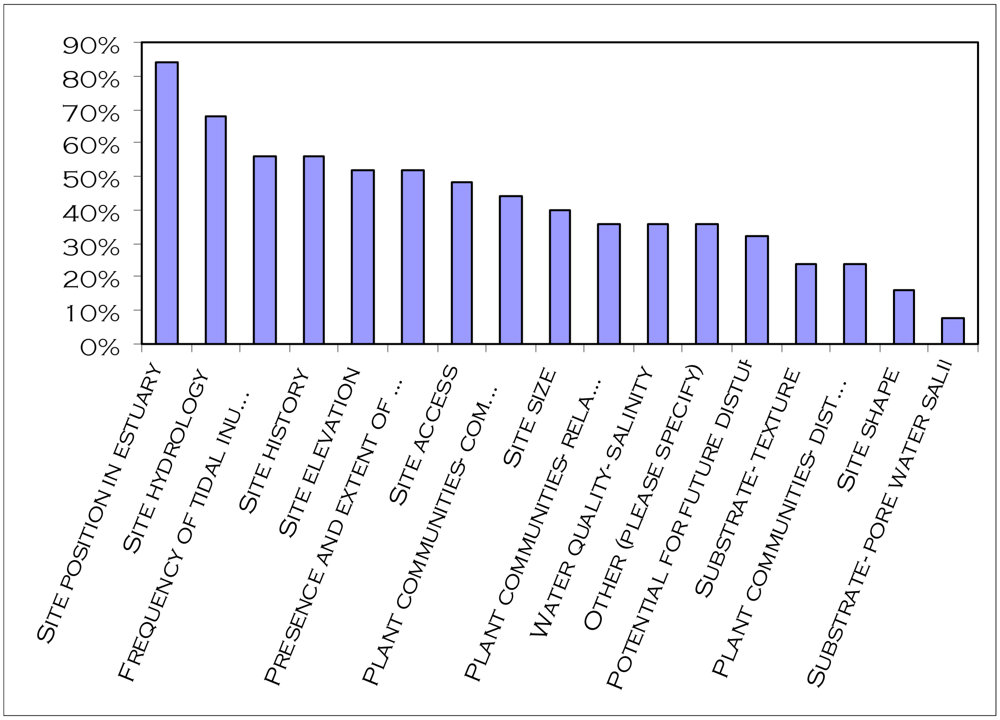


Answered	27
Skipped	4

Other (explain)

- Depends on the wetland habitat type. Little information available on forested and scrub/shrub wetlands.
- It varies, and largely depends on the proximity of the mitigation site to a relatively undisturbed area in the same hgm class and soil type. We use regional data sets based on a number of reference sites in most cases.
- The majority of reference sites that I have seen people use may not have adequate application to the site that is being restored or enhanced.
- Habitat are altered by land management, we attempt to replicate reference conditions within the current social, political, and economic realities that exist.and economic realities that exist.
- Within-system reference site exists, but it may be different than restoration site in terms of sediments, salinity, location, etc.

16) If you use reference sites, what criteria do you use in site selection?



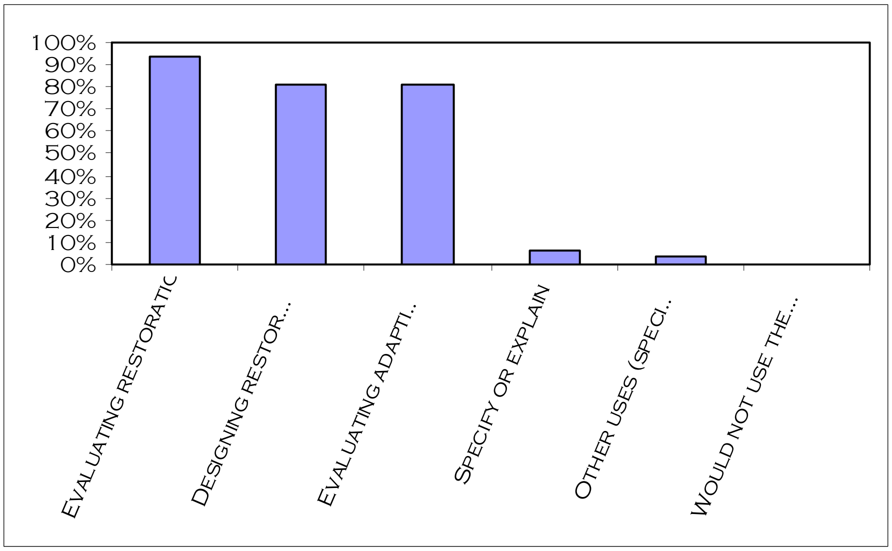
Other (please specify)

- Typically don't have resources for formal reference site selection, but use subjective observation of presumed patterns at available sites.
- Whether data are already available for the site from other studies
- Similarity to the restoration--hydrogeomorphically and location
- I use a large suite of sites in the Skagit River Delta and I use landscape allometry to generate predictive models of landform geometry. I also use the whole remaining tidal marshes to generate predictive models of vegetation distribution.
- HGM class (river source or marine source; high marsh or low marsh or mudflat; fresh, brackish, marine; low disturbance; etc)
- Relatively close proximity and similarity to project site.
- animal species present in tidal flats
- direct comparability with restoration site attributes.
- Site proximity to restoration site

Site position in estuary	84.00%	21
Site hydrology	68.00%	17
Frequency of tidal inundation	56.00%	14
Site history	56.00%	14
Site elevation	52.00%	13
Presence and extent of tidal channels	52.00%	13
Site access	48.00%	12
Plant communities- composition	44.00%	11
Site size	40.00%	10
Plant communities- relative condition	36.00%	9
Water quality- salinity	36.00%	9
Other (please specify)	36.00%	9
Potential for future disturbances	32.00%	8
Substrate- texture	24.00%	6
Plant communities- distribution	24.00%	6
Site shape	16.00%	4
Substrate- pore water salinity	8.00%	2

Answered	25
Skipped	6

17) If long term data sets quantifying one or more estuarine wetland attributes (e.g., vegetation, soils, invertebrate communities, tidal channels...etc.) were made available from a network of reference sites representing a variety of estuarine wetland habitat types in the Pacific Northwest, would you use them for...



