Addressing Elevation and Inundation Issues in Habitat Restoration Planning and Implementation

A Guidance Document

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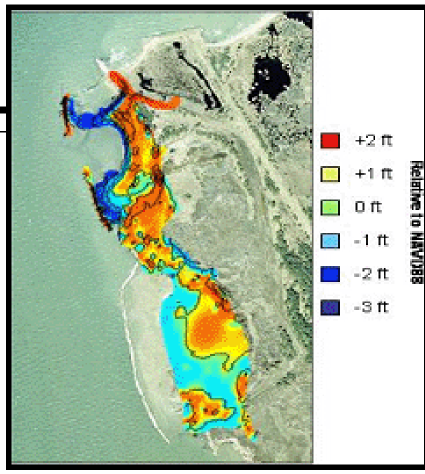

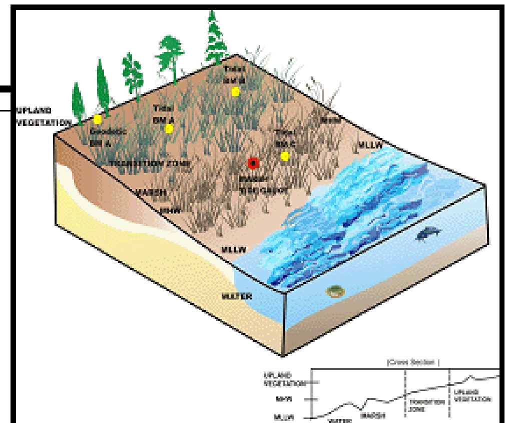

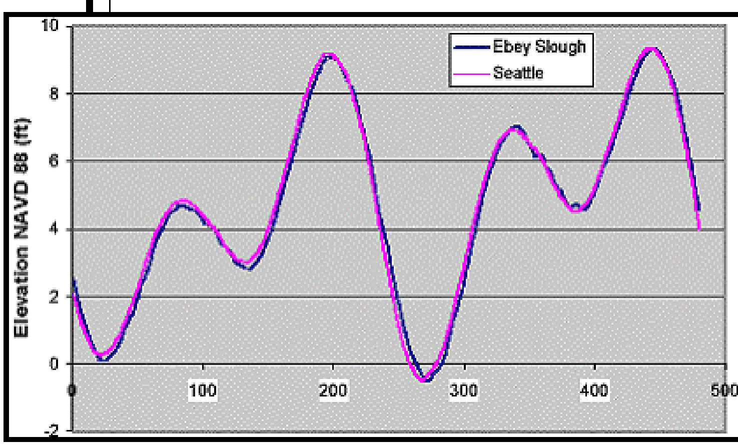

National Ocean Service

Direct comments and/or edits to Tracy Minick - Tracy.Minick@noaa.gov

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Draft May 2004

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I. Purpose and Background

This document is for coastal restoration professionals in government, industry, academia, and non-governmental organizations who need to know **whether and how** to use geodetic positioning tools, water level information, and other technologies to support restoration project planning and implementation. Restoration projects must consider the requirements necessary for vegetation to grow successfully, the environment that will allow target species to flourish, the long-term stability of the habitat, and the preservation of surrounding properties. Restoration planners and practitioners may not be aware of new tools and technologies which may assist with construction designs, determining elevation requirements, and evaluating potential inundation scenarios. This document is designed to illustrate how NOS' tools and methods can be applied to restoration projects. These include the measurement of geodetic and water level data, the determination of reference elevations from these data, and the application of the information to a project area. Necessary measurements include geodetic positioning using GPS or traditional land leveling, water levels using water level gauges, and physical environmental characterization using wind sensors or current and wave measurement systems. Geodetic and water level information are integrated to produce a baseline elevation map (or Digital Elevation Model) of a project area. Case studies are presented in this document to illustrate typical concerns, evaluation techniques, and potential solutions.

An increasing number of wetland restoration projects have been initiated around the country. While many success stories exist, several restoration projects have failed due to poorly understood water level and land (geodetic) elevations at the restoration site. Understanding water level (tidal) elevations is important for flood control, and because many species of plants and animals rely on habitats defined by very narrow (on the order of centimeters) elevation contours. Due to the high ecological value of wetlands, (note: incomplete thought, so deleted) and the political backlash when a restoration project fails to deliver as promised, it is essential that managers be aware of the potential limitations and sources of uncertainty inherent in a wetland restoration plan. It is equally important that the practitioners who devise and implement these plans understand how to develop and apply information to minimize potential errors. It is hoped that this document will provide basic approaches to gaining the reference information required for appropriate planning that minimizes errors in the planning and implementation phases of a project. Both design and monitoring phases may require information on tide and geodetic datums, waves, and currents. Waves and currents can be important contributors to coastal erosion and, therefore, understanding them is important when designing restoration projects (as well as other coastal engineering projects).

This guidance document introduces the application of datums to habitat restoration. A datum can be either horizontal or vertical. For many marine applications, a vertical datum is a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide and is determined by measurements from a tide gauge. Examples are Mean High Water (MHW), the reference mapping datum for the National Shoreline, and Mean Lower Low Water (MLLW), the NOAA Chart Datum reference for soundings in tidal waters. For land-based references, a geodetic datum is a fixed reference determined by horizontal and vertical nation-wide network surveys. The surveys used traditional land leveling techniques and currently utilize high precision GPS surveying. The North American Vertical Datum established in 1988 (NAVD88) is the existing geodetic vertical reference datum for the U.S. This datum was established using a nation-wide network adjustment to a specific geoid surface. Established bench marks (survey disks and monuments) are connected to measurement systems for both tidal and geodetic datums. This preserves the elevations of the datums relative to the land. Tidal and geodetic datums can have complicated and varying elevation relationships depending upon the geographic area and its water level variations.

II. Identifying Project Needs/Applying the Techniques

This document describes how geodetic and water level data can be applied in coastal habitat restoration. The application of these technologies can help to both maximize the success and effectiveness of restoration projects and minimize the risk to adjacent properties. This document does not attempt to describe detailed methods, but rather gives project managers enough background on the tools to facilitate planning and project management. The appendix contains detailed references for each section.

Seven basic questions must be answered prior to beginning any restoration project:

1) What are the basic conditions of the project area now?
2) What is the nature of the critical variations of the water levels, tides, currents and waves?
3) What is the physical setting of the project area?
4) What environmental and human stressors affect the area?
5 What are the goals for the restoration project?
6) How much functionality is desired?
7) What are the timelines and budget for the project?

Most marsh restoration projects require significant engineering study and analyses. In determining which precise engineering analyses are needed, begin by considering the goals of the project and associated information needed to successfully implement those goals. Generally, habitat restoration activities are intended to improve ecological or human use functions. These functions might include spawning or breeding for fish and wildlife; shoreline stabilization; flood control; sediment trapping; or nutrient recycling. To improve these functions, it may be necessary to establish specific types and patterns of vegetation, create streams or channels with specific water flows and depths, stabilize a shoreline, or allow a mudflat to be exposed for a specific number of hours per day. In some cases, establishing appropriate physical characteristics of slope and substrate may be all that is required to restore function to a habitat. Many projects require the breaching or removal of existing levees, the grading of existing topography, the deposition of dredged material, and the construction of new sloughs and ponds. The preliminary designs may include several alternatives for consideration. The surrounding land use and water conditions may indicate potential problems associated with implementing your project. There may be concerns about flooding adjacent properties. If the shoreline is exposed to heavy wave action, it may be more difficult to stabilize. The local area may be subsiding and habitat may not persist over time. In some instances, a restoration project may be underway, and more precise elevation information is required before proceeding or for evaluating options.

Some basic information that could help improve project design, depending on the scope of the project, may include:

For planning:

- The tidal prism before and after construction
- Knowing the seasonal or average tidal stages for hydraulic model input
- The tidal and residual circulation patterns, wave patterns, morphological studies, and sediment budgets
- Existing and future coastal erosion rates due to currents, waves and flooding
- How present and future water levels may affect surrounding infrastructure (for instance, upland levees, drainage, existing marshland, existing and planned development for population and industry)
- Geographic scope of the project

For design and implementation:

- How to access the site with heavy equipment; how to physically perform the construction
- How to design the details of the marsh topography in terms of upland and lowland marsh, seasonal wetlands, permanent ponds, etc.
- How to design functional tidal sloughs
- How much and where to place needed dredged material
- Where and how high to place protective structures such as geotubes, breakwaters, new levees and drainage
- The characteristics of the frequency and duration of inundation of the high waters at various elevations of existing and future marsh topography that will allow for proper planting
- The decision to apply hydraulic and hydrological modeling techniques

Considerations for monitoring include:

- The impact of repeat frequency of storm surges on the marsh
- The effects of existing rates of long-term sea level rise and subsidence on the project
- Marsh sedimentation rates (both existing and predicted)
- How water levels and elevations will affect evolution to a functioning marsh
- How water levels and storm surge elevations will affect the need for design changes and corrective measures over time
- The long-term stability of geotubes and other protective engineering structures
- The long-term functionality of newly created sloughs and ponds
- The availability of dredged material over time
- The plant growth and stability

Knowledge of tides and water levels, tidal and geodetic datums, and other important physical parameters (waves, currents, meteorology) may be critical to all phases of a restoration project. There are two important aspects of the application of this information. First, understanding the time-varying nature of the parameters at the marsh site is fundamental to the engineering, design, and post-construction monitoring of the marsh. Assessing impacts of the variation extremes over time is also required. Second, the reference levels and long-term average values are important baseline information for planning and feasibility studies. These levels and values are also important for establishing reference vertical datums for topographic and hydrographic surveys required for the engineering designs.

For example, elevation issues include determining how much of the site will be under water when any existing obstructions to water flow are removed or altered. Pre-project elevations and final elevations should be determined to inform decisions on material grading and volume. The amount of material placed at the site and how it is graded will determine which areas will be under water in different tidal, storm, and flooding conditions. Typically marsh creation uses continuous planting, which involves placement of planting units at a certain distance on-center over the whole site. Once the site fills in (coalescence), the habitat type may be unbroken continuous marsh. Planting the marsh with discrete access corridors based on lower elevation tidal inflow guts may enhance faunal use and marsh success.

In most projects, follow-up monitoring to determine success has been typically limited to evaluating vegetation persistence, and the persistence of the site or function of the habitat. Longevity and resiliency of the created sites have not been fully determined. The methods used and data obtained to evaluate vegetation and topography of marsh restoration remain largely the same as that typically collected for many projects. However, the frequency might need to be increased regularly or for specific short durations. Additional analyses will come from the comparison (both statistically and geo-referenced) and correlations of vegetative and hydrologic results. If possible (and desirable), the collection of monitoring data can be used to calibrate and refine models and analysis. This type of on-going monitoring is also useful in evaluating the effectiveness of predictive models and modifying the model. Long-term management goals can also be supported by incorporating feedback from monitoring into modifications or trend evaluation.

Marsh edge change (advance or retreat) can be designed based on known marsh elevations prior to planting, but resulting marsh edge should be correlated back to tidal height, storm surge, and length and depth of inundation. To be successful, a site must have enough tidal flux to alternately flood and drain the marsh. Elevation, slope and tidal regime are the primary influences on hydrology. All of these together determine the extent of the intertidal zone. Detailed site-specific data on inundation cycles, water surface elevations, and frequency tidal data can help determine the amount of time the marsh surface is inundated by water since vegetation is sensitive to amount of time it is dry versus wet.

Exposure to waves can also be a limiting factor in establishing tidal marsh vegetation. The orientation of shoreline and the amount of fetch (the distance the wind travels over the water) can influence the success of establishment, especially if wave activity dislodges plants before they establish a root system. Long-term, seasonal site surveying is required to evaluate sediment erosion and transport through elevation change. The changes will also define the natural hummocks (rises) and pannes (pooled low lying area) that may be too wet or dry and thus require different vegetation. These surveys will inform decisions about pre-planting by site contouring or post planting following settling, scour and deposition.

III. Summary of Methods

A. Geodetic Control

The safety and efficiency of the buildings we live and work in, the roads and bridges we drive on, the trains, airplanes, and ships that carry the products we use every day, all depend on a universally compatible system of geodetic reference points that tie our nation together. Geodesy is the basic ability to determine the location of a particular point in three-dimensional space, and to accurately relate it to another point. Small, even centimeter-level, variations in water level differences can have significant ramifications in levels of inundation, legal boundaries, impacts on ecosystems, and depth-sensitive organisms. Being able to confidently determine accurate heights is crucial to successful marsh restoration.

NOAA’s National Geodetic Survey (NGS) manages the National Spatial Reference System (NSRS) which is the national coordinate system that defines latitude, longitude, height, scale, gravity and orientation throughout the United States. NSRS comprises a consistent, accurate, and up-to-date national shoreline; a network of continuously operating reference stations (CORS) which supports 3-dimensional positioning activities; a network of permanently marked reference points (or bench marks); and a set of accurate models describing dynamic, geophysical processes that affect spatial measurements. Establishing geodetic control for a project means performing the field surveys and measurements necessary to tie in project survey reference systems with the NSRS, thus providing consistent and accurate geodetic control to national standards. The restoration project survey reference systems might be engineering drawings, topographic surveys, bathymetric surveys, or biological transects. The tie–in of the existing project references and the creation of new reference systems into the NSRS make the application more useful, extendable, and recoverable. Geodetic control uses horizontal and vertical national reference datums.

The national vertical reference datum, as mentioned earlier, is NAVD88, which has superceded the older National Geodetic Vertical Datum of 1929 (NGVD29). NGVD29 has also been misused as representing mean sea level (MSL). Establishment of NAVD88 was not based on variations on mean sea level around the coasts. NGVD29, although originally based on fitting mean sea level elevations from tide stations around the coasts, no longer has any meaningful relationship to present mean sea level elevations. For surveys using reference maps with NGVD29 as the reference, updated maps should be prepared using NAVD88. This transformation may require updated surveys using leveling or GPS, depending upon the existence of geodetic control points or bench marks in the project area. Whereas NAVD88 is a vertical datum reference, the present horizontal reference datum maintained by NGS is North American Datum 1983 (NAD83). Having knowledge of the horizontal and vertical datum reference used in existing or older site maps and drawings is important so that they can be translated into updated reference systems. Using GPS surveys tied to the Continuously Operating Reference System (CORS) network is the key to establishing horizontal and vertical control in project areas. **Figure 1** shows the configuration of the present CORS network.

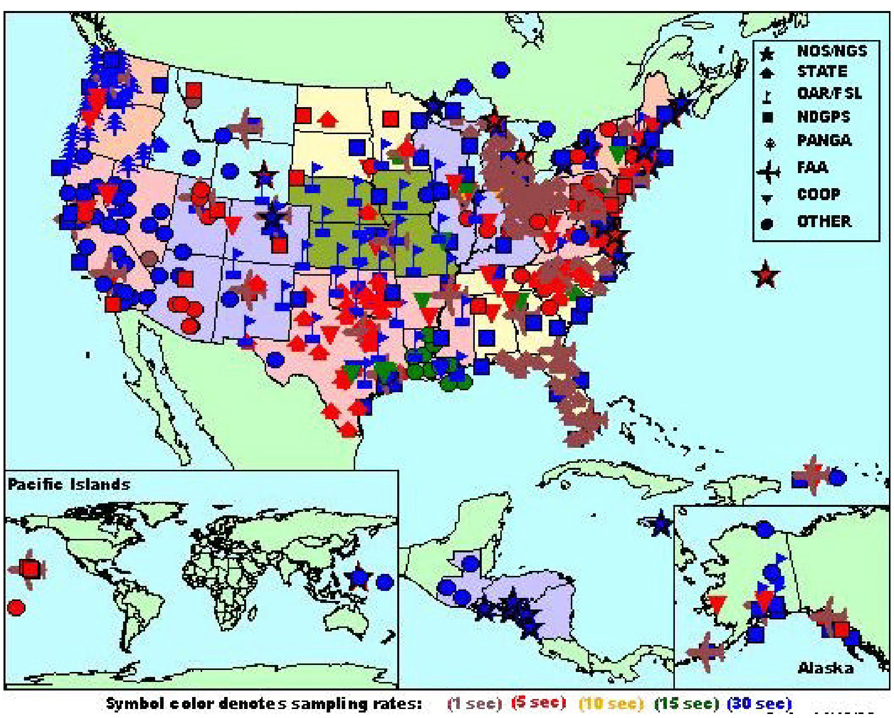


Figure 1. The national Continuously Operating Reference System (CORS) of GPS systems.

Steps involved in establishing geodetic control for a typical marsh restoration site may include:

1) The first step in any geodetic control survey should always be to coordinate with interested local parties. Coordination is especially important in high visibility undertakings such as marsh restoration projects. The State and local surveying organizations should be contacted not only to notify them of the upcoming survey, but to find out if they are interested in participating in the survey. The primary mechanism for doing this is through the NGS State Geodetic Advisors.