Answered	31
Skipped	0

Evaluating restoration projects	93.55%	29
Designing restoration projects	80.65%	25
Evaluating adaptive management options	80.65%	25
Specify or explain	6.45%	2
Other uses (specify below)	3.23%	1
Would not use them (explain below)	0.00%	0

Specify or explain

- the duration of monitoring (i.e. the long term part), would only add value for parameters where variation over time is of interest. This is not something I have thought through.
- Research on basic estuarine ecology

18) What do you think are the most common and important questions that, if answered, would improve your ability to prioritize coastal habitat restoration project site selection more effectively?

- What was the historic extent of tidally-influenced wetlands? What was the composition and distribution of pre-settlement vegetation in the tidal wetlands of the upper estuary (current 1:24k GLO mapping lacks resolution in these areas). How should the possibility of geologic change (sea level rise, major seismic events and associated land subsidence) affect our tidal wetland restoration and conservation priorities?
- change analysis that identifies the distribution of lost ecosystem services in the landscape. Understanding adjacency effects, where restoration of habitat A adjacent to existing habitat B increases the benefits of habitat A restoration as compared to where habitat B is absent. Increase analysis of off-site scale dependent effects of restoration and what thresholds may exist such that a certain aggregate area of restoration triggers recovery of off site ecosystem processes. Determining how site characteristics affect outcome of restoration actions through consistent measurement of multiple restoration projects over time.

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- What habitats are in most need of restoration or enhancement in a given watershed?
- 1. What is the likely trajectory of potential restoration actions compared to reference sites? 2. What are the limiting factors to achieve specific goals based on readily measurable wetland attributes.
- How will sea level rise affect current habitat distribution, function, and dependent species, and how will SLR alter our ability to restore habitats to some level of ecological viability?
- My projects are driven by compensatory mitigation requirements of clients, so my most important questions (at the onset) are related to the governing agencies and their priorities for site selection.
- What is the extent and character of wetland losses across the landscape. how does proximity to existing habitat types or functions enhance or diminish the functional gain from restoration? what real estate parcels are potentially available for restoration activity? What management measures provide the greatest diversity of functional benefit.
- 1. Which landowners are willing to consider restoration. 2. What combinations of marshes and other habitats at a landscape level support the most fish and wildlife numbers and diversity
- What types of projects/habitats get the most "bang for the buck" when it come to benefiting watershed health?
- How do various species (salmon, waterfowl, shorebirds, etc) use habitat--specific aspects of habitat, such as tidal channels, marsh surfaces, mudflats, eelgrass? How do they move between different parts of the landscape? How does this pattern of habitat use affect energy budgets, growth, survivorship? How does natural disturbance (floods, storms) affect patterns of habitat use. How will climate change affect all of the above.
- Better information on functional performance of restored systems from various restoration strategies
- Where is the greatest need and is that property available for restoration/enhancement.
- more fully understanding fish use and growth potential in the variety of different sites
- In combination: 1)A set of reestablished reference sites representing the a full spectrum of estuarine habitat types that are routinely monitored via standard protocols and reporting formats for a broad suite of parameters and data sets/reports are made available for download via a geodatabases; and 2) Watershed level analyses of priority areas for restoration and recovery.
- True measures of functionality
- 1) what are the potentialities for restoration in a particular area (e.g., Humboldt Bay area); 2) which are the most 'ready' sites (access, owner support, funding availability) that meet high priority goals for the area
- What restoration is needed at any particular site to restore estuary function? What sites are more important to conduct restoration at given global warming concerns?
- Which habitat type, per "watershed", has been most adversely impacted?
- What is the capacity for restoration at the site? What are the future land management actions that may influence the site?
- In what ways are estuarine controlling factors vulnerable to climate change impacts? What actions will have greatest effect on increasing system adaptability or functional resilience to CC? (e.g. how would different dike removal locations affect sediment delivery/capture?) How do cumulative restoration actions in an estuary affect the system's function and its resilience to CC? What are the lower food web dynamics - relative importance of riverine vs. tidal marsh vs. algal sources of detritus, benthic vs. pelagic sources? Are there signs of anthropogenic changes in nutrient regimes that are affecting the base of the food web? What are the time scales for restoration actions to become fully functional?

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- impacts of climate change on estuaries -importance of habitat diversity to estuarine functioning
- What does the estuarine landscape need?
- Size of site and connectivity to other high-priority sites, preferably following a regional or local wetland conservation plan.
- What lands are currently in active management, and which ones are not. Also a layer of sites that have mutliple landowners.
- datasets on ecosystem function, e.g. sites of "high quality" due to presence of rare or endemic plant species or communities, rare wildlife, intact habitats, unpolluted conditions, etc. Stressors data are much more frequent in publicly available spatial data (GIS) than functions. frequency distributions of habitat types: historical and present sea level rise from climate change
- I think that more info is needed on the sediment characteristics that will allow restoration actions to succeed is needed. Also, info about how to create those characteristics when they do not exist is needed.