2) The next step is to determine what geodetic control may already exist in the project area. Inquire with the State and local surveying organizations to learn of any geodetic control they may have established. NGS maintains an extensive database of geodetic control information contributing to NSRS. Search the NGS database, for whatever geodetic control may already exist in the area of the marsh and has been archived by NGS. Data sheets are a standard product of NGS, which provide information about a geodetic control station's location, its coordinates, and other ancillary data.

3) Existing high accuracy geodetic control stations are the starting points for marsh restoration surveys. If there are any GPS Continuously Operating Reference Stations (CORS) in the area, they should be included. Also include High Accuracy Reference Networks, which include the Federal Base Network (FBN) stations and/or Cooperative Base Network (CBN) stations in the area. Data sheets for both FBN and CBN stations are available from the NGS database. These high accuracy stations, along with the CORS provide the foundation for these types of surveys.

4) Once the contacts have been made and the data retrieved from the NGS database, visit the site and perform an initial reconnaissance to ensure the marks in the database still exist and are usable. It's also a good idea to see the terrain and get a sense of what logistics will be necessary for accomplishing the survey.

5) The actual field survey will establish one or two geodetic control stations at or near the marsh site. The time required for GPS observations depends upon how far away the existing high accuracy control is.

6) The data from the field is then processed and adjusted in accordance with procedures described in Input Formats and Specifications of the National Geodetic Survey, known as the "NGS Blue Book" procedures. The final adjustment will produce coordinates on the NAD83, along with heights on NAVD88, and, when loaded into the NGS database, will become part of the NSRS.

The appendix to this document includes the references for the detailed explanation of terms, programs, and the details of the instrumentation and field procedures necessary and a complete list of the URL references for specific topics.

B. Tides and Water Levels

Tide stations are measurement systems that are installed at desired locations in the coastal zone for the purpose of measuring the rise and fall of the water level over time and for determining tidal datum elevations relative to the land. Within NOAA, tide stations are established as part of an "end-to-end" system of data collection, quality control, data management, and product delivery for NOAA's National Water Level Program (NWLP). Data (observations) from tide stations are processed and analyzed to produce standard output products such as tidal datums and tide predictions. The NWLP and its methodologies and standard operating procedures for data collection and production of tidal datum products are seen as national standards for certification of information for legal applications and for technology transfer. The NWLP is seen as a national authority and NOAA accepts responsibility for the accuracy of its products.

A tide station configuration consists of a physical structure on which the data collection platform (DCP) or data logger, power supplies (solar panel) and communications components such as satellite or line-of-sight radios are mounted; the water level sensor(s) installed above or below water depending on type, ancillary sensors (such as wind and barometric pressure); and a local bench mark network. The water level sensors reference points are connected to the local bench marks by differential leveling. In this way the water levels and the tidal datums computed from the water level measurements can be determined relative to the land. The hourly heights and the times and heights of high and low waters are tabulated from the measurements, monthly means are computed, and tidal datums are computed from the tabulations and monthly means. Monthly means and tidal datums, such as Mean High Water (MHW), are computed from the means of the high tides tabulated each day.

The tidal datums are referenced to specific 19-year periods called National Tidal Datum Epochs (NTDEs). The present NTDE in use is the 1983-2001 NTDE. NTDEs are updated over time so that the datum elevations relative to the land take into account long-term sea level change. The previous NDTE in use until April 2004 was the 1960-78 NTDE. Tidal datum elevations are computed for the tidal bench marks and published bench mark sheets are issued by NOAA on-line for each tide station. If connected to geodetic bench marks of the NSRS, tidal datum elevation relationships to geodetic datums such as NAVD88 are computed. **Figure 2** shows the elevation relationships of the various tidal datums, ranges of tide, and geodetic datums for Baltimore, MD.

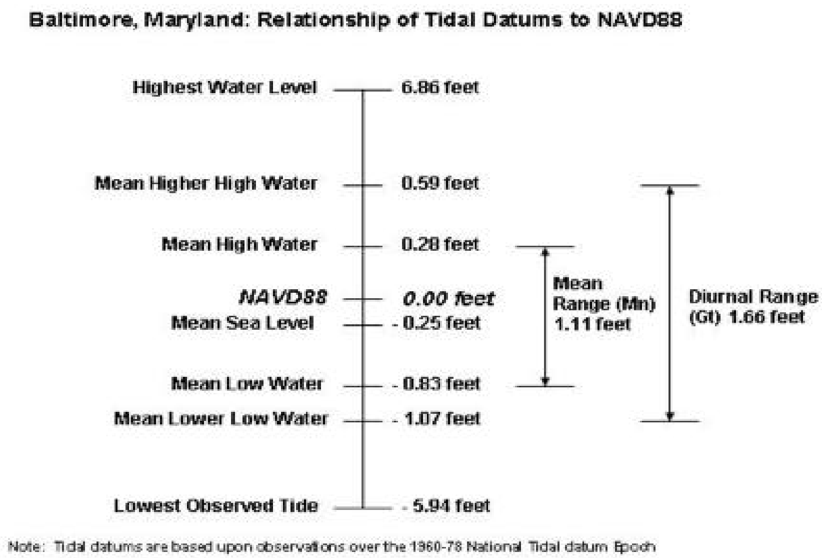


Figure 2. A stick diagram showing datum relationships for the tide station at Baltimore, MD.

NOAA operates a National Water Level Observation Network (NWLON) of 175 stations, including the Great Lakes and Ocean Island Possessions, to provide the long-term water level measurements necessary to update NTDE periods and to provide tide and water level datum control for the Nation (see **Figure 3**). The NWLON is a national control network for tides, analogous to how CORS is the national control network for geodesy. Not every tide station can be operated for a complete 19-year period for tidal datum computation purposes. For locations in between NWLON stations, short-term tide stations are established and operated anywhere from a few weeks to several years, depending on the application and the accuracy of the datums required. Tidal datums at short-term stations are referenced to the NTDE by performing a comparison of simultaneous observations between the short-term (subordinate) and the closest long-term (control) NWLON station.

Figure 3. The NOAA National Water Level Observation Network (NWLON).

Tidal datums have traditionally been important primarily for navigation and shoreline boundary purposes. For example, water level measurements were needed for charting coastal waters and to fulfill the need to establish a plane of reference, or a datum plane, to which the water level observations and tide prediction tables could be referred. Similarly, soundings taken during hydrographic surveys could also be referred to such a datum. Mean Lower Low Water (MLLW) is NOAA Chart Datum, and Mean High Water (MHW) represents the shoreline on nautical charts. Tidal datums also provide baseline determinations for the Exclusive Economic Zone (EEZ), Territorial Sea and Contiguous Zone, as well as boundaries between private, state, and federal ownership and jurisdiction as seen in **Figure 4** below.

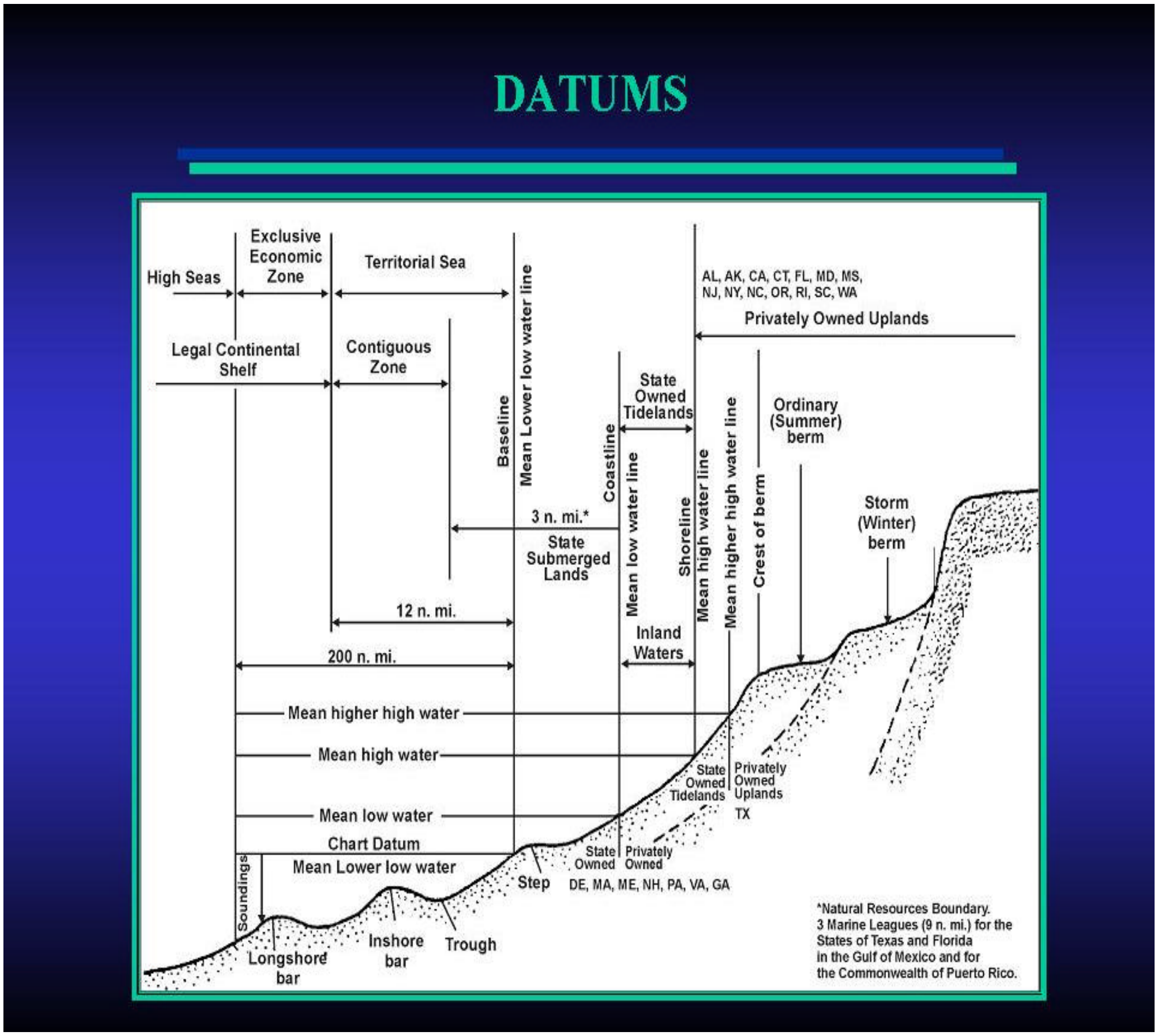


Figure 4. Traditional tidal datums and their applications.

Additional applications of tidal datums have been explored and utilized, including the need for accurate tidal datum elevations to control dredging operations, to design coastal construction projects, and specifically, for the successful design and engineering of marsh restoration habitats.

When conducting a marsh restoration project, there are five basic processes that are necessary in nearly every case:

1. Characterize the tidal regime of the project area: Using historical data sources and literature searches, assess the tidal characteristics and assess the seasonal and long term water level variations for the area. Determine the existing tidal datum and geodetic datum control.

2. Establish tidal datum control for the project area. Establish a tide station(s) if required to compute local tidal datums relative to bench marks. If an existing tide station does not exist, short-term tide stations should be established for a minimum of one year to measure seasonal variations. Tidal datums are computed using simultaneous observations with a nearby existing control station. Longer term stations may be required if there is significant year-to-year variability.

3. Establish geodetic datum control for the project area. Geodetic datum control is established using direct leveling or GPS surveys to the National Spatial Reference System. Connections to tidal datums are made by leveling or GPS connection to the tidal bench marks.

4. Develop digital topographic maps of the project area as required. The topography of the marsh surface is establishing systematic Kinematic GPS surveys or LIDAR surveys that can be used to develop Digital Elevation Models (DEM's). These are established to provide marsh engineers knowledge of the existing marsh elevations and can be re-done as the project develops.

5. Water level analyses and sea level trends are performed and overlaid on the DEM's. Frequency and duration of inundation analyses of the water level data are conducted and the impacts of sea level rise and return periods of storm surge on the design plans are estimated. Because vegetation is sensitive to elevation, how often and hot long it is inundated, frequency (or the occurrence of high waters for different elevations above the marsh surface) and duration of inundation (or the amount of time that the marsh surface is inundated by water) analyses must be performed. The analyses results are referenced to the same vertical reference system as the DEM's so that proper guidance can be obtained for planning.

Figure 5 shows a generic marsh restoration study site complete with a tide gauge, local bench marks, critical zones of elevation for vegetation, and important tidal datum elevations.

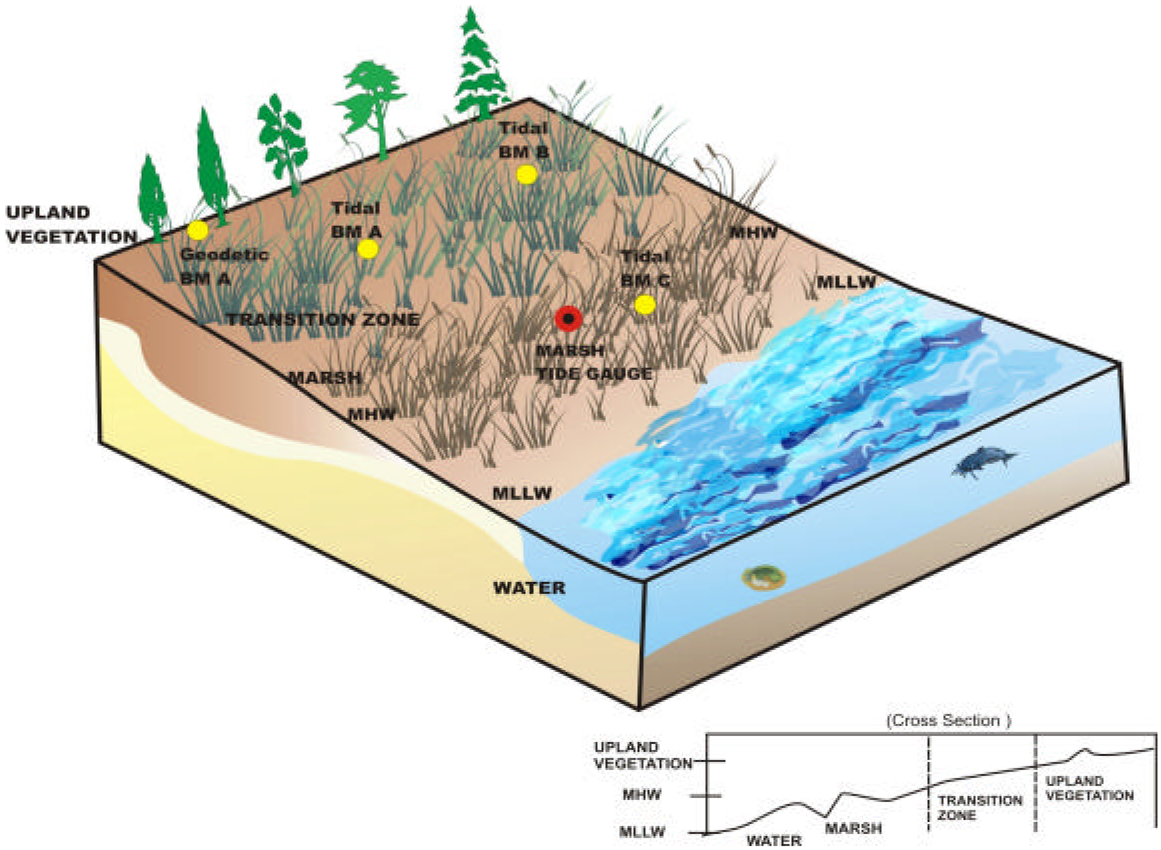


Figure 5. Generic marsh study site.

C. Topography

A topographic map is usually desired to provide most of the physical information needed to plan and implement a restoration project. In its complete form, the topographic map is made up of planimetric and hypsographic detail. Planimetric mapping is the mapping of the horizontal location of all natural or human-made features found within the area of interest. These features may include grass species, retention walls, channels, drainage ditches, box culverts and other features that may have an impact on the management of the wetland. Hypsographic detail concerns the vertical location of natural and manmade features in reference to some vertical datum such as NAVD88 or Mean High Water (MHW). A typical product produced from hypsographic information would include elevation contours representing the contour and relief of the marsh surface but would also include spot elevations on important features, such as, culvert inverts, levees, roads, and existing buildings. Traditionally, planimetric and hypsographic details were located through a number of classical surveying methods.

Because subtle changes in the topography of a marshland translate into not so subtle changes in habitat, we collect a large amount of precise and accurate data to properly model the existing environment. Although this is currently being practiced by classical survey methods, we can now collect more data, quicker, easier, and with higher precision using Global Positioning System (GPS).

Classical survey methods require a clear line of site (*i.e.*, you can see from one point to the next, for each measurement). When the points are miles away from the site, multiple measurements must be made to bring the datums to the site. This not only takes up a large amount of time but also introduces error that propagates throughout the measuring process. Also, different equipment and procedures are required when using classical methods to transfer information to the site from both horizontal and vertical datums. This vastly increases the time spent and, ultimately, the cost of acquiring the measurements. **Figure 6** is an example of a topographic map of marsh surface.