19) What do you think are the most common and important questions that, if answered, would improve your ability to design/engineer coastal habitat restoration projects more effectively?

- What were the physical characteristics of undisturbed tidal wetlands, particularly the types that are now rare (scrub-shrub and forested tidal wetlands)? Physical characteristics include site elevation relative to tidal range (tidal inundation regime), particularly seasonal variation in that regime; salinity of surface water; magnitude of freshwater inputs; tidal channel density, width:depth ratio, sinuosity, order and bifurcation ratio; soil organic matter content, texture, porewater salinity, bulk density and nutrient status. How "restorable" are upper estuary tidal wetlands, given basin-wide hydrologic change? What can we do to speed the restoration of tidal channel networks? (i.e., what is most effective -- channel initiation, channel excavation, passive restoration,etc.?) How does this vary by tidal wetland habitat type, landscape position, etc.? If engineering (initiation, excavation etc.) is needed, what design parameters are appropriate for Oregon wetlands in different landscape positions? What are the different effects of dike breaching vs. dike removal? How long will it take for subsided sites to restore to their original elevations, given today's sedimentation regime? How does this vary by restoration practice (dike removal vs. dike breach; channel excavation vs. passive channel development)? How does this vary by landscape setting, degree of subsidence, basin? What is the relatively importance of freshwater flow vs. tidal flow in structuring tidal channel systems? How does this vary by landscape position and estuary zone?
- Increase analysis of soil/sediment charactetistics and correlation of those parameters to ecosystem services. Increase analysis of off-site scale dependent effects of restoration and what thresholds may exist such that a certain aggregate area of restoration triggers recovery of off site ecosystem processes. Better understanding of controls exerted on system function by soil/sediment condition.
- What's the difference in site hydrology and associated nutrient exchange, sediment dynamics, plant community recruitment, and fish use in restoring diked wetlands using complete dike removal versus breaching the dike in a few locations? Likewise, what's the difference in site hydrology and associated nutrient exchange, sediment dynamics, plant community recruitment, and fish use in restoring a diked wetland with no constructed tidal channels versus a fully constructed tidal channel network?
- Detailed and accurate topographic and elevation data. What is the reference condition? What plant species are appropriate? How can invasive species, such as reed canary grass be controlled, or prevented from colonizing?
- 1. Is there a vertical control network that we can use to link monitoring and site designs. 2. See

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responses to Q18.

- see sea level rise issue raised above
- What hydrological restoration designs and construction techniques have proven effective (in terms of sustained re-naturalization of biological and hyrdological systems) in similar conditions?
- how does short term vector of change indicate long term outcome of restoration actions. how do short term soil/sediment parameters predict long term ecosystem function. what assessments indicate the presence/absence or level of function of those processes critical to maintain habitat function. What are cost effective species specific approaches for establishing suitable surfaces for natural regeneration of vegetation or for propagaing species where natural dispersal is comporomised?
- What designs will allow the most rapid maturation of newly established tidal marshes
- Is there a database that catalogues all past coastal habitat restoration projects and their overall success/effectiveness?
- Is it cost effective to create new wetlands? (Both salt water and freshwater.)
- see tidal wetland design guidelines
- Same answer as in question 18, but we need to create predictive models of tidal channel geometry and vegetation distribution, as well as animal movement and use of habitat.
- Generally better data on factors that control the distribution and abudnance of key vegetation habitat types. Eg, elevation, temperature, water tolerances, salinity range, etc.
- Where are the case records of site prep, management, and ensuing estuarine habitat responses collectively available? Where is the collective history of trial and error with lessons learned? Where are the shapefiles, databases, and geodatabases that are designed to act as a common library for all mitigation and restoration practitioners? How do we link quickly and seamlessly into spatial raster imagery and othe spatial data at adequate resolution to evaluate and manage our sites over time. How do we link our data into such a system as we collect it?
- A system of about 10 reference sites distributed along the PNW coast each with a documented history and data set demonstrating recovery from profound disturbance
- physical (geomorphic and hydrologic) relationships in properly functioning sites
- What aspects of sediment delivery, that we now encounter in coastal watersheds, are important in designing effective restoration projects in estuaries? What are the site goal(s) in estuaries as they currently exist given historic and future land use?
- How can we most effectively mimic natural processes without having to over design or over engineer them?
- How to design projects in a manner that increases resilience of controlling factors to CC (e.g. will increasing tidal freshwater prism increase the system's resistance to upstream salt wedge migration?; If much of river sediment is being firehosed out to deep water due to dike system, are there ways to enhance sediment capture in marsh habitats? Are there better locations or designs for dike removal projects that will result in greater sediment capture?) Should we excavate channels during restoration or allow natural evolution of geomorphology? What are the system-scale effects of a dike project (e.g. how are salinity/sediment/hydraulic conditions affected outside the project footprint)? Do different types of estuarine habitats require active revegetation? Are there some that seldom require active revegetation? Is LWD important to geomorphic development in estuaries and project sites? Is LWD important to fish and bird use of estuarine habitats?
- comparison of costs/benefits of dike breach vs. removal -active vs. passive approach to reversing subsidence
- How can I minimize or avoid "designing" and "engineering" restoration projects?
- Predictive effects
- plant species-elevation relationships sea level rise from climate change relative effectiveness of hydrological reconnection methods: dike removal, dike breaching, tide gate, culvert, at creating channel network.

20) What do you think are the most common and important questions that, if answered, would improve your ability to evaluate/monitor coastal habitat restoration projects more effectively?