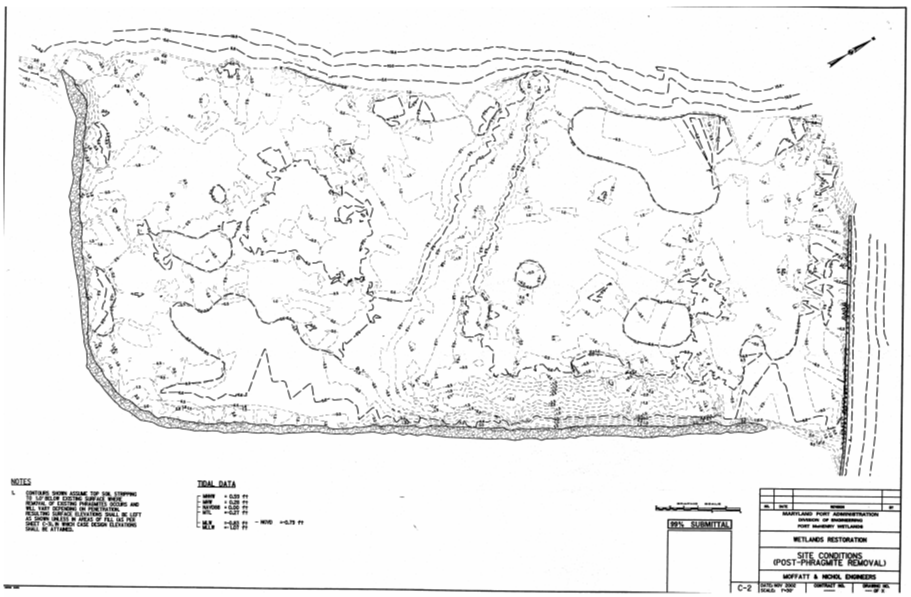


Figure 6. Engineering drawing showing topography of marsh surface.

The use of Differential GPS (DGPS) procedures is what allows the operational application of GPS to obtain vertical and horizontal positioning required for topographic and bathymetric surveying. Regular hand-held GPS units do not provide the vertical and horizontal accuracies required for surveying. DGPS is a technique that improves this accuracy by determining position error at a known location and incorporating a corrective factor into the position calculations of another GPS receiver. This receiver is operating in the same area and simultaneously tracking the same set of GPS satellites.One of the most versatile DGPS tools is known as Real-Time Kinematic GPS (RTK). RTK uses a base station and a rover. The rover is a mobile GPS receiver collecting data during a field session. The position of the rover is computed relative to the stationary base station GPS receiver. RTK GPS provides a quick and efficient link between the measurement process and inputting attributes in GIS tables because while the positional data is collected in the field it is also tagged with name, symbols, and attributes. The data is then downloaded to an external software package. The software takes the positional data with the tagged information and creates a digital map requiring minimal manual editing. The maps and the tables are than exportable to various GIS packages.

The operational challenge in using RTK is getting full access to the site and being able to move freely from point to point. Typical use of RTK in the portable mode is by carrying a backpack and the hand-carried GPS staff as shown in **Figures 7a and 7b**. Highway surveys have used the GPS unit mounted on the automobile bumper, and ATVs have been used for some shoreline surveys. RTK can collect data as fast as every second. A successful marsh survey requires walking the terrain in some sort of systematic manner that provides dense enough coverage of the terrain features for a reference topographic map. It is rare that the project site can be completely accessed without wading through sloughs or ponds or having to use small boats to reach the bottoms of creeks, etc. Some areas have tall overgrowth of trees and large shrubs, making measurements difficult. In addition, many areas may be remote, such as on an island, making logistics with the instrumentation difficult.

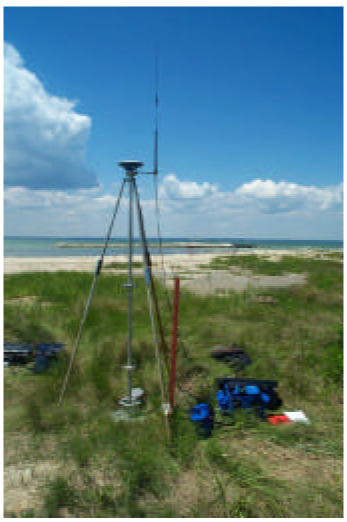


Figure 7a and 7b. RTK Base Station and Using Rover GPS on Geotubes

By using GPS, the data are collected in a format that allows it, without manual calculations or manipulations, to be easily imported to a GIS. Furthermore, this data will be referenced to the National Spatial Reference System (NSRS) before it even leaves the field. A GIS will contain a number of "themes" or "layers" of information. These themes or layers may either describe different attributes, e.g., road layer, water layer, plant species layer, etc., and/or they may be from different sources, e.g., aerial photography, satellite imagery, GPS, etc., but they all need to be referenced to the same coordinate reference system.

The attributed digital data allows for the creation of a Digital Elevation Model (DEM). A DEM is a collection of horizontal and elevation information covering the entire site. From this data, products can be easily created such as contour or shaded relief maps. The more elevation points collected with RTK, the more detail can be shown and the better the final product will be. An example of a DEM is shown in **Figure 8.**

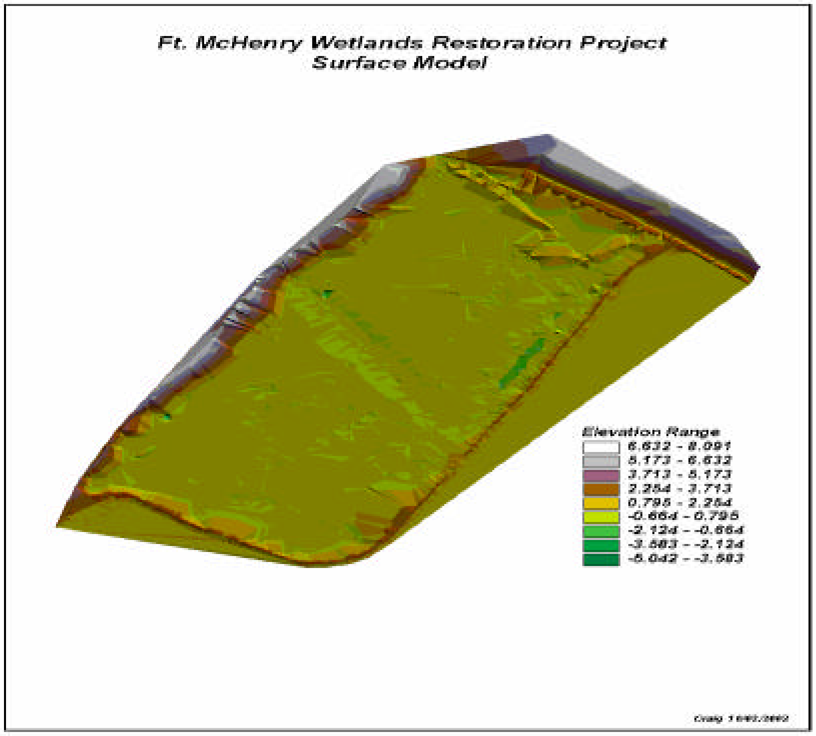


Figure 8. DEM of Ft McHenry Wetlands

Steps involved in evaluating topography of the site may include:

1) Accessing existing topographic data and determining the reference datum being used.

2) Determining requirements for an updated topographic map or the enhancement of existing maps. Determining areas of coverage and desired resolution and accuracies. Determining needs for pre-construction and post-construction surveys.

3) Planning and performing the required topographic surveys using traditional or Kinematic Global Positioning System (KGPS)methodology.

4) Providing an elevation contoured reference surface showing elevations of the topography to NAVD88. This serves as a base map on which to overlay tidal datum relationships, water level inundation elevation information, or sea level trend projections. This can be done using Digital Elevation Modeling (DEM) software.

5) The DEM can then be merged with other digital source data in the same reference frame, such as topography or bathymetry from LIDAR or other remotely sensing data sets.

References for performing topographic surveys are found in the appendix. The case studies show examples of the production and use of DEMs.

D. Bathymetry

Hydrography is the science dealing with the measurement and description of the physical features of bodies of water and their littoral land areas. A hydrographic survey may be conducted to support a variety of activities: nautical charting, port and harbor maintenance (dredging), coastal engineering (beach erosion and replenishment studies), coastal zone management, and offshore resource development. The one data type common to all hydrographic surveys is water depth, or **bathymetry**. Most surveys also record the nature of the sea floor material (i.e. sand, mud, rock) due to its implications for anchoring, dredging, structure construction, pipeline and cable routing and fisheries habitat. Bathymetric surveys determine water depths. The resulting data, depending upon accuracy, have a multitude of uses. NOAA uses such information to create and update nautical charts for safe navigation. The data is also used in marine geology, archaeology, modeling, marine engineering, and habitat assessment.

Bathymetry Tools: Major tools for bathymetric surveys are single and multibeam sonar systems and bathymetric Light Detection and Ranging (LIDAR) systems (flown on aircraft platform). "Feature search" surveys employ side-scan sonar. By towing a side-scan sonar fish, hydrographers locate dangers to navigation in areas with low relief, such as the gently sloping bottom in the Gulf of Mexico. The feature search has also been used to locate parts of a downed aircraft and, in marine archaeology, to determine precise locations of wrecks.

Bottom type surveys are useful for habitat assessment. The remote sensing tools used to determine bottom type are multibeam and side-scan sonar systems (see **Figure 9**). Acquired data are then processed through software capable of unsupervised pattern recognition, signal classification and time series analysis. Once the data is processed, it is usually necessary to ground truth the resulting polygonal regions with bottom samples, or by diver/remote video observations to determine actual composition. Before starting a survey it is important to decide its purpose so that the proper tools can be utilized. The four general types of remote sensing surveys are Bottom-typing, Sub-bottom Profiling, Bathymetry, and Feature Search.

Sub-bottom profiling lies in the realm of marine geology, oil exploration, marine construction and archaeological investigations. Sub-bottom profilers are a direct extension of echo-sounders; by transmitting a relatively low frequency acoustic pulse, a portion of the outgoing pulse is transmitted below the seabed and will reflect off layers in the sediment pile, thus producing a pseudo-cross-section of the subsurface. This is analogous to digging a trench on land. However, the major advantage of sub-bottom profiling is that it is a non-invasive technique.

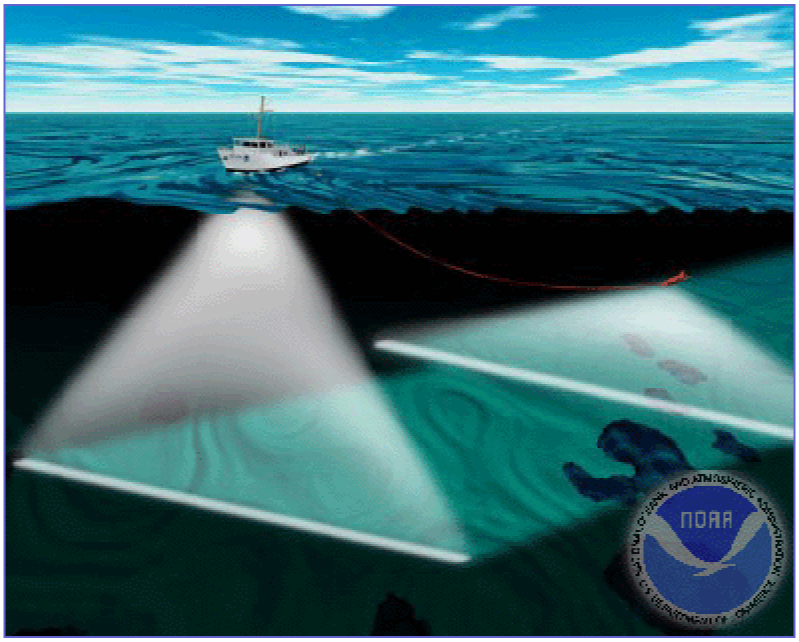


Figure 9. Hull-mounted multibeam sonar (left) and towed side scan sonar (right).

<u>Horizontal Control</u>: Once the type of survey is identified, horizontal accuracy must then be determined. For horizontal control, the use of Global Positioning System (GPS) technology is now standard, but it comes in many varieties. GPS can be roughly divided into three categories: **Stand-alone GPS**, with an accuracy level of 10 meters; **Differential GPS** (DGPS), with an accuracy level of 3-4 meters; and **Carrier Phase Differential GPS** (CDGPS), presenting an accuracy level of 3-4 centimeters. Generally, bathymetric work requires horizontal positioning accuracies at the meter level. Costs increase with required accuracies. NOAA uses, and recommends using, North American Datum (NAD) 1983 for regions within North America.

<u>Vertical Control</u>: The reference vertical datum to be used for the survey needs to be determined. For NOAA Chart Datum and all NOAA hydrographic surveys, NOAA uses the tidal datum of Mean Lower Low Water (MLLW) in tidal waters and Low Water Datum (LWD) for non-tidal waters. Soundings are taken over time or throughout the tidal cycle and must be corrected so that they are all referenced to Chart Datum. These corrections are made by taking water level measurements during the survey, determining the water level elevations relative to Chart Datum, and correcting the soundings for the water level elevations above or below datum at the time of the sounding. Depending on the area of the survey and the complexities of the tide and water level variations, this may take one or several tide gauges to provide accurate coverage. For soundings made considerable distances from an operating tide station, time and range correctors are often applied to the observations from the gauge to estimate the tide at the sounding location. This technique is called tidal zoning.

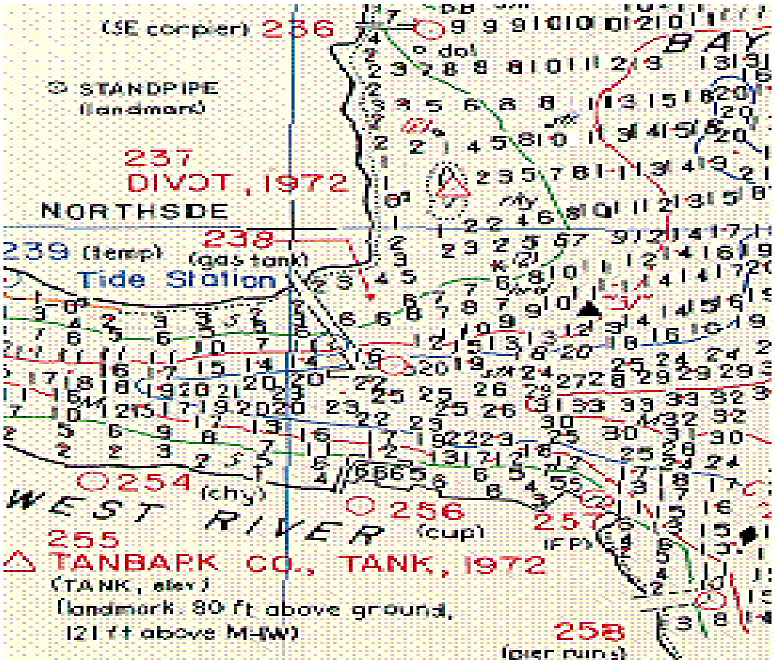


Figure 10. Example of hydrographic survey sheet.

Steps involved in evaluating bathymetry include:

1) Determine level of precision required for project objectives.

2) Before acquiring, and possibly re-acquiring, costly survey data, one should search available sources of bathymetry information.

3) If needed, perform hydrographic survey(s)(SONAR, LIDAR).

4) Generate new bathymetric analysis at required precision.

Steps involved in conducting a survey include:

Assuming a survey will be conducted for near shore bathymetric data for the purposes of habitat examination, the primary interest would be high-resolution depiction of geomorphology. The survey data could be used to assess different habitat types such as rocky or flat bottom, and also give a clear understanding of the way depths vary over the project area.

1) Examining existing data such as nautical charts or GEODAS in the project area gives a sense of the type of system required. If the depths are shallower than 200 meters, a high frequency shallow water system is appropriate. The need for high-resolution data drives the use of a multibeam system.

2) Using existing data in a GIS or project planning software, create a line plan, draw lines for the multibeam system parallel to the shoreline and spaced at 3 times the water depth to allow for overlap.

3) Calculate the total linear nautical miles for the lines and, using survey vessel speed, calculate the time to complete acquisition

4) Determine the requirements for establishing the necessary horizontal and vertical control.

5) Sound velocity is critical to producing quality multibeam data, but can vary both temporally and spatially. To deal with this issue, sound velocity casts should be made at a minimum of every 4 hours. Proximity to a fresh water source or a change in the water column due to currents or tidal forcing can increase casting frequency.

6) Survey data should be processed during the acquisition phase to resolve the errors that WILL occur. A good rule of thumb is that for every hour of acquisition, it will take approximately 3 hours to process the data. The data should be cleaned and merged with other sources to create a Digital Terrain Model (DTM) encompassing all of the previously acquired data. The DTM is useful as a quality control tool (most errors are plainly visible), and to determine the location of “holidays” or gaps in survey coverage.

7) Determine the resource availability to accomplish the above steps and redefine project area as needed.