- Most of the same questions as in #19, especially the first one. The reference data used for design are also used for evaluation. If we understand processes that form tidal wetlands, we will be much better able to evaluate whether we are successfully restoring those processes.
- Simplification of benthic invertebrate analyses that would reduce per sample costs by using indicies or indicator species. multivariate analysis of multiple ecosystem function surrogates to evaluate the realtive importance of different soil parameters as predictors of key ecosystem functions.
- Why don't more restoration grant programs support effectiveness monitoring at useful and realistic funding levels?
- How long does it take for a wetland to achieve natural conditions?
- 1. Vertical control network (see Q19). 2. What is the relationship of physical habitat measures to biological productivity?
- What are the best indicators of a specific restored system's health? Project owner's funds must be used efficiently in the monitoring phase through selection of fewer, essential indicators. This, in turn, results in longer term, fully funded monitoring regimes and increases the potential for collaborative adaptive management.
- What parameters correlate well with with complex and self-regulating functional recovery? What parameters indicate functional recovery trends that are not subject to year-to-year variation. How can invertebrate monitoring be simiplified to reduce per sample costs while providing ecologically meaninful information.
- Which species or thresholds for biogeochemical processes are most predictive of long term project success
- What are the outcomes we are looking for from a restoration project, and what are the best ways to evaluate success?
- Which of the many measures are the best to monitor effectiveness of wetland restoration?
- Funding for monitoring is the bottleneck, not information.
- a better resolution of the key controlling factors vs vegetation tolerances. Could reduce number of paramters. Better understanding of time for full development of a stable system.
- Where is the overarching oversight needed to organize researchers and managers into using common protocols and standardized data management systems? How can we get researchers to listen to managers when we tell them what tools are missing in the toolbox and then to help us develop them instead of taking our ideas, developing what they think we need, and then handing us back something that often misses the original target?
- 1) what is the post-project geomorphic stability; 2) how have important species responded; 3) have multiple goals been met (e.g., reduced flooding of pasturelands, improved estuarine aquatic habitat)?
- What are the most important parameters to monitor per habitat restoration or enahcement type? I believe that the questions will differ per type of "restoration"
- What elements are most critical to monitor to determine success / failure, and for how long?
- What parameters will alert me to a project's fate in the face of rising sea levels? How do I measure resilience to change? Is there a quick way to measure pore-water salinity? Is there an affordable way to monitor inorganic and organic accretion rates? How do we measure ecological function or infer it from structure? What reference sites/data are available? Long-term data sets? Is there a way to coordinate regional aerial photo/IR photo efforts to make site-specific photo acquisition more affordable? How do we store and manage long-term data sets? Is there a way

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to coordinate/share regional modeling expertise?

- what are the most important attributes to monitor in PNW estuaries?
- What is the desired outcome of the restoration?
- What do we want to see?
- Background variability in the system, intraannual and interannual.
- I think that distinguishing between site characteristics that can be measured remotely and those that need to be either ground truthed or measured directly in the field is important. Many characteristics about distribution of vegetation and sediment types, sediment temps, water temps, can be measured remotely and remote monitoring will provide data at a more appropriate scale. Sampling for higher resolution data as direct data or as ground truth data can then be designed based on the remotely sensed data.

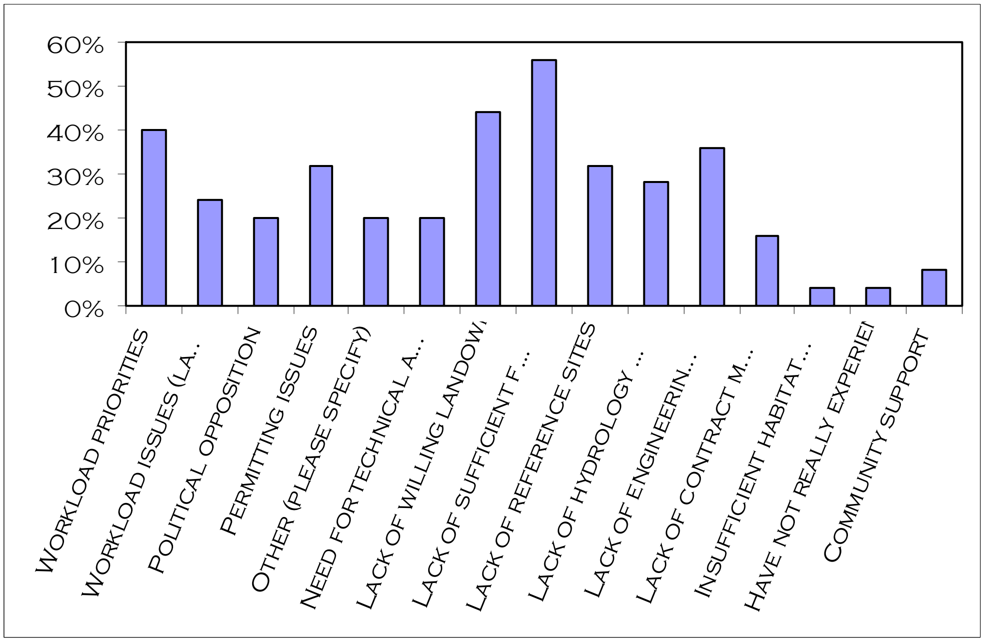
Answered	24
Skipped	7

21) In general, what information do you need to improve your ability to complete high quality estuarine wetland restoration projects?

- Continuous synoptic aggregation and redistribution of scientific literature on a heirarchy of restoration topics to reduce the need for independant literature review for each action.
- WE need more tidal hydrologists to provide site/project specific guidance.
- Elevation data, vegetation data
- 1. Vertical control network. 2. Readily available and usable tidal elevation modeling
- Reference site best management practices; design and construction elements, initial rates of naturalization, long term indicators of systems strength (both bio and hydro).
- Develop sustained (but not necessarily substantial) funding sources that can effectivel catalyze long-term habitat site stewardship? Develop a mechanism for transfering non-quantitative information on best practices and procedures between practitioners. Develop best methods and certificated training for earthwork and revegetation work for habitat restoration.
- Need indicators that are cheap, practical, accurate, and highly predictive.
- Access to information on similar projects, as well as information of how to obtain planting success in the midst of heavy animal disturbance (deer, elk, beaver).
- See answer to question 19 above.
- geomorphic predictions of habitat change at the estuary scale over time frames of ~100 years
- I need funding more than information.
- see 19 and 20
- I need to know how to get my agency to prioritize positions dedicated to collecting and assess monitoring data with the goal of putting the results into useable formats that can be turned around and used by mitigation and restoration practitioners.
- funding aimed at cost-effective projects with an emphasis on utilizing local expertise
- A list of willing volunteer land owners who would be willing to conduct restoration on their lands.
- See above responses. Reference sites and long-term data sets. Knowledge of how estuarine controlling factors are vulnerable to climate change and the mechanisms that are most effective at reducing vulnerability. Greater modeling ability.
- -how to move forward in the face of uncertainty
- A more landscape-scale perspective.
- Social buy in
- Long-term vision that includes substantial funding for monitoring and adaptive management.
- Access to remote sensing data (aerial photo, side-scan, multibeam, lidar, etc.)

Answered	22
Skipped	9

22) In your experience, what obtacles, if any, have impeded your ability to implement high quality estuarine wetland restoration projects?



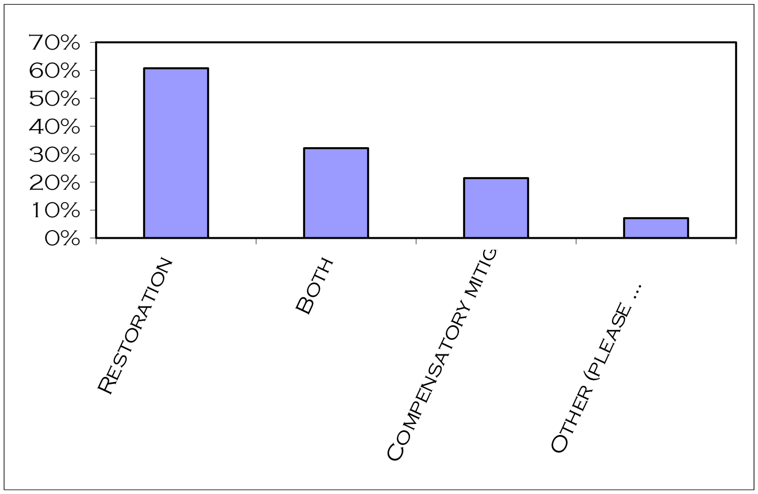
Workload priorities	40.00%	10
Workload issues	24.00%	6
Political opposition	20.00%	5
Permitting issues	32.00%	8
Other (please specify)	20.00%	5
Need for technical assistance	20.00%	5
Lack willing landowners	44.00%	11
Lack sufficient funding	56.00%	14
Lack reference sites	32.00%	8
Lack hydrology expertise	28.00%	7
Lack engineering/modeling expertise	36.00%	9
Lack contract management experience	16.00%	4
Insufficient habitat maps	4.00%	1
Have not experienced any obstacles	4.00%	1
Community support	8.00%	2

Anwered	25
Skipped	6

Other (please specify)

- lack of learning from previous projects or from similar projects completed by other practitioners; no feedback loop. Conflicting land use (industrial ports).
- lack of rigorous/accountable planning and design methodology - 'wiki design' by stakeholder and science advisory groups. - confusion over the difference between restoration as scientific research and restoration as applied science. Sciencism, including the emphasis on uncertainty rather than what we know how to do can be self defeating
- Knowledge and time
- I've had very satisfying experiences to date with restoration, and I believe the results have been good quality. But, improvements could always be made, and there's a lot of potential out there. It would be nice to have all the above bases covered (pie-in-skying).
- Lack of tidal geomorphology expertise.

23) What kinds of estuarine wetland projects do you work on?



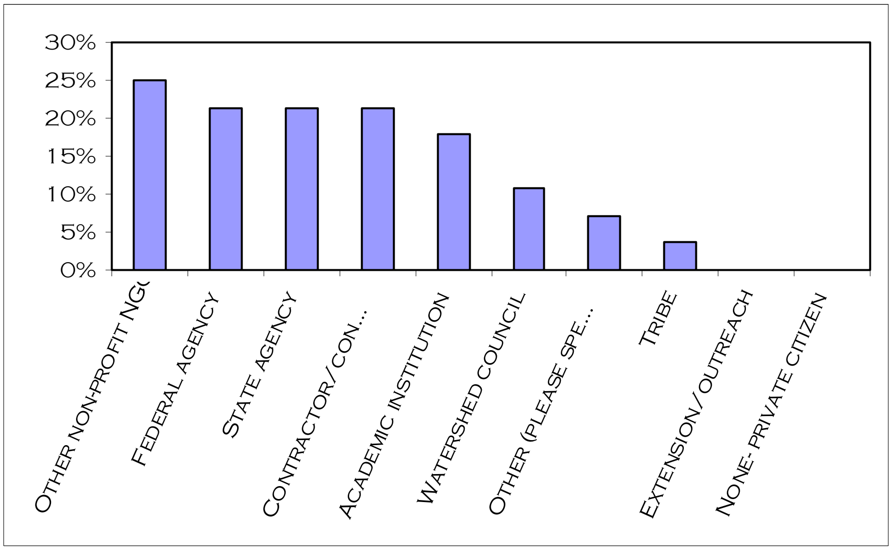
Other (please specify)

- assessment & prioritization of key activities required to protect & restore estuarine habitats for biodiversity, and methods for evaluating restoration and protection activities
- Research

Restoration	60.71%	17
Both	32.14%	9
Compensatory mitigation	21.43%	6
Other (please specify)	7.14%	2

Answered	28
Skipped	3

24) What kind of organization(s) are you most closely associated with?