References for sources of existing bathymetry and for conducting new surveys are found in the appendix.

IV. Case Studies Illustrating Key Issues

Qwuloolt Restoration Site

- Critical Issues:
  - Re-establishment of functional marsh and natural tidal regime
  - Potential flooding of nearby community
- Preliminary Analysis/Instrumentation:
  - Tide station installed to establish local datums
  - Thorough analyses of vegetation, sedimentation, and hydraulics of project
- Data Analysis:
  - Datum computation and high water analysis using a nearby control gauge
  - Frequency and duration analysis

Introduction/Background

The Qwuloolt project is a wetland restoration project in Marysville, WA along the Ebey Slough, just outside of Everett, WA. The project is called Qwuloolt which means "great marsh" in the Salish language of the Tulalip Tribes. The Tribes will be taking over the 370 acre property and maintaining it once the restoration work is complete. The natural resource trustee council for the Tulalip Landfill site, which includes NOAA and three other agencies, purchased the main parcel of land in 1998. Several adjacent parcels have been purchased since then. The property will be used for wetland restoration. When complete, the project will compensate for injuries to wetland habitats in and around the nearby Tulalip Landfill. The property, located at the old Poortinga farm has been diked since the early 1900s. The intention is to remove the dike and flood the property, recreating wetland habitat and reinstating a functional marsh. However, the goal is to achieve this result without flooding the surrounding houses and commercial developments located on the periphery of the property. In order to accomplish this, significant modeling and evaluation has been conducted on this site and nearby reference sites. A water level station was installed along the slough that remained in operation for a year and a half in order to gain important water level and trend information. This is an interesting project because it shows the necessity of planning a marsh restoration site that is surrounded by developments, as well as illustrating how tidal data were incorporated into hydraulic models.

Plan/Approach

A tide gauge was in place at the Qwuloolt site from November 1, 2000 until March 31, 2002, a total of 16 months. The station, designated number 944-7729, was located along Ebey Slough on the south side of the property at the Marysville Public Works Facility, where the slough begins to bend to the west towards Possession Sound. The station consisted of a pressure sensor (a digital/bubbler with a Paroscientific pressure transducer) and a data collection platform (DCP) which transmitted data to NOAA headquarters in Silver Spring, MD for quality control and processing via a GOES satellite radio. Benchmarks used for leveling at this tide gauge consisted of two existing NGS benchmarks and three newly installed NOS marks. Leveling is done to establish a geodetic datum when Kinematic GPS is not utilized. Of the three benchmarks installed by NOS upon installation of the tide gauge, two were disks and one was a Class A deep rod driven 36.3m. (119ft.) into the ground. Leveling was done upon installation and removal of the tide gauge.

Preliminary Analyses

The U.S. Army Corps of Engineers published a comprehensive study of the project area in 2002, which includes a vegetation analysis, sediment analysis, hydraulic analysis, several options for levee breaches, and potential repercussions of each option. It essentially hypothesizes the outcome of various potential actions, using nearby locations for reference, so that the most effective course of action can be selected with adequate background. In order to conduct a vegetation analysis, two reference sites adjacent to the property were examined. Species present include spike rush, brass buttons, soft rush, broad leaf water plantain, Lyngby's sedge, Hard stem bulrush, Pacific silverweed, Birdsfoot trefoil, and Cattail. Spike rush is the dominant vegetation in this area. While there is a mix of both salt water-tolerant and freshwater plants, a common factor between several of the predominant species is that they are typically early marsh invaders or associated with disturbance. The main controlling factor of marsh vegetation growth in this area is elevation. Using a site directly south across Ebey Slough, an elevation of vegetation analysis was conducted, illustrated in **Table 1**. Small spike rush was present at lower elevations, while Lyngby's sedge, Hard stem bulrush, and Cattail were present at slightly higher elevations. Typically, no plant growth was present below about a 4-foot elevation (NAVD88). Salinity is likely to be an associated controlling factor in what will be established in the newly flooded marsh. Salinity in this area ranges from about 0.5 parts per thousand in the spring to 12.0-16.5 parts per thousand in the fall, with salinity decreasing in higher elevations, as water travels further into the marsh surface. If the dikes are removed at Qwuloolt, much of the site is likely to remain at or below the minimum elevation to sustain vegetation, but at elevations high enough to sustain vegetation, spike rush is likely to colonize first, followed by Lyngby's sedge, Hard stem bulrush, and cattail, at higher locations. (U.S. Army Corps of Engineers, 2002)

Plant Type	Lowest Elevation (NAV88 ft.)	Highest Elevation (NAV88 ft.)
Small spike rush	3.74	6.64
Lyngby's sedge	6.29	8.79
Hard stem bulrush	8.38	8.79
Cattail	7.27	8.38
Multi-species communities	7.27	9.43

Table 1. Plant elevation in an adjacent Marysville reference site (from 2002 U.S. Army Corps of Engineers Technical Report)

Sedimentation rates are also a fundamental aspect of planning in marsh restoration, as they will impact elevation, as well as location and effectiveness of drainage channels. Core samples were taken in the reference area in order to approximate sedimentation deposition rates, both at the marsh surface and the bottom of one of the creeks. Sedimentation rates were similar between the marsh surface and the bottom of the creek and have been mostly uniform over the last 50 years. Once an estuary has its hydrologic connection restored, there is an initial pulse of sediment entering the system. In three cases of dike breaches in the nearby Salmon River Estuary (OR coast), the sediment accretion rate was initially 4-7cm, and then diminished over time. It can be assumed Qwuloolt would exhibit similar characteristics. Models were used to examine how the hypothesized sedimentation for Qwuloolt (3-7cm over the first few years, tapering off to less than 1cm per year) would affect the vegetation patterns of the new marsh surface. The vegetation would not be initially affected, though once the elevation was increased by 30cm (bringing the surface to a general elevation of 6' (NAVD88), a dramatic increase in vegetation would occur. (U.S. Army Corps of Engineers, 2002)

Finally, models were produced to analyze the hydraulics and hydrology of the newly inundated marsh surface. The U.S. Army Corps of Engineers Seattle Division completed aerial and topographic surveys of the project site in 2001, including spot elevations, plant communities, and locations of structures on the property, and a Digital Terrain Model (DTM) was established. This DTM was used to develop hydraulic models, evaluate modifications to the present structures (dikes), illustrate proposed designs for the marsh surface, and perform an inundation analysis. Analyses were done to predict seasonal and peak flood hydrology. The one dimensional, unsteady-state UNET hydraulic model was calibrated to reproduce the flooding that occurred during a 1990 flood. It was then used to determine the 10, 50, 100, and 500-year flood profiles, floodplains, and floodway. The sources of flooding in this location are Puget Sound and the Snohomish River. Flooding mechanisms for Puget Sound are astronomical high tides alone or in combination with storm surge associated either with a low-pressure system or high waves. Flooding mechanisms for the Snohomish are rain-on-snow floods during the fall and winter and snowmelt floods in the spring. Extensive flooding concerns exist if both the Snohomish and Puget Sound experience a 100-year event simultaneously. A positive relationship exists between the tidal high of Puget Sound and the riverine high of the Snohomish, although there does not seem to be a relationship between tide frequencies. Because flood sources seem to be independent between the two water bodies, only a .01% chance exists that 100-year events will occur simultaneously. With consideration of levee removal, however, this is a fundamental consideration, especially because the site has a history of failing levees on the right bank, and urbanization has increased flooding and sedimentation along Allen and Jones Creeks, which run through the middle of the project area. (U.S. Army Corps of Engineers, 2002)

Levee Breach

Several options exist for breaching the existing levees, and models were drawn up for a 25 foot, 50 foot, 100 foot, 200 foot, and two 200 foot breaches, as well as full levee removal. The levees currently in place surrounding the project area range in height from 6.5 to 15.3’ (NAVD88). The most complicated aspect of breaching the levees is opening them enough so that water is able to move sufficiently in and out of the marsh to reestablish a functional habitat and natural hydrologic system without allowing flooding of the neighboring developments, which may occur if all flood prevention measures are completely removed. The U.S. Army Corps of Engineers technical report examined and compared each model for the most effective course of action. One 200-foot breach was found to produce “acceptable” (but not ideal) restoration of the tidal range. Full levee removal was found to have several flooding risks. Based on total square footage of breach area and the hydraulics of the drainage canals, two 200-foot breaches were selected as the most effective option. Breach location must be chosen carefully because of the hydraulic elements present within the marsh, such as the two large tidal channels extending through the interior of the site. The ideal location for a breach in this marsh would utilize the conveyance provided by these channels to achieve a maximum hydraulic connection to far reaches of the marsh surface. Any additional breach should be at lower elevation, high-energy areas so that tidal channel formation would be increased. It should be carefully placed somewhere close to Ebey Slough, as a location further inland or near another marsh may allow water to enter and remain in the marsh for a longer duration or connect with another tidal channel, which could result in enlarged channels and increased channel activity where they connect. While several mechanisms will have to be instated to monitor marsh function regardless of which breaching option is selected, effective selection of breach location will allow for a more natural return to wetland habitat by designing the new marsh to utilize elements of the previous marsh, such as reactivating old channels (U.S. Army Corps of Engineers, 2002). **Figure 1** illustrates recommended improvements to restore the marsh, regardless of levee breach size and placement.

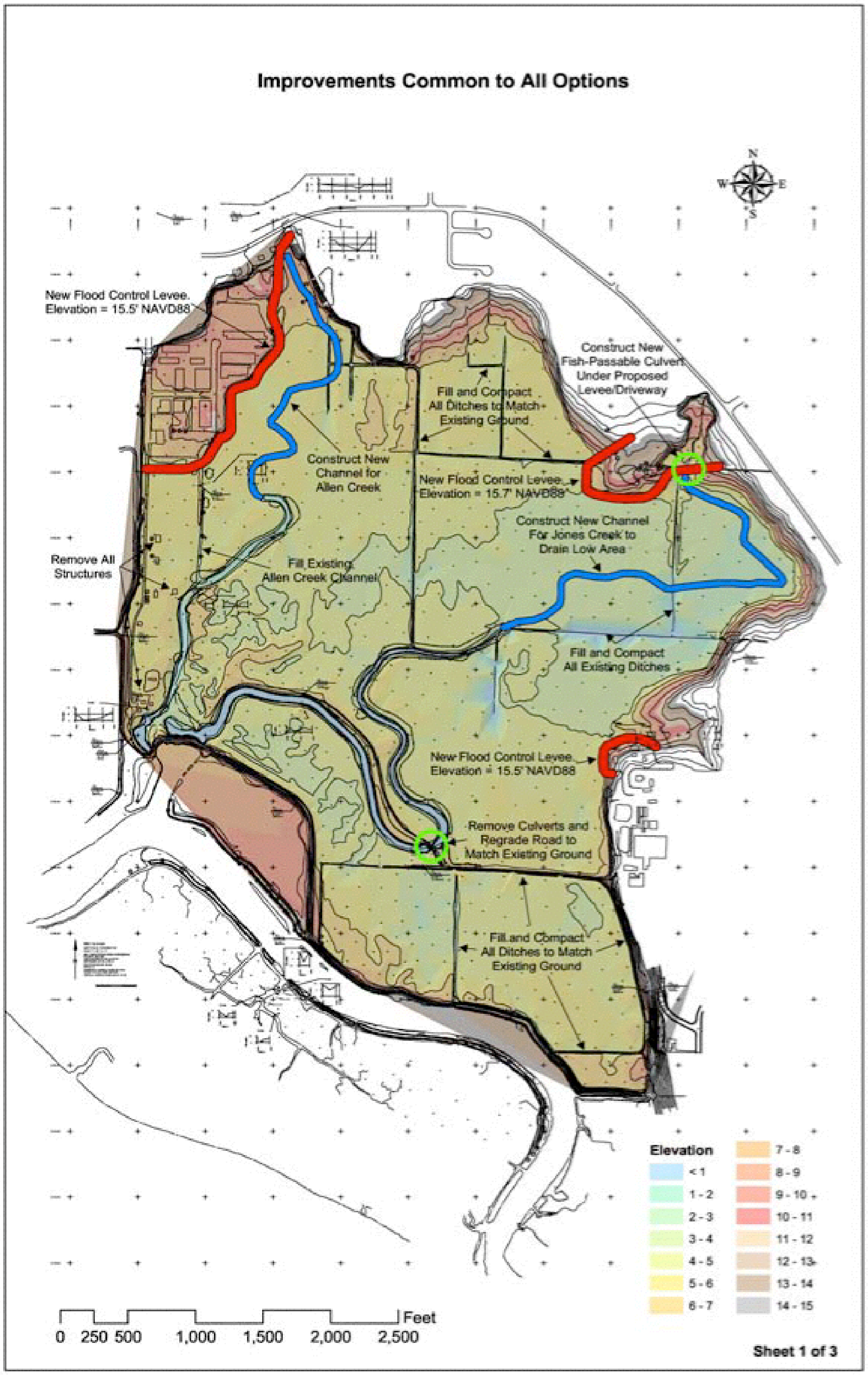


Figure 1. Features common to all breach options (from 2002 U.S. Army Corps of Engineers Technical Report)

Analysis

Importance of Tidal Datums

The most important tidal datum for marsh restoration is MHW. This reference elevation is computed from observations and represents the average elevation of the high waters relative to the land. Thus, it is important to know MHW for the success of vegetation over time, for a target species to thrive, and, among other reasons, for protection of surrounding properties from marsh engineering changes. The latter is particularly true for the Qwuloolt marsh site. In **Figure 2**, the existing elevations of the Qwuloolt marsh site can be seen. There are three different critical elevations on the map: 4 feet, 8 feet, and 12 feet, all relative to the geodetic datum, NAVD88. The red line (the 12-foot contour) represents the existing levees in place. Some developments are present in the northwest corner of the site between the blue line (the 8-foot contour) and the levees. New developments also exist along the eastern portion of the site bordering the levees. The green line is the 4-foot contour and approximates the present surface of the marsh.

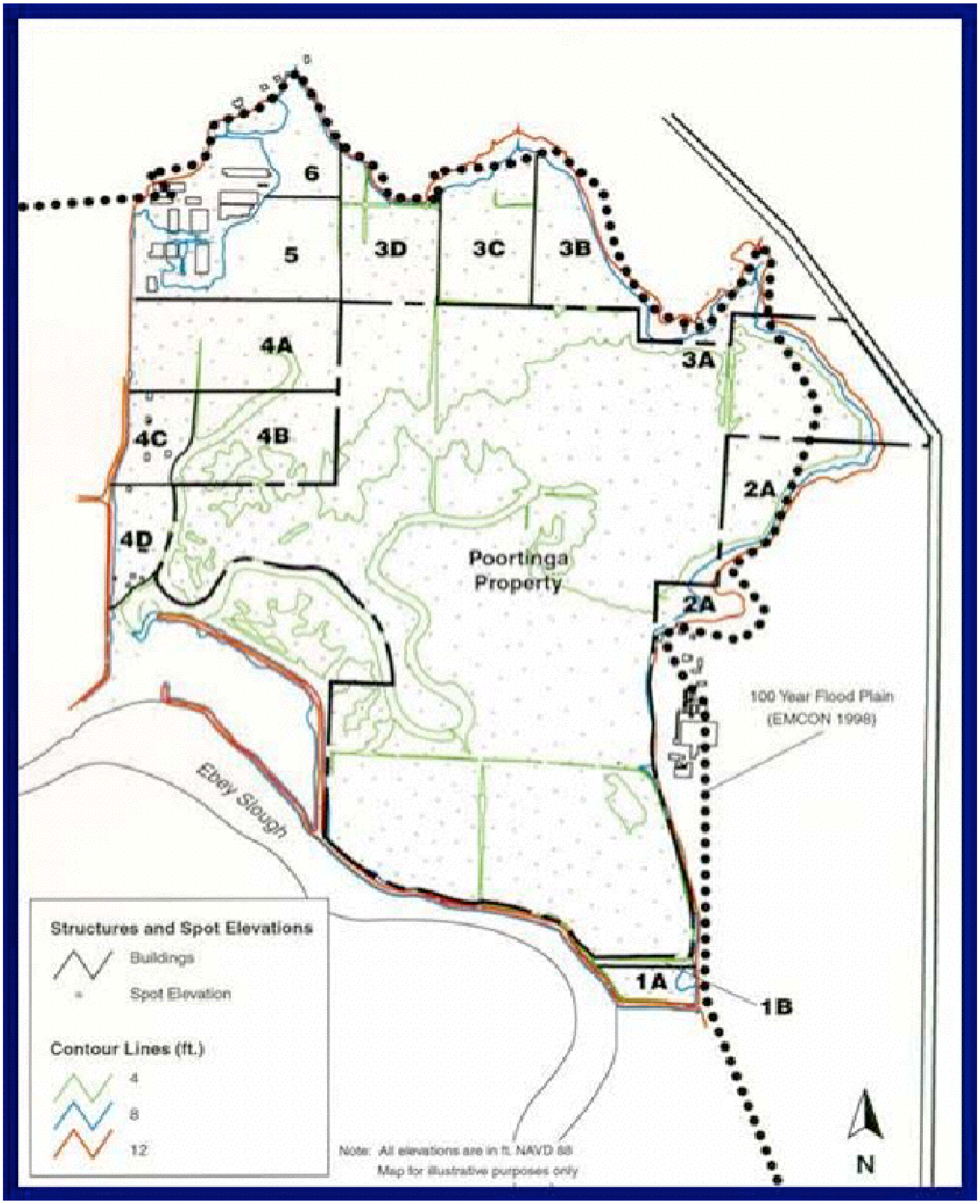


Figure 2. Existing elevations at Qwuloolt marsh site. Critical elevations are 4 feet, 8 feet, and 12 feet relative to NAVD88

High Water Analyses

Effective marsh restoration techniques require knowledge of long-term tide variations over several years, not just the isolated period during which an on-site tide gauge was operational. In order to attain information on these trends, simultaneous comparisons of observations between short-term stations and long-term stations are typically utilized to compute an equivalent 19-year tidal datum at the short-term station (NOAA, 2001). Examination of tidal data from both Ebey Slough and Seattle for a simultaneous time period reveals that there is a very close correlation within both the tidal stage and pattern. **Figures 3.1 and 3.2** illustrate a month of data plotted for both stations for the same time period. One plot is from January and the other is from June, to ensure that seasonal variations are taken into consideration and similarities exist throughout seasonal tidal fluctuations. Tides at Ebey Slough are typically a few minutes behind Seattle, and there is generally a slightly higher high (0.0-0.3 feet) and a higher low on Ebey Slough than Seattle, most likely due to the phase lag in the tidal cycle and cumulative backwater effects as the tidal wave moves upstream (U.S. Army Corps of Engineers, 2002).