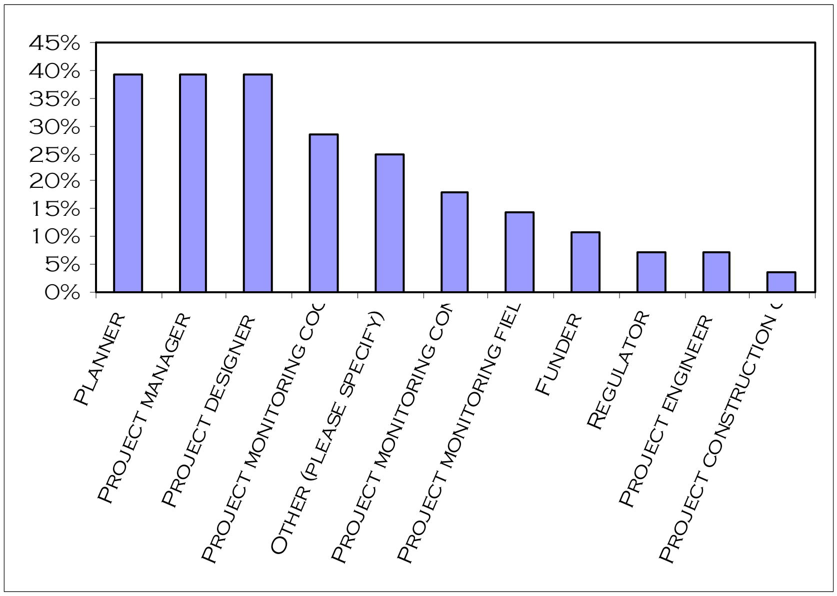
Other non-profit NGO	25.00%	7
Federal agency	21.43%	6
State agency	21.43%	6
Contractor/consulting firm	21.43%	6
Academic institution	17.86%	5
Watershed council	10.71%	3
Other (please specify)	7.14%	2
Tribe	3.57%	1
Extension/outreach	0.00%	0
None- private citizen	0.00%	0

Other (please specify)

- non-profit research
- Soil and Water Conservation District

Answered	28
Skipped	3

25) Which of the following descriptions most closely match your role in estuarine wetland restoration and/or compensatory mitigation projects?



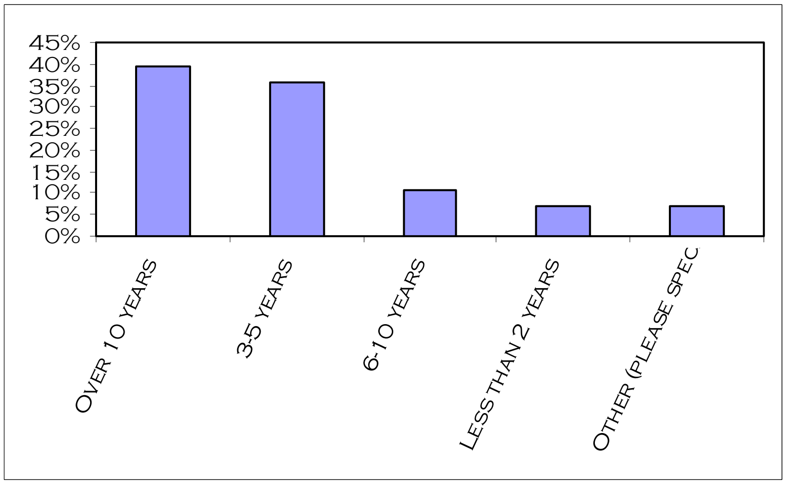
Answered	28
Skipped	3

Planner	39.29%	11
Project manager	39.29%	11
Project designer	39.29%	11
Project monitoring coordinator	28.57%	8
Other (please specify)	25.00%	7
Project monitoring contractor	17.86%	5
Project monitoring technician	14.29%	4
Funder	10.71%	3
Regulator	7.14%	2
Project engineer	7.14%	2
Project construction contractor	3.57%	1

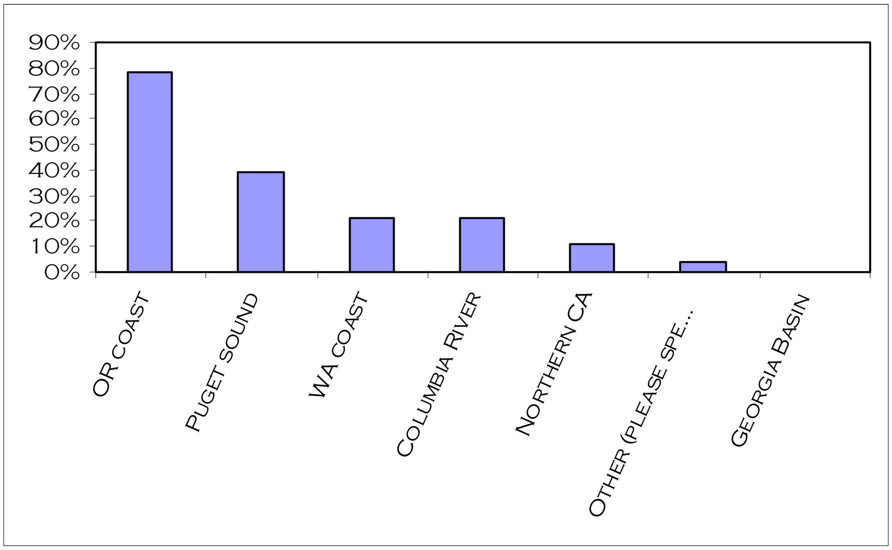
Other (please specify)

- Prepare grant proposals to obtain funding.
- organization scientist
- Scientist charged with evaluating effectiveness of policy and regulation.
- Research Scientist
- Researher
- researcher
- Data analyst

26) About how many years have you been working with any aspect of estuarine wetland restoration and/ or compensatory mitigation projects?