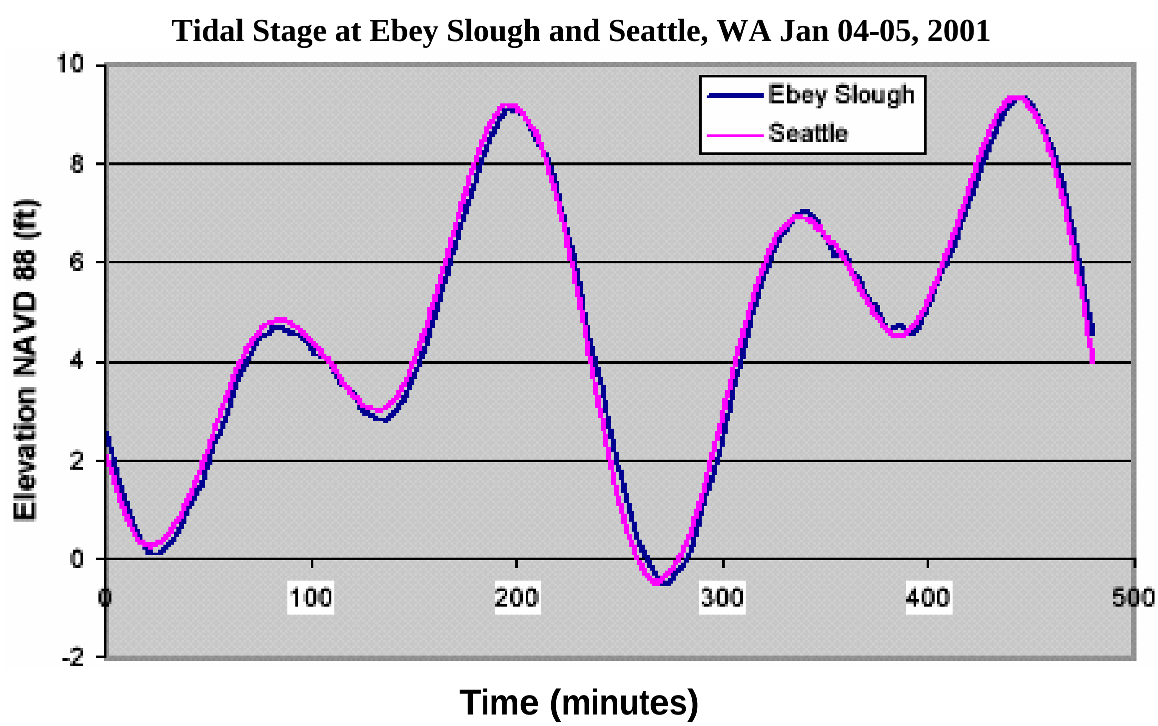


Figure 3.1. Ebey Slough Tide Stage Vs Seattle, Jan 04-05 2001

Tidal Stage at Ebey Slough and Seattle, WA July 23-24, 2001

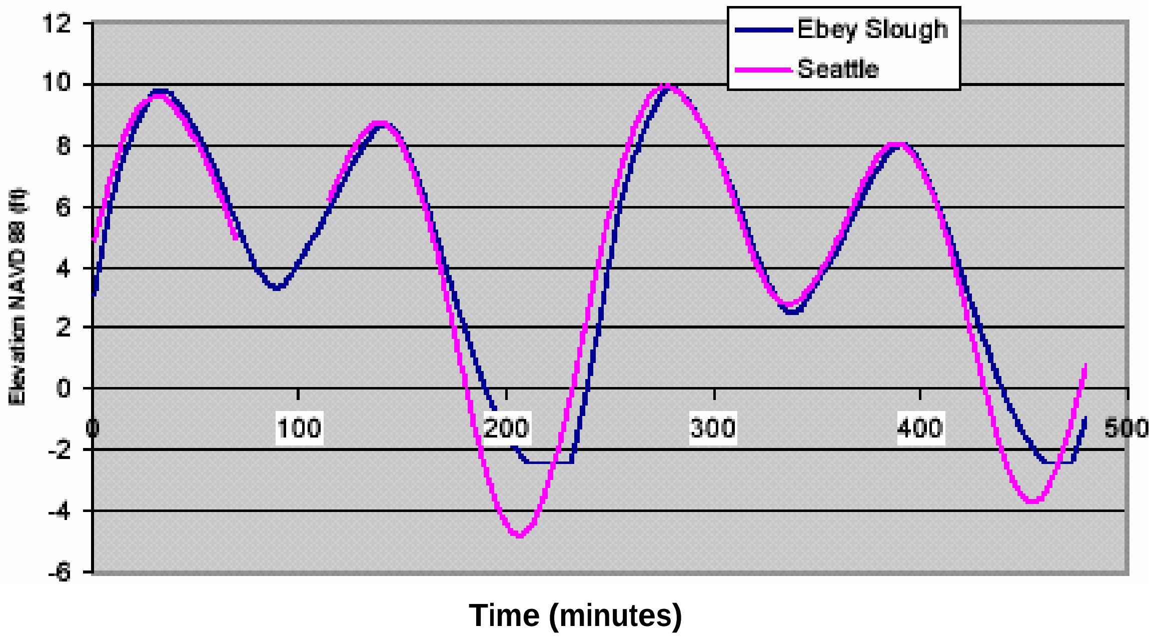
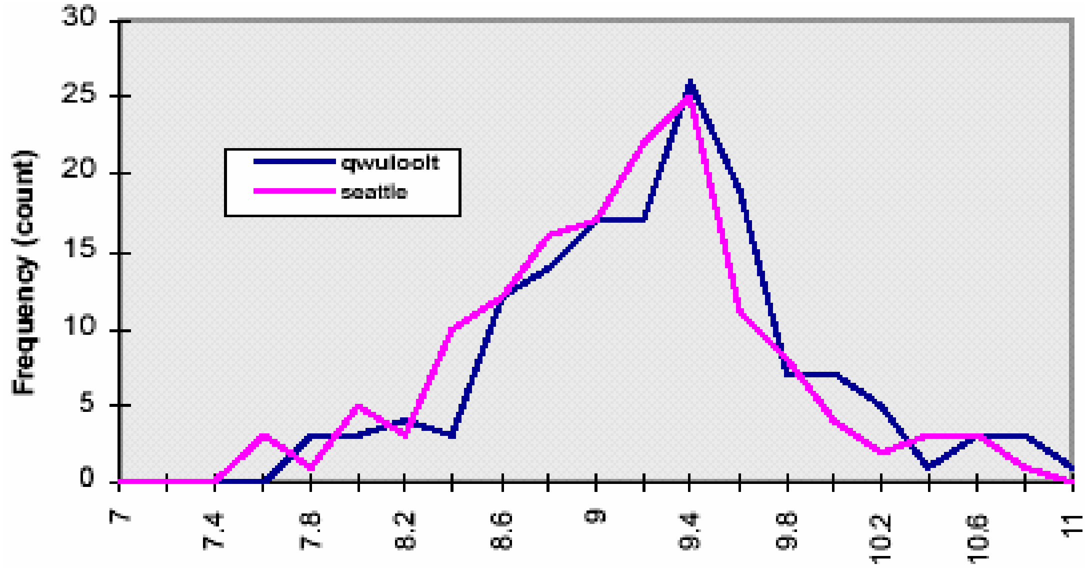


Figure 3.2. Ebey Slough Tide Stage Vs Seattle, July 23-24, 2001

Similarly, distributions of high waters can be compared between short-term (temporary gauge installed in the marsh) and nearby long-term stations to determine whether analyses of the long-term observations can be extended into the local marsh. This can be done both for the characterization of seasonal variations and for long-term sea level variations. A comparison of the higher high water distributions between Seattle and Qwuloolt in **Figure 4** shows that the distributions from the two stations match closely, that Seattle can be used to control Qwuloolt, and that the longer data series from Seattle can be extrapolated to Qwuloolt. For example, **Figure 5** shows a comparison of the distributions of higher high tides at Seattle broken down by season for 20 years (1980 - 2000). In this example, there is considerable difference in the distributions between the fall/winter months and the spring/summer months. Thus, seasonal variations at Qwuloolt can be expected to be similar to those at Seattle. Further, it can be expected that the long-term trends in sea level rise experienced at Seattle **(Figure 6)** are similar to those at Qwuloolt.

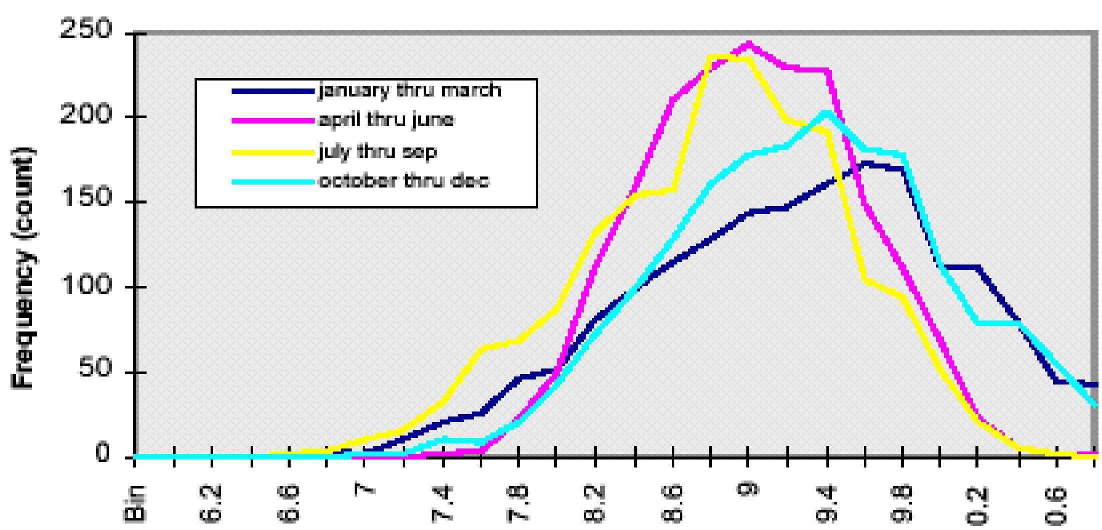
Comparison of Higher High Water Distributions



Elevation Relative to NAVD88 (feet)

Figure 4. Simultaneous comparison of higher high waters from December 1, 2000 through March 31, 2001 between Qwuloolt and Seattle

Comparison of Distributions by Season - for Seattle - Higher High Tides - 1980-2000



Elevation Relative to NAVD88 (feet)

Figure 5. Seasonal analyses for higher high tides at Seattle from 1980 – 2000

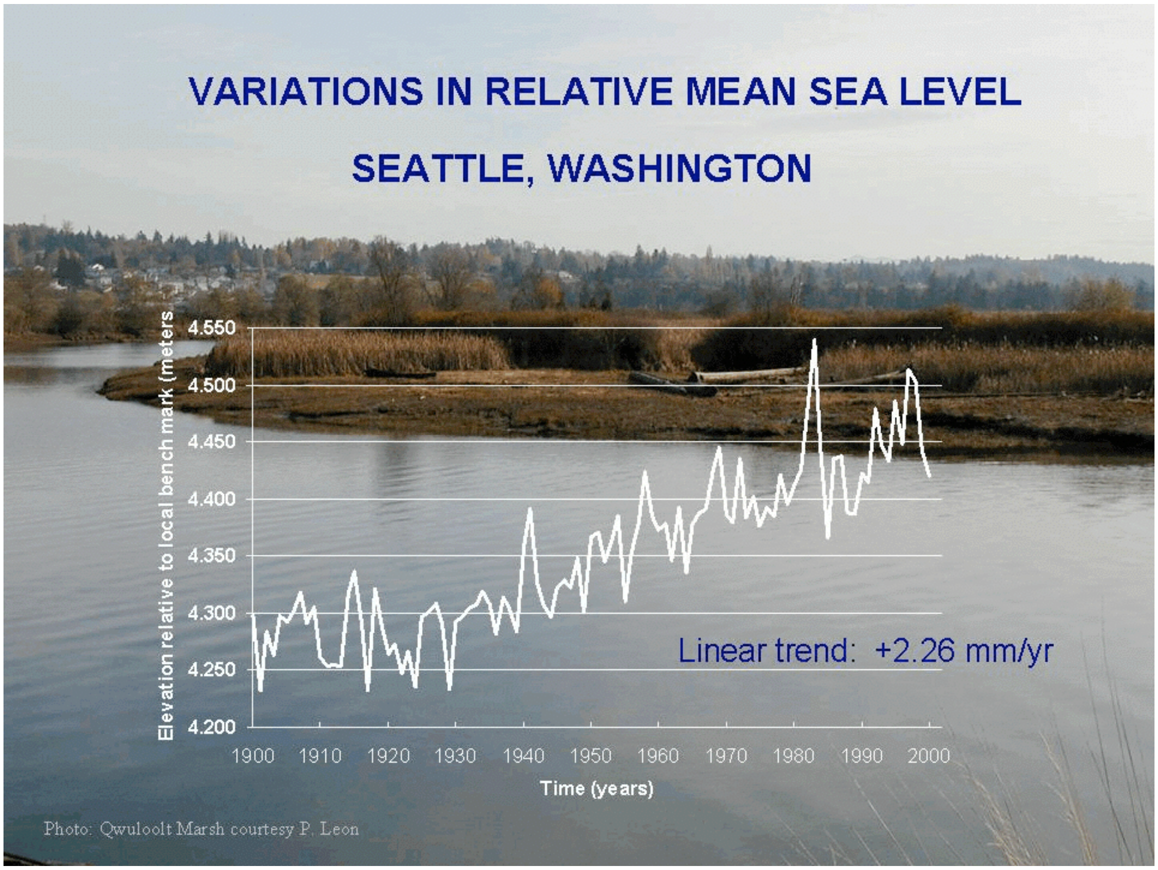


Figure 6. Relative sea level variations at Seattle, WA. The spike in the early 1980's represents the 1983 el Nino event.

Datum Calculation

Datum calculation for Qwuloolt was complicated by the fact that water level data at the marsh surface does not reflect the entire tidal range. Because of the location of the gauge at the marsh, the lowest tides are not accurately represented. The marsh sometimes drains completely (becoming dry at the site of the gauge) and the water level drops below the marsh surface before it reaches its lowest point in the tidal cycle. The resulting tide curve can be seen in **Figure 7**, and appears to have "cut-off" or "flat" low tides, instead of a smooth, continuous curve (also evident in **Figure 3.2**). Datums can be calculated in such a case by implementing the direct method. The datums are determined by comparison of high tides with a control exhibiting similar tidal characteristics for the available part of the tidal cycle (Gill, 2002). In this case, the control selected was Seattle, WA for similarities in tidal trends noted earlier. For this datum calculation, the Seattle gauge record was compared directly to the gauge on Ebey Slough without adjustment, as there appears to be no widespread, identifiable difference in tidal phase or range that would warrant introduction of a corrector. Because of the lack of adequate low tide information, only the MHW and MHHW datums were calculated.

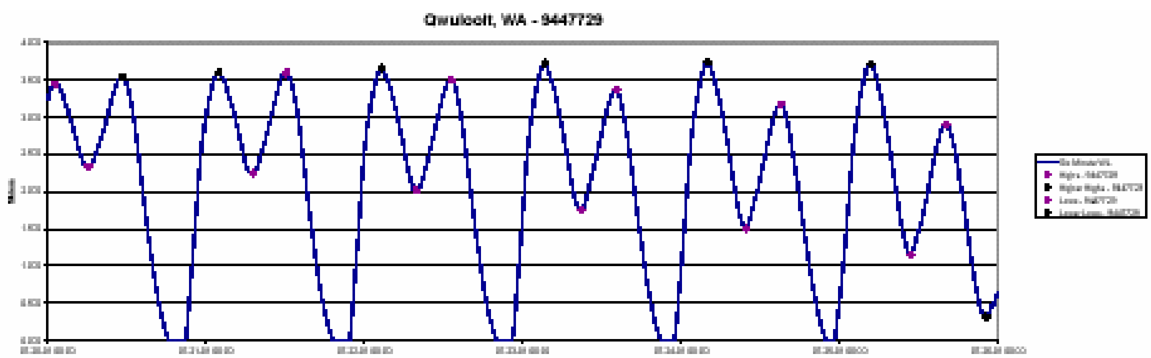


Figure 7. Preliminary 6 minute water level data for July 2001, including high and low water marks

A stick diagram displaying the calculated datums for Qwuloolt relative to NAVD88 can be seen in **Figure 8**. The preliminary tidal datums (MHW and MHHW) were calculated from one year of data (January 1, 2001 through December 31, 2001) and are based on the 1983-2001 National Tidal Datum Epoch (NTDE). The MHW datum is 2.54 meters relative to NAVD88, which is higher than both the 4-foot and 8-foot elevation contours of the existing marsh site. Referring to the marsh elevations in **Figure 2**, it is evident that at MHW, if the levees are breached, the marsh surface will be completely flooded below 12 feet, including the developments in the northwest corner of the property, which lie on the 8-foot contour. **Figure 8** also shows that the estimated highest tide (based on comparison with long-term Seattle data) is 3.7 meters. This means the water level would rise above the 12-foot contour in an extreme event, flooding the developments to the east as well. These datums proved to be critical in marsh planning by showing that the levees must be extended in the upper reaches of the marsh to prevent flooding at especially high tides.

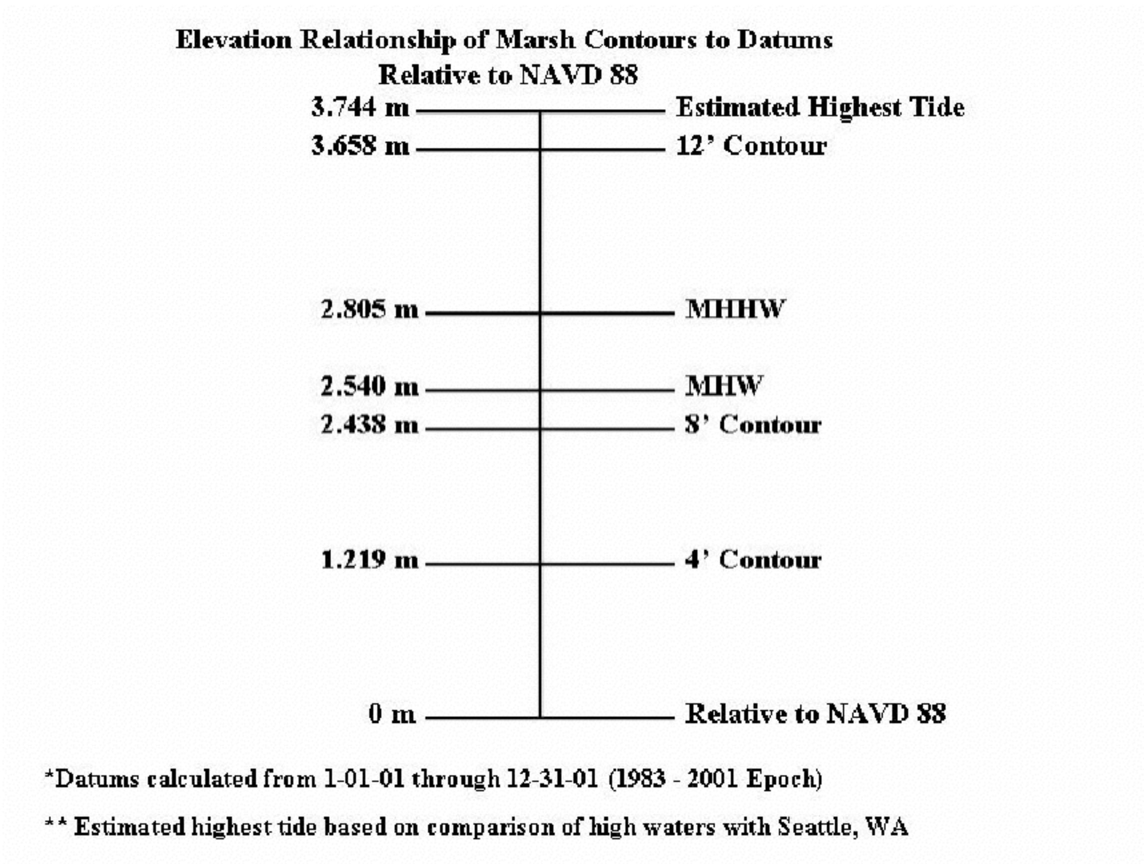


Figure 8. Stick diagram showing MHW and MHHW relative to the existing Qwuloolt marsh elevation contours relative to NAVD88

Frequency and Duration Analysis

Information regarding frequency and duration of inundation of the marsh surface is pivotal not only to establish planting schemes, but in this particular case, to plan mechanisms for flood prevention for nearby developments. In order to conduct a frequency and duration analysis, 6-minute water level data above the 4-foot contour was utilized. **Figure 9.1** is a graphic representation of the frequency of inundation of the marsh surface during the period in which the tide station was operational, including both high tide and higher high tides in the tidal cycle characteristic of the area. **Figure 9.2** is a frequency of inundation graph for the same time period, but includes elevations of the MHW and MHHW local datums, relative to the marsh surface (assumed for this study to be 4 feet in elevation). This shows that approximately half of all high tides can be expected to rise above the majority of the marsh surface (both the 4 and 8-foot contours). This indicates not only potential flooding of the surrounding area, but in fact frequent flooding, again reiterating the need for flood prevention for peripheral areas. Without any flood barrier, the developments on the northwest side of the property will be flooded not only in extreme events, but during at least half of all high or higher high tides experienced in the project area.

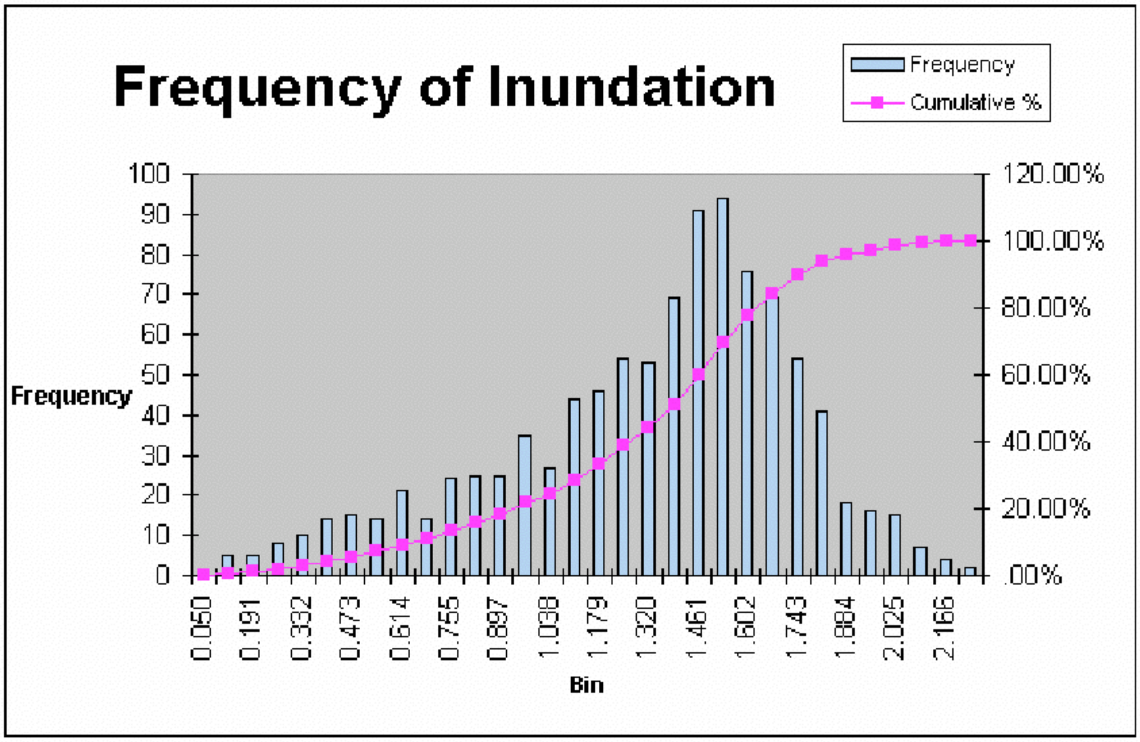


Figure 9.1. Frequency of inundation relative to the 4 foot contour from November 2000-March 2002

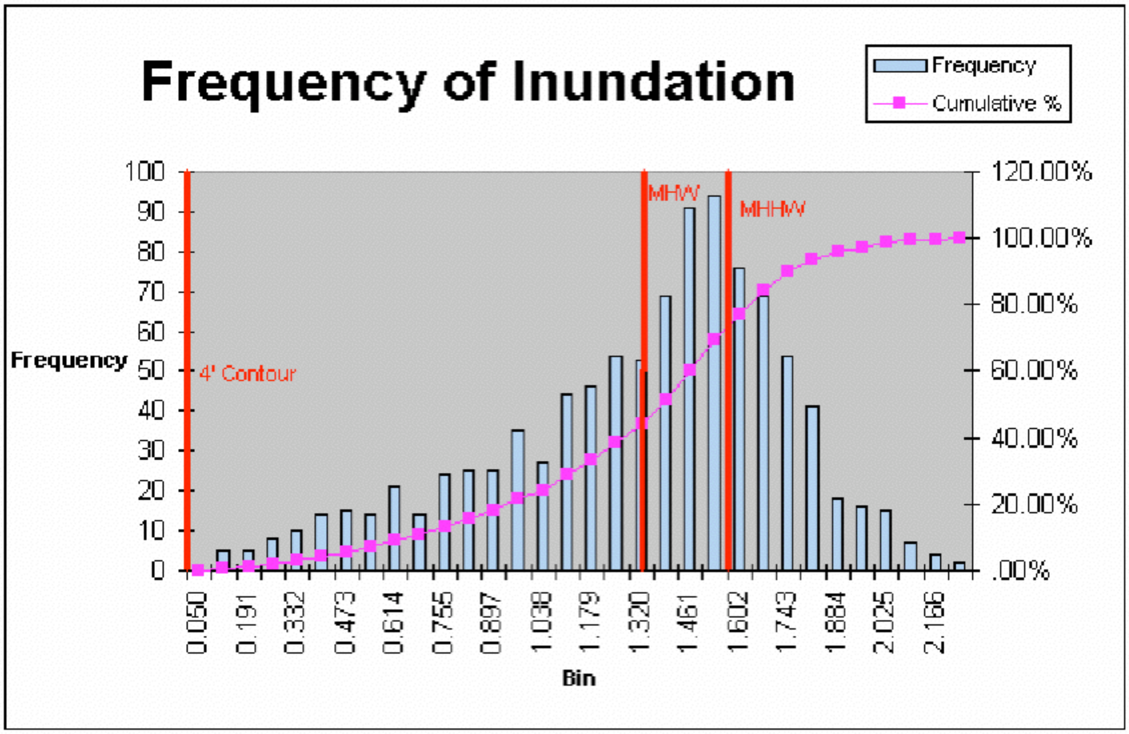


Figure 9.2. Frequency of inundation in reference to the 4 - foot contour including local datums

For the sake of this analysis, three months of data (November 2000-January 2001) were examined to determine trends in the duration of inundation at the Qwuloolt site. Over the course of each month, the period and range of the tides in the area vary, to appear at times mixed and at others almost semidiurnal, because of the lunar cycle. This affects Qwuloolt especially because depending on each particular tide, the marsh surface is sometimes flooded for more than one tidal cycle. The duration of each period in which the water level was higher than the 4-foot contour was measured, and is illustrated in **Figure 10** with respect to water level. The trend primarily exists that a higher water level leaves the marsh inundated for a longer period of time. However, a second tier becomes evident at about a 16-hour duration. These points represent tides in which a high and higher high were experienced consecutively without water level dropping enough to completely drain the marsh surface (4 foot elevation). This only occurs at water level heights of more than a meter above the 4-foot contour. Duration of inundation becomes especially important when planning vegetation for the newly restored marsh. In the case of Qwuloolt, reference sites show that vegetation is significantly sparser below the elevation of the marsh surface, which is usually inundated (U.S. Army Corps of Engineers). Vegetation in this marsh will have to be able to sustain frequent inundations, sometimes for periods of nearly 18 hours. This is a typical trend and does not indicate the presence of an extreme event, during which the marsh is likely to be inundated for a significantly longer period.

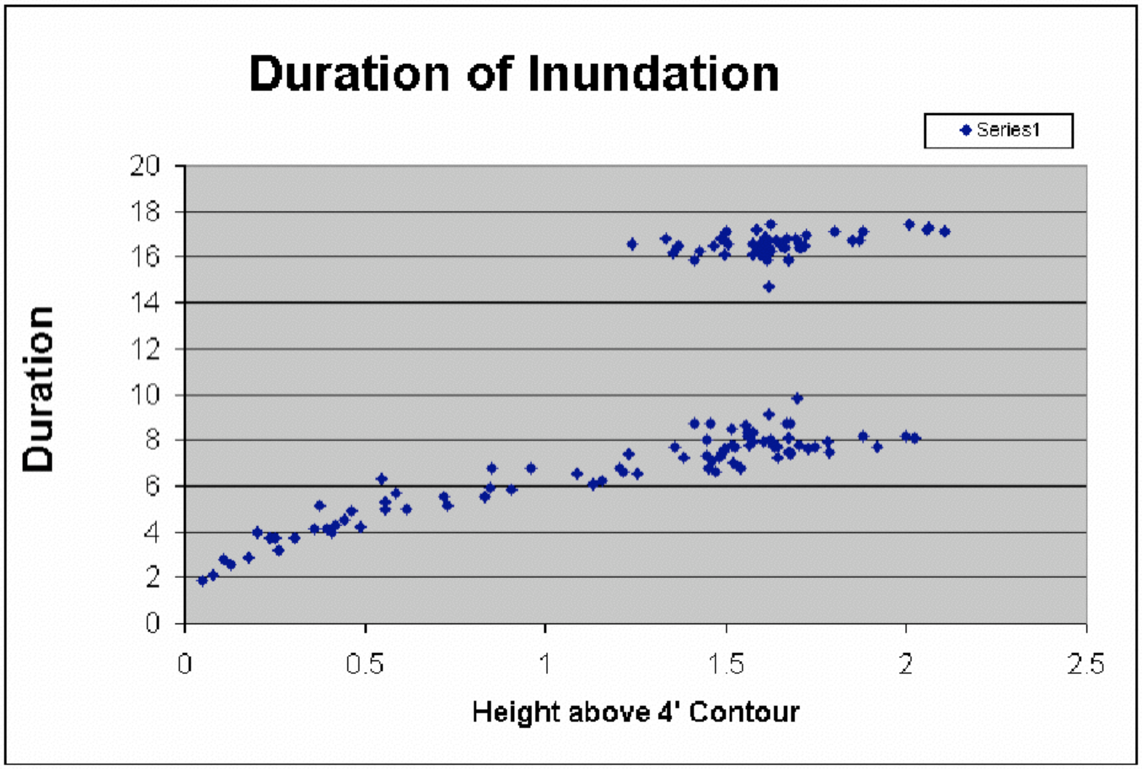


Figure 10. Duration of inundation of the marsh surface relative to 4 foot elevation, November 2000-January 2002

Conclusions

A great deal is known about the project area, which will ultimately allow for a more effective restoration plan. Local MHW and MHHW datums for Qwuloolt reveal that upon inundation, the marsh surface will become flooded above the 4-foot and 8-foot elevation contours at certain points in the normal tidal cycle. This puts the northwestern developments at risk of flooding. The estimated highest tide, based on a comparative study with Seattle, WA, is above the 12-foot elevation of the marsh surface, putting the developments on the eastern side of the property at risk of flood as well, in the case of an extreme tidal event. If the levees are to be completely removed at this site, preventative measures will need to be put in place to protect outlying developed areas, as flooding is a certainty. Any future planning must take this into consideration. Hydraulic modeling has provided essential information about this site in order to allow for educated decisions in this particular marsh restoration project. Qwuloolt is a typical example of a Pacific coast marsh and while it has some site-specific characteristics, it provides a good model for typical restoration protocol.