27) In what region(s) have you been working on estuarine wetland restoration and/or compensatory mitigation projects?



Answered	28
Skipped	3

Oregon coast	78.57%	22
Puget Sound	39.29%	11
Washington coast	21.43%	6
Columbia River	21.43%	6
Northern California	10.71%	3
Other (please specify)	3.57%	1
Georgia Basin	0.00%	0

Other
Hudson River

28) What did you think of the format and/or content of this survey? Please comment on how it could be could be improved in the future.

- Very good. Lots of thought went into this!
- Good and easy to use.
- overall I am very excited to learn about the results. And those results will better define the effectiveness of the survey than anything I can say!
- Mostly liked it. Very straightforward and user friendly. Some of the choices should have been framed or worded more precisely.
- Good format and content
- Good set of questions.
- Nicely done
- Good.
- very good
- Answers to some of the questions depend specifically on the type of habitat restoration or enhancement.
- Reasonable; keep time required to complete ~5 - 10 minutes!
- Overall great effort. Could not however answer the question on most important parameters, without separating the habitat types (to solve this you could merge all of the vegetation types into one, e.g. vegetation percent cover, vegetation stem density). Also would have been useful to separate the kind of roles one plays in restoration up front, and then to track different respondents to different questions; i.e. I had to leave the questions about restoration implementation blank because although I have my opinions and vicarious experiences I really just monitor restoration projects.
- It would have helped to know what the goals were...could perhaps tailor answers better. Hard survey to construct, I'm sure.

Appendix 13. Presentations by CICEET Project Team

2006-2007

Brophy, Laura. Estuary Assessment and Prioritization: The Oregon Method. Oregon Watershed Enhancement Board Biennial Conference. Seaside, Oregon. October 25, 2006.

Brophy, Laura. Monitoring and characterization of reference conditions for tidal wetlands in the Siuslaw estuary. Siuslaw Watershed Initiative partners meeting, Mapleton, Oregon. January 4, 2007.

Brophy, Laura. Estuarine Wetlands 101. West Coast Symposium on the Effects of Tide Gates on Estuarine Habitats and Fishes. South Slough NERR, Charleston, Oregon. October 31-November 2, 2006.

Brophy, Laura. Ecological monitoring for tide gate design and evaluation. West Coast Symposium on the Effects of Tide Gates on Estuarine Habitats and Fishes. South Slough NERR, Charleston, Oregon. October 31-November 2, 2006.

Brophy, Laura. Restoration design and monitoring at oligohaline forested tidal wetland sites on the North Fork Siuslaw River. Regulatory review meeting, Oregon Department of State Lands, Salem, Oregon. February 2, 2007.

Cornu, Craig. South Slough NERR Estuarine Wetland Advisory Group Meeting (coordinated and conducted by Craig Cornu and others at South Slough NERR). Charleston, Oregon. July 11-12, 2007.

Brophy, Laura. Oregon Estuarine Wetland Reference Site Study. South Slough NERR Estuarine Wetland Advisory Group Meeting , Charleston, Oregon. July 12, 2007.

Brophy, Laura. Estuary prioritization and assessment. Oregon State University Hydrophiles Seminar Series, Oregon State University, Corvallis, Oregon. March 7, 2007.

Tully, Rebecca. In-Situ Multichannel Wireless Sensor Networks and iButton Temperature Logger Arrays for Characterizing Habitat Drivers in Tidal Wetland Reference Sites. Student seminar series, Oregon State University College of Oceanic and Atmospheric Sciences, Marine Resource Management Program. Corvallis, Oregon. April 20, 2007.

Brophy, Laura. Tidal Wetland Restoration in Oregon: Resources and Approaches. Guest lecture to Coastal Ecology and Resource Management class, Hatfield Marine Science Center, Oregon State University, Newport, Oregon. September 23, 2007.

Brophy, Laura. Tidal Swamp Restoration in the Siuslaw River Estuary. Video segment for EPA Targeted Watersheds Initiatives Grants outreach program. September 2007.

2008

Tully, Rebecca. The use of low cost “iButton” Temperature Logger Arrays to Generate High Spatial Resolution Tidal Inundation Regime Data. Masters’ Research Project final seminar, Oregon State University College of Oceanic and Atmospheric Sciences, Corvallis, Oregon. March 2008.

Brophy, Laura. Estuary Assessment and Prioritization: The Oregon Method. Presentation to Pacific Estuarine Research Society, Newport, Oregon. March 1, 2008.

Brophy, Laura. Estuary Assessment Training. Southern Oregon Community College, Coos Bay, Oregon. June 10-12, 2008

Brophy, Laura. Site-Scale Monitoring for Tidal Wetland Restoration and Conservation. Joint Meeting of the Association of State Wetland Managers and the Pacific Northwest Chapter of the Society of Wetland Scientists, Portland, Oregon. September 2008.