Recommendations for future action could involve further water level monitoring. A second tide gauge in a stream considered as a site for a potential levee breach might be beneficial in order to better determine the effects of that breach. Effects of a levee breach are very site specific and will have a tremendous impact on the hydrologic flow of the marsh, sedimentation rates, frequency and duration of inundation, and fish passage, among other things. Determining the potential outcomes in a more site-specific way would be useful. Once the marsh has been restored to a functional wetland, placement of a tide gauge further up into the marsh would be beneficial to long-term monitoring efforts by providing information about the dynamics of water flow into the marsh. It would help to provide the final link in frequency, period, and range of the tide in the upper marsh reaches and allow for more effective supervision of the wetland.

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Barren Island Restoration Site

- Critical Issues:
  - Protect and rehabilitate eroding mid-Chesapeake Bay Island
  - Beneficial use of dredged material
- Preliminary Analysis/Instrumentation:
  - Complete hydraulic analysis of waters around restoration site
  - Geodetic investigation using various methods
- Data Analysis:
  - Tidal datum computation
  - Frequency and duration analysis
  - Water-land intersection determination for proper planting

Introduction/Background

Originally, Barren Island was not an island, but rather part of the central Delmarva Peninsula that jutted into the Chesapeake Bay from the eastern shore. Over the past several hundred years, erosion and over-wash episodes induced by storm surge, formed several small connections from the main body of the estuary into what is now known as the Honga River. These small tributary connections slowly grew under tidal forcing and currents, creating an island chain that reached from the central Chesapeake Bay region to the southern region in a longitudinal orientation. The main geologic component of this peninsula is of clay origin and not silica sediments (sand), typical of coastal islands. Due to this extremely fine grain clay composition, the island chain has eroded very quickly with rise in sea level and has seen more recently accelerated erosion rates with the introduction of waves created by large vessel wake.

The island, best described as two lobes (northern and southern) connected via a thin shrub-covered tidal flat, has a mix of coniferous and deciduous tree types. It hosts a small population of deer that cross over to the island on ice during the winter. Along with deer, a resident population of raccoons, fiddler crabs, and other small ground animal species inhabit the island. It is located in Dorchester County, MD, which ranks first in the abundance of coastal wetlands in the mid-Atlantic region (~37-45% of total county area) (Reyer and Shearer, 1990).

Although never formally inhabited, a few fish camps and waterfowl hunting lodges were built on the island in the last century. The island came under jurisdiction of the U.S. Fish and Wildlife Service (USFWS) in 1993. This occurred within a mitigation process after a real estate magnate over-developed various properties (other than Barren Island) against regulation. The USFWS placed the newly acquired island within the Blackwater National Wildlife Refuge in an attempt to return the island to its previous pristine state. The island continues to be a stop-over location for a variety of migratory birds, as well as a place for improving environmental abundance.

Plan/Approach

Originally a U.S. Army Corps of Engineers (USACE) demonstration project for beneficial use of dredged material, the Barren Island site became an opportunity for an array of federal, commercial, and community organizations to use their particular skill sets together for a common benefit – tidal marsh restoration. This was highly effective because Barren Island presented a unique set of obstacles not found at most tidal marsh restoration sites, allowing scientists to use a variety of new techniques such as Kinematic Global Positioning System (KGPS), inundation analysis, and Geographic Information System (GIS) modeling.

Prior to the initial studies, USACE had placed several large geotextile tubes, (geotubes) composed of high-strength, UV-resistant nylon and filled with dredged material, on the northwest corner (bay side) of Barren Island's northern lobe (Davis and Landin, 1997). These geotextile tubes (**Figure 1**) served a dual role: 1) a sediment retention structure for dredged material pumped from a nearby shipping channel and, 2) a wave break for protection of Barren Island's quickly eroding shoreline. USACE pumped and graded several thousand cubic yards of dredged material with similar characteristics to those found naturally on Barren Island, landside of the geotubes to create new marsh uplands.

Figure 1. Geotextile tubes placed on the northwest side of Barren Island by USACE retain dredge material used to create new marsh uplands while providing a wave break for the eroding island.

The National Aquarium in Baltimore (NAIB), with help from the Beaufort Laboratory of the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal Ocean Science (NCCOS) and Restoration Center (RC) made a preliminary investigation of the biological and botanical species found on the island. To help NOAA and NAIB scientists determine baseline vegetation type and structure, the restoration site was surveyed along a variety of transects. Biological transects extended from the upland/tidal marsh boundary to the low marsh/bay (open water) interface. The profiles created from these transects provided data on the relationship of vegetation type (species) to the gradient of the existing marsh plane, and overall coverage of vegetation at the restoration site. Two species of marsh grass, *Spartina alterniflora* and *Spartina patens,* were selected as the best match for the island's natural species. These marsh grass species serve as both habitat for small Barren Island fauna and retention of dredged material.

NOAA's tidal experts from the Center for Operational Oceanographic Products and Services (CO-OPS) determined that a one-year water level station would provide key high water information, determine critical tidal datum elevations, and provide comparison data to other long-term water level stations for sea level trends. To ensure vertical and horizontal stability of the water level station and other elevations, NOAA National Geodetic Survey (NGS) installed a series of deep rod benchmarks. These tidal benchmarks were connected to the geodetic datum, North American Vertical Datum of 1988 (NAVD88), via second-order-leveling and KGPS techniques, thereby establishing a vertical reference frame for the tidal datums. This reference frame is used to depict various tidal scenarios onto Digital Elevation Models (DEMs) described later in this case study. KGPS elevation data were also collected for the marsh surface, geotubes, and various elevations of interest at the site. This was critical for the proper placement of marsh grass vegetation and determination of dredged material compaction and movement.

Preliminary Analysis/Instrumentation

Hydrodynamic determination

To better understand and analyze the waters affecting the Barren Island marsh site, two different types of instrumentation were deployed to collect data. First, a one-year NOAA water level station was installed on the northeast coast of Barren Island. Due to Barren Island's lack of buildings and/or permanent fixtures, a small, heavily reinforced tide stand was built adjacent to a seawall. A weatherproof box mounted to the tide stand enclosed a data collection platform (DCP), nitrogen gas tank, IP modem, Paroscientific pressure gauge and batteries for instrument operation (**Figure 2**). A semi-hard rubberized tube connected the Paroscientific pressure gauge inside the box to a brass tide orifice mounted to a piling in waters off the seawall. This nitrogen gas-driven digital pressure sensor converts pressure of the amount of water above the orifice into elevation. Barren Island's remote access forced NOAA scientists to rely on two solar panels for instrument power instead of a power grid connection. This power combination (batteries and solar panels) allowed the station to continuously operate collecting tidal and meteorological data, such as wind speed/gust, wind direction, and barometric pressure, whether in darkness or during large weather events. Communications with the water level station via IP modem were critical in assessing and making changes to the DCP and instrument configurations because access to the gauge could only be attained by boat. A GOES antenna mounted to one of the platform's two masts delivered tide and meteorological data every three hours to NOAA headquarters in Silver Spring, MD where it could be processed and quality assured. Water level data were collected at 6-minute intervals and meteorological data were collected at hourly intervals. The water level station collected a total of 11 months of data over a 14-month time period from Jan. 2002 to March 2003 and was designated as 857-1579, Barren Island, MD. The data obtained from this station were used to determine tidal datums, relate weather events with tidal outliers, and understand long-term sea level trends at Barren Island.

Figure 2. Barren Island water level station featuring GOES antenna, solar panels, barometer, and wind sensor.

The other tools for analyzing the hydrodynamics around Barren Island were two distinctive measurement systems for collecting waves and currents. The first, a TriAxys® wave buoy (**Figure 3**), was moored in two different locations near Barren Island for a total of 1.5 months (Oct.-Nov. 2002). The first location placed the buoy 0.4 miles NW from the restoration site, while the second location was 2.1 miles from the southern tip of the island. At each location, the buoy was moored in approximately 13 feet of water and had a scope of 25 feet. The wave buoy's ability to operate and collect data in shallow water conditions was vital to the NOAA scientists' understanding of the wave regime that affected the Barren Island shoreline. The wave buoy measured significant wave heights, wave period, and wave direction by using 6 different motion sensors and a fluxgate compass to correlate its movement and position in relation to the earth's gravitational field. A directional RHF antenna at a base station on the eastern shore mainland was used in conjunction with the buoy's line of sight radio to receive wave data every 28 minutes. These data were then downloaded and sent to NOAA headquarters in Silver Spring, MD where they could be analyzed. This allowed NOAA scientists to access the status of the wave buoy and its data before the wave buoy recovery date.

Figure 3. TriAxys ® Wave Buoy collecting data in waters around Barren Island.

Another oceanographic measurement system, an acoustic doppler current profiler (ADCP) with WAVES ® software from RD Instruments was operated simultaneously with the wave buoy. This bottom-mounted ADCP with WAVES ® software was beneficial to the project area because it could be placed in deeper waters outside the near-shore zone thereby giving NOAA scientists a variation of wave/depth data to compare with the wave buoy. The ADCP collected significant wave height, wave direction, and wave speed based on three different measurement parameters. A pressure sensor measured long-wave components, while orbital velocity and surface track were measured with the ADCP echo ranging beam produced from the transducer head. The ADCP deployment window of October, 2002 to January, 2003 allowed for a 3-month collection of both current and wave data. This cross comparison of data allowed NOAA scientists to quality assure data while testing a new instrument (the TriAxys ® wave buoy). The location of both the wave buoy and ADCP in relation to Barren Island can be found in **Figure 5**.

Figure 4. The bottom mounted ADCP transducer head (in blue) can be seen as it is lowered to the Chesapeake Bay floor for waves and current data collection.

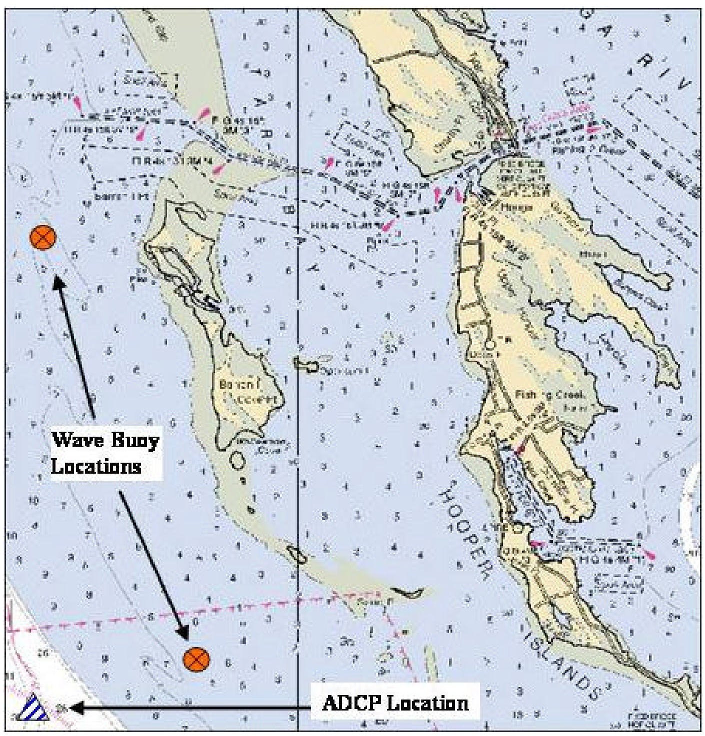

Figure 5. Locations of TriAxys wave buoy and RDI ADCP with WAVES software relative to Barren Island.

Geodetic Investigation

In order to maintain correct horizontal and vertical positioning on Barren Island, five deep rod tidal benchmarks were installed to an average depth of 32.7 meters, the deepest being set to 53.6 meters. The upper portions of these rods were encased in a special greased sleeve to prevent upheaval by permafrost that the island might see in cold Bay winters. A steel-capped PVC pipe flange protects the rod tip benchmark from any over-washing episodes, and allows for easy recovery in the event that a future geodetic data collection is needed (**Figure 6**). These bench marks provided a framework for two separate styles of geodetic data collection that related tidal characteristics to the marsh surface, second-order leveling and kinematic/static GPS. This fundamental relationship was the basis for GIS data manipulation seen later in this case study.

Figure 6. Tidal benchmark with capped PVC flange denoted as 8571579 A TIDAL.

Barren Island's remote island location was a perfect situation for the utilization of GPS. Normally, several long and arduous 'over water' standard level runs would have been required to bring geodetic datums to the island. Simultaneous static GPS measurements made over a two-day period tied Barren Island's network of tidal benchmarks into NAVD88 through a high accuracy geodetic mark on a Hoopers Island bridge abutment. Using cross comparison with an NGS Continuously Operating Reference Station (CORS) at Solomons Island, this static GPS setup attained accuracy levels of approximately 1-2 cm at the tidal benchmarks on Barren Island. Tying in of mainland geodetic datums paved the way for the traditional leveling of the second-order. Using an electronic leveling unit with barcode levels, each benchmark was referenced to one another as well as to the tidal orifice. This method of leveling allowed for millimeter accuracy standards and would be key in understanding whether there was movement at the tidal orifice, or a long-term shift of Barren Island itself.

KGPS, the use of a fixed GPS receiver base station located on a bench-mark, and a second 'roving' GPS receiver, was decisive in relating key marsh features to the geodetic frame-work. Two separate periods of KGPS data were collected for the Barren Island marsh site. These data sets were timed with predicted low water events for Barren Island in order to reach as much of the marsh surface as possible. During each of the collection episodes, several unique marsh features, such as obvious sand berms, distinct plant gradation, and the geotubes were 'hit' by the roving receiver in order to tie them to vertical and horizontal positions. **Figure 7** shows KGPS being collected at different locations on Barren Island.

Figure 7. Kinematic GPS showing the roving receiver collecting data at various points of interest such as land/water interface, abrupt vegetation change, and geologic features.

Post-processed data points from the kinematic and static GPS collection methods were brought into GIS spatial software by NOAA scientists and used to create a Digital Elevation Model. An advanced Natural Neighbor interpolation method allowed scientists to best mimic the Barren Island terrain through statistical regression by including areas that were not 'hit' by the GPS receiver. **Figure 8** shows KGPS data geo-located onto an aerial photograph of the restoration site, while **Figure 9** shows the DEM developed from this data. Note on the DEM that the blue colors are below NAVD88 while the red tones are elevated above it.

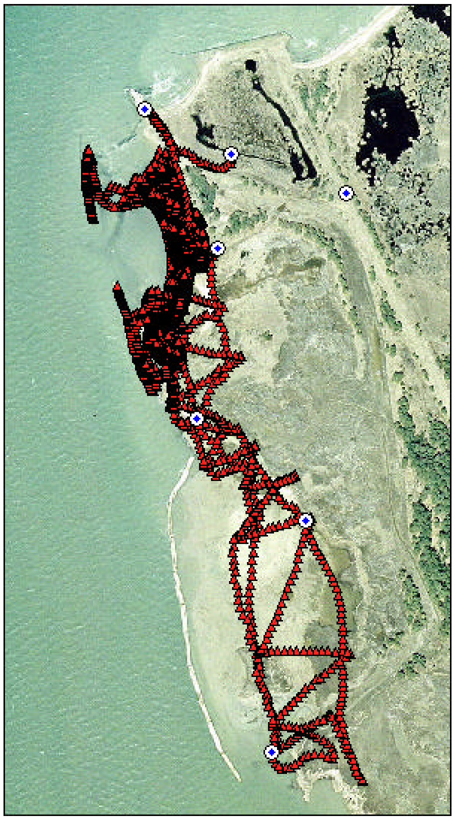

Figure 8. Kinematic GPS data overlaid on aerial photography of Barren Island

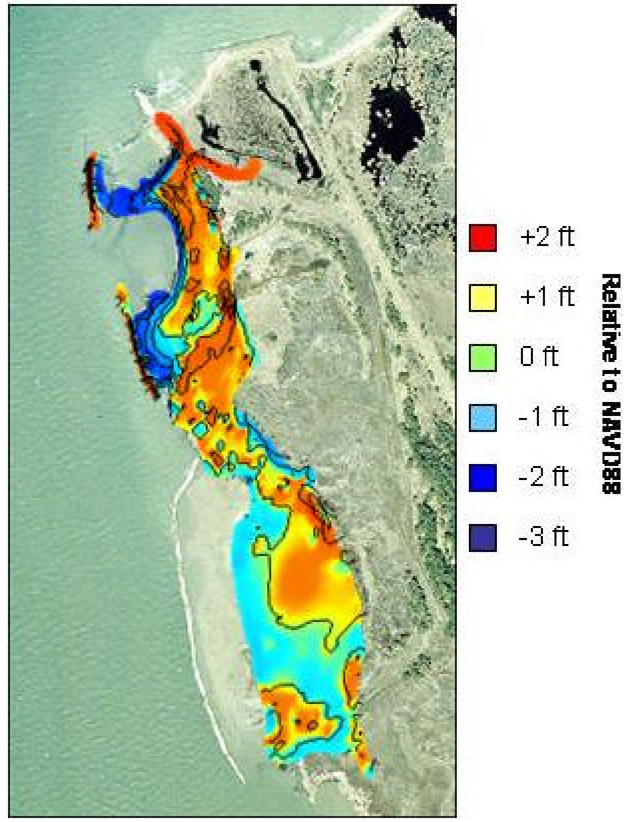

Figure 9. Digital Elevation Model (DEM) created from GPS

Data Analysis

Tidal Datum Computation

Tidal datums were computed for the Barren Island site using 11 months of data collected over a 14-month time period. A data set of this length was needed to factor seasonal, lunar, and solar variations of tidal components to produce a precise snapshot of tides affecting the restoration site. Barren Island was found to have a semidiurnal tide type - 2 lows and 2 high tides per day - similar to other locations in the Chesapeake Bay area. Tidal datums were computed relative to the 1983-2002 National Tidal Datum Epoch using comparison of simultaneous observations with the National Water Level Observation Network (NWLON) station at Solomons Island, MD. **Figure 10** shows the accepted tidal datums relative to NAVD88 for Barren Island. Interpretation of tidal datums reveals a tide range of 1.22 feet present on Barren Island from Mean Higher High Water (MHHW) to Mean Lower Low Water (MLLW). Although this may not seem like a large difference, abnormally large tidal fluctuations and severe weather events permit water levels to inundate a large portion of Barren Island's flat terrain. NOAA scientists used a "Marsh Surface Control Point" - a previously established R-bar bench mark centralized to the restoration effort - to initially quality assure geodetic/tidal data conformity prior to accepted datum configuration.