Brophy, Laura. Steps to Successful Tidal Wetland Restoration. Oregon Watershed Enhancement Board Biennial Meeting, Eugene, Oregon. November 2008.

Cornu, Craig. Piloting a Regional Reference Site Network Designed to Improve Tidal Wetland Restoration Planning and Monitoring. Restore America's Estuaries National Conference, Providence, Rhode Island. October 2008.

Brophy, Laura. Oregon Estuarine Wetland Reference Site Studies at Oregon Coast National Wildlife Refuge Complex sites. Field trip, restoration science leaders from USFWS and USGS, Oregon Coast. September 2008.

Brophy, Laura. Oregon Estuarine Wetland Reference Site Study. Guest lecture to Coastal Ecology and Resource Management class, Oregon State University/Hatfield Marine Science, Newport, Oregon. September 2008.

2009

Adamus, Paul. Oregon Wetland Assessment Protocol (ORWAP) training sessions. Oregon Division of State Lands, Salem, Oregon and field sites. July 2009.

Brophy, Laura. Building a blueprint for restoration: Using high-accuracy land surface elevation survey, electronic sensors, and tidal inundation regime modeling to link site structure and function in least-disturbed estuarine wetlands of Oregon, USA. Coastal and Estuarine Research Federation 2009 Biennial Conference, Portland, Oregon. November 5, 2009.

Brophy, Laura. Analyzing fluvial and tidal components of inundation regimes in outer coast estuaries of Oregon. Center for Coastal Margin Observation and Prediction, Oregon Health and Science University, Beaverton, Oregon. October 23, 2009.

Brophy, Laura. Developing a reference conditions database for tidal wetland restoration in Oregon. U.S. Forest Service Northwest Oregon Ecology Group, Corvallis, Oregon. December 8, 2009.

Doumbia, Julie. Temperature Sensor Method for Detecting Tidal Inundation Period and Frequency Coastal and Estuarine Research Federation 2009 Biennial Conference, Portland, Oregon. November 5, 2009.

2010

Adamus, Paul. Potential Effects of USFWS Actions on Carbon in Wetlands. USFWS staff training session on Ecosystem Services in Salem, Oregon. September 8, 2010.

Brophy, Laura. Making the coastal connection: Progress and opportunities for tidal wetland restoration in the Umpqua River estuary and beyond. Keynote presentation to the Annual Meeting of the Partnership for the Umpqua Rivers, Elkton, Oregon. July 20, 2010.

Brophy, Laura. Building a blueprint for tidal wetland and salmon habitat restoration in Oregon in collaboration with the National Geodetic Survey and the Center for Operational and Oceanographic Products and Services. NOAA Hydrographic Services Review Panel, Vancouver, Washington. October 12, 2010.

Brophy, Laura. Tidal wetland hydrology in Oregon: New tools for defining reference conditions, mapping resources, prioritizing actions, and evaluating project results. Workshop on Estuaries, Climate Change, and Conservation Planning, Newport, Oregon. November 19, 2010.

Doumbia, Julie. Temperature Sensor Method for Detecting Tidal Inundation Period and Frequency. Presentation to the Oregon State University College of Oceanic and Atmospheric Sciences weekly seminar series, Corvallis, Oregon. February 5, 2010.

Doumbia, Julie. Use of the Temperature Sensor Method for Detecting Tidal Inundation Regime in Chinese Mangrove Habitat. Masters' Research Project final seminar, Oregon State University College of Oceanic and Atmospheric Sciences, Corvallis, Oregon. September 7, 2010.

Huang, Lijuan. South Slough NERR/Oregon State University CICEET Project Overview. NOAA Brown Bag seminar series, Silver Spring, Maryland. August 25, 2010.

2011

Brophy, Laura. Estuarine wetland responses to sea level rise. Pacific Northwest Climate Science Conference, Seattle, Washington. September 13, 2011.

Brophy, Laura. Effectiveness monitoring at the Pixieland tidal wetland restoration site. Salmon Drift Creek Watershed Council, Neotsu, Oregon. July 26, 2011.

Brophy, Laura. Estuarine wetland responses to sea level rise. Guest lecture, Hatfield Marine Science Center, Newport, Oregon. May 16, 2011.

Brophy, Laura. Estuarine wetland responses to sea level rise. Siuslaw National Forest Coast Range Climate Change Workshop, Yachats, Oregon. May 16, 2011.

Brophy, Laura. Tidal wetland restoration monitoring: Multi-project integration in Oregon. Estuary Restoration Science and Monitoring Workshop, USGS Western Fisheries Research Center, Seattle, WA. April 1, 2011.

Brophy, Laura. Estuarine wetland responses to sea level rise. National Research Council Committee on Sea Level Rise in California, Oregon and Washington. Portland, Oregon. March 28, 2011.

Brophy, Laura. Addressing climate change in tidal wetland restoration and conservation planning: New tools and approaches. Workshop on Modeling for Estuaries, Climate Change, and Restoration and Conservation Planning. Newport, Oregon. February 1, 2011.

Cornu, Craig. Partnership For Coastal Watersheds. NERRS Stewardship Coordinators annual meeting in Mount Vernon, Washington. February 2011.

Cornu, Craig. Estuarine Marsh Habitats in the Oregon: Perspectives from the South Slough NERR. Oregon Department of State Lands Regulatory Professionals Estuarine Wetlands Training, Salem and Newport, Oregon, January 2011.

Doumbia, Julie. Use of the Temperature Sensor Method for Detecting Tidal Inundation Regime in Chinese Mangrove Habitat. Pacific Estuarine Research Society Annual Meeting, Astoria, Oregon. March 4, 2011.

Appendix 14. Acknowledgments

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