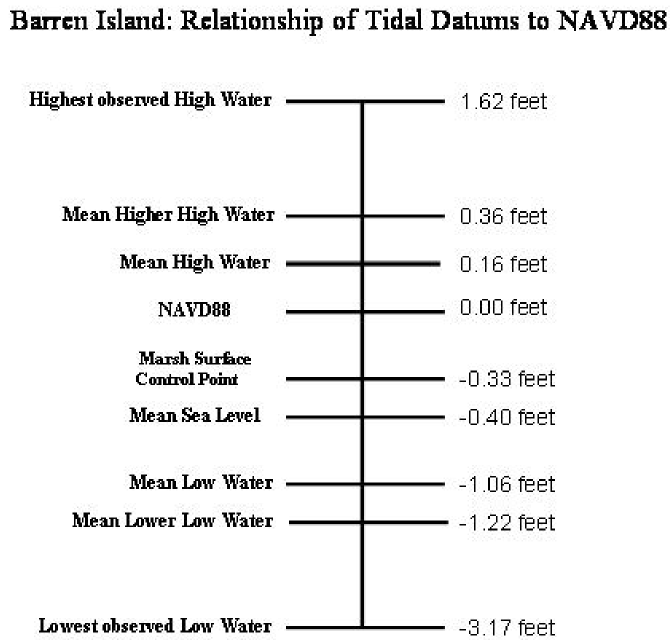

Figure 10. Tidal Datums computed for Barren Island based on an 11-month series.

However, this data set would be irrelevant if it were not linked to the long-term station at Solomons Island. That could show a progression of sea level trends for the life of the marsh surface. The daily and seasonal tidal signature at Solomons Island was extremely consistent with that of Barren Island and revealed similar tide stages and patterns. **Figure 11** shows Solomons Island's long-term sea level trends from 1937 to 1999, which has a sea level rise of + 3.29 millimeters per year. Barren Island, and the marsh restoration site, is expected to experience this same upward trend. The degree of similarity between Barren and Solomons Island will allow for future tide level–marsh surface correlations without the need for a water level station present on Barren Island itself.

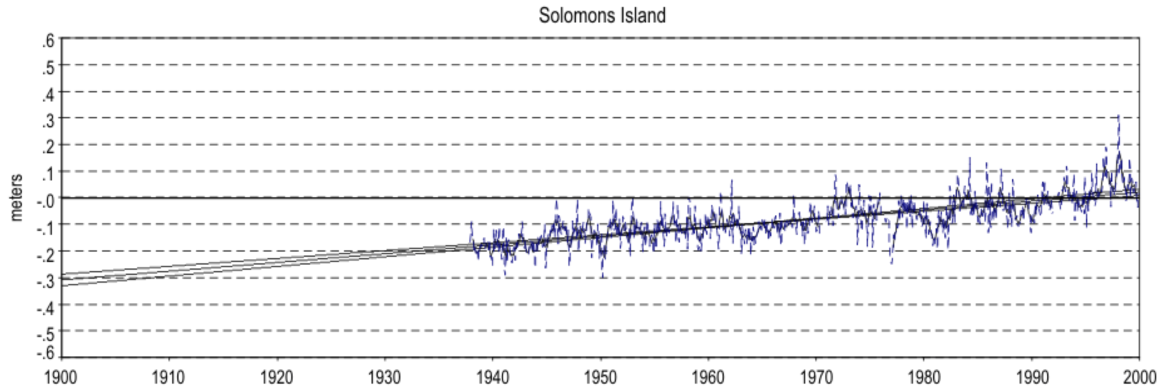

Figure 11. The mean sea level trend for Solomons Island is + 3.29 millimeters/year (1.08 feet/century) with a standard error of 0.17 mm/yr based on monthly mean sea level data from 1937 to 1999.

Tidal analyses were critical because it has been shown that the number of tides per day and the equality of the two daily high tides set limits to which specific marsh plants can thrive and grow (Zedler and Callaway, 2001). Specifically for *Spartina alterniflora*, it was found that the elevational range was positively correlated with tidal range and that tidal range accounted for 70 and 68 percent of variation in upper and lower limits of its distribution, respectively (McKee and Patrick, 1988, Zedler and Callaway, 2001). Also, the tidal datum of Mean High Water (MHW) typically delineates the boundary between *Spartina patens* and *Spartina alterniflora*, with *S. patens* inhabiting higher, less flooded areas lying above the MHW line and *S. alterniflora* requiring more drenched conditions below MHW (Gleason and Zieman, 1981).

Frequency and Duration Analysis

Information about the number and lengths of water inundation is critical to the health and responsiveness of a working marsh. For this reason, the 6-minute high water data series from January 2002 through March 2003 at Barren Island was analyzed in order to place the two aforementioned species of marsh grass. A histogram of frequency versus elevations relative to MLLW for the observed high waters is depicted in **Figure 12**. The graph is partitioned off so that one can see how many cumulative high waters affected each specific growing zone of marsh grass. Below MHW (or to the left) of the green dashed line shows the frequency at which high waters submerged the *S. alterniflora* zone while the right section delineates areas above MHW in which *S. patens* were inundated by high waters. Anything below MLLW would likely not have enough dry time to support effective growth of either species and was not included in these analyses.

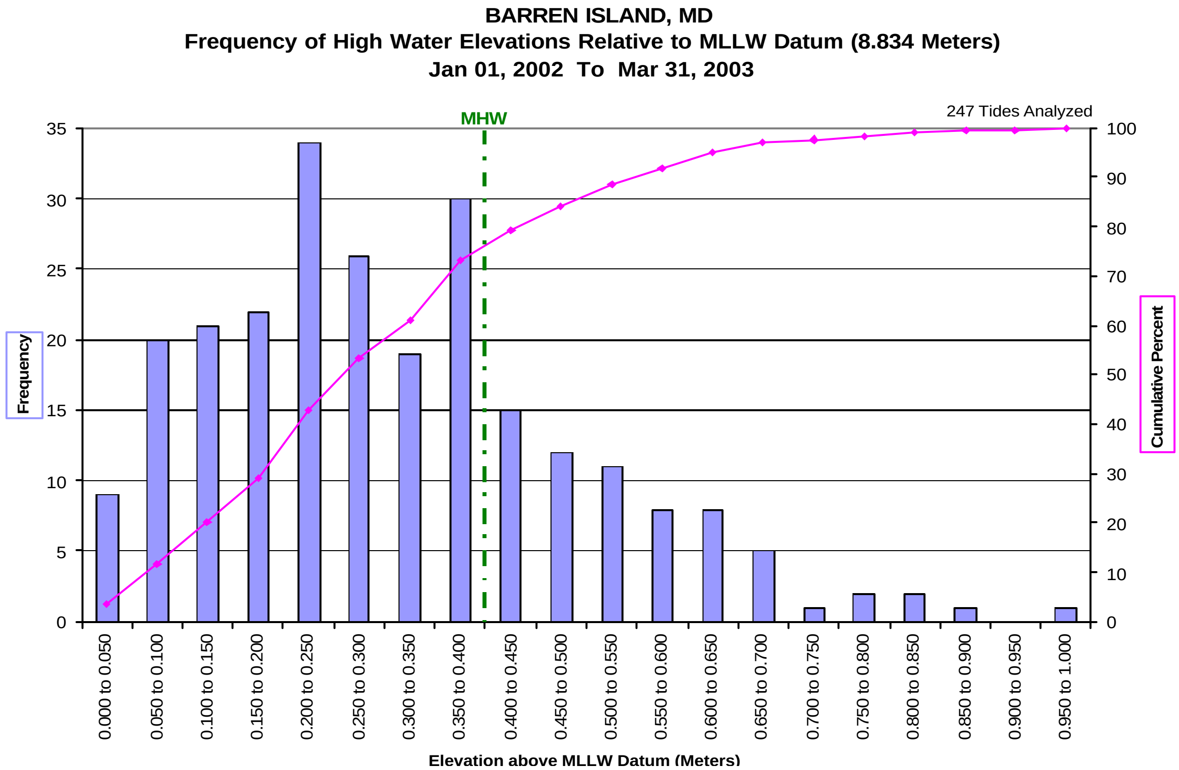

Figure 12. Frequency of high waters for Barren Island relative to MLLW tidal datum.

Notice that the majority of the high waters fell below the MHW line (74%) with a few high waters reaching close to a meter above MLLW. Once scientists had tidal datums and knew the positioning of the MLLW and MHW lines, special attention was made to the more pronounced inundation events. These outliers would be the critical make or break point for the plant species, especially the *Sp. patens* and their need for fairly dry conditions. **Figure 13** shows the duration of inundation versus the elevation of high water above MHW. The figure shows a relatively well-behaved relationship between frequency and duration, with most duration episodes lasting under 12 hours and the majority lasting 7 hours or less. A few events, however, lasted more than 20 hours and overtopped the MHW gradation line by over half a meter.

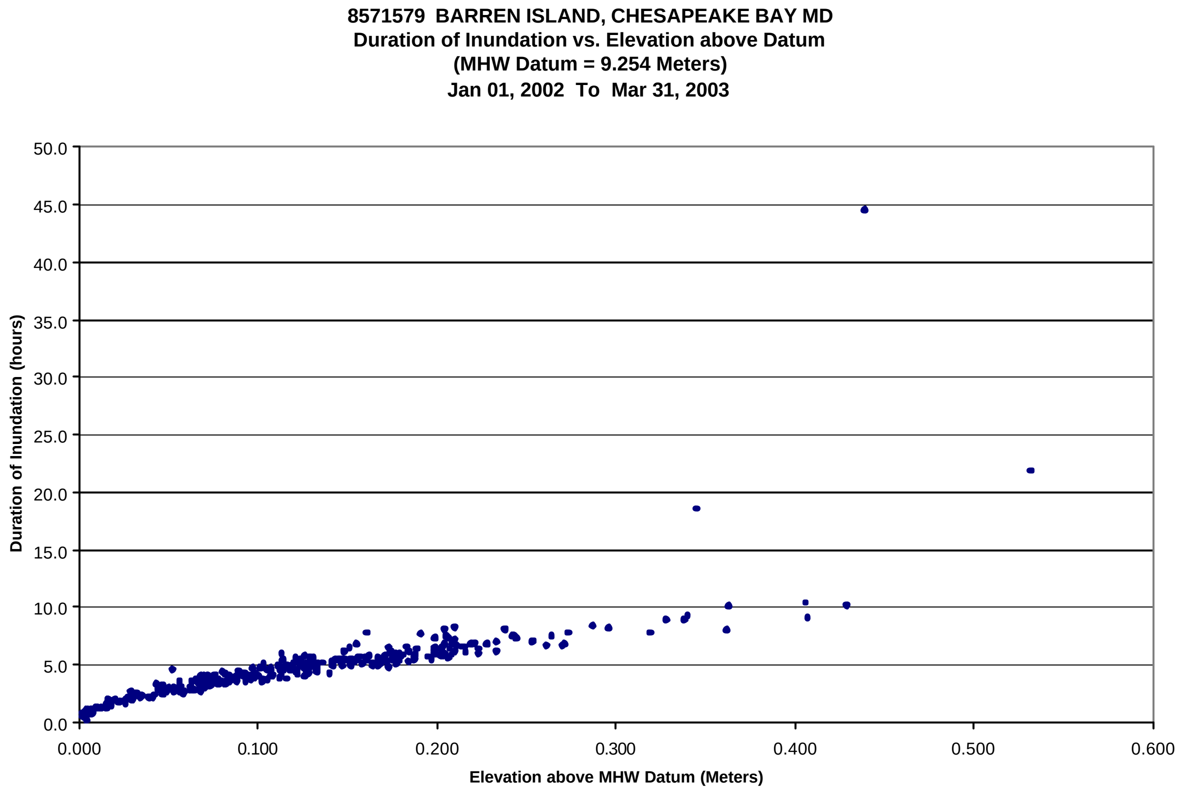

Figure 13. Relative to MHW, an inundation analysis for the 11 month period of tidal collected on Barren Island, MD.

Due to its direct link with Barren Island as a long-term analysis gauge and regional datum control, Solomons Island was used to relate the tidal levels of Hurricane Isabel (Sept. 17-20, 2003) to the marsh restoration area. The site would have seen water levels that reached well over 1.624 meters above MLLW. Due to its flat terrain and small tidal range, storm surge from Isabel completely submerged Barren Island including the marsh restoration area. It is calculated that the marsh restoration site was on-average, under 1.120 meters of water for a period of 56 hours.

Wave data

Early in the characterization of the Barren Island restoration site, scientists realized the critical role that waves had on shaping the coastline. The data produced by the two unique wave instruments, TriAxys wave buoy and ADCP with WAVES software, only stand to reinforce this initial thought. Barren Island, like other islands of the mid-Chesapeake Bay, is subjected to small (0.1 ft – 2.8 ft.), high frequency (3-8 second) waves that are induced by localized winds. **Figures 14** and **15** show that these wind-induced waves are characteristic of the restoration site for a four-day period of data from November 9-12, 2002 collected by the TriAxys wave buoy. **Figure 14** shows the relationship of wave period and direction from which the waves were transiting. NOAA scientists found that when the winds slacked and changed directions, longshore Kelvin waves could be seen in the data. This is seen to occur on Nov. 11th in **Figure 14** when the period jumps up to around 26 seconds.

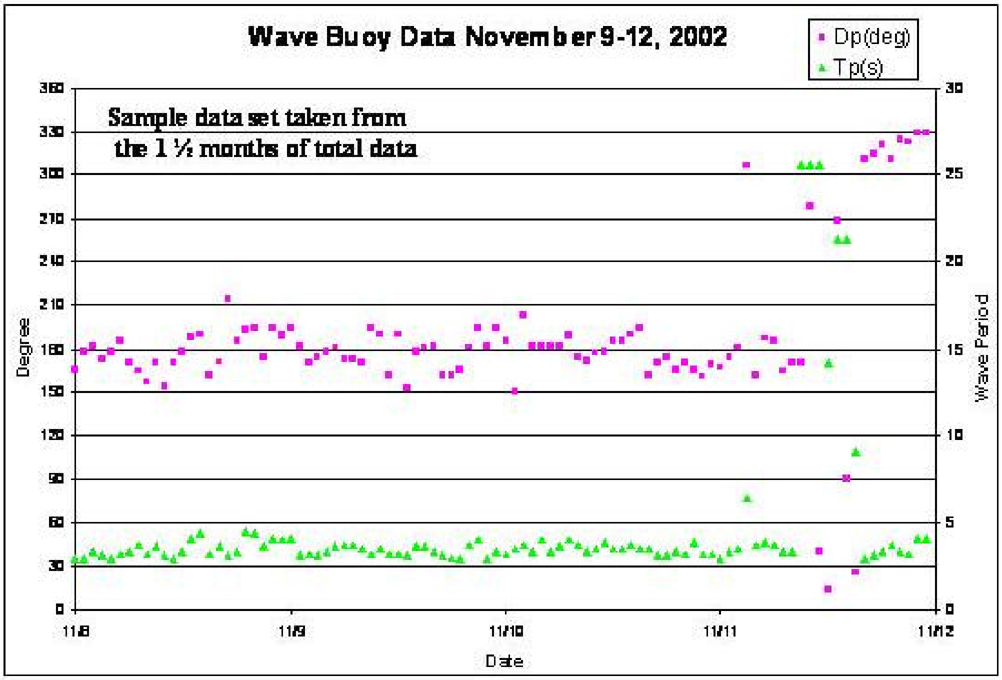

Figure 14. Triaxys wave buoy data for Nov. 9-12, 2002 showing period and direction.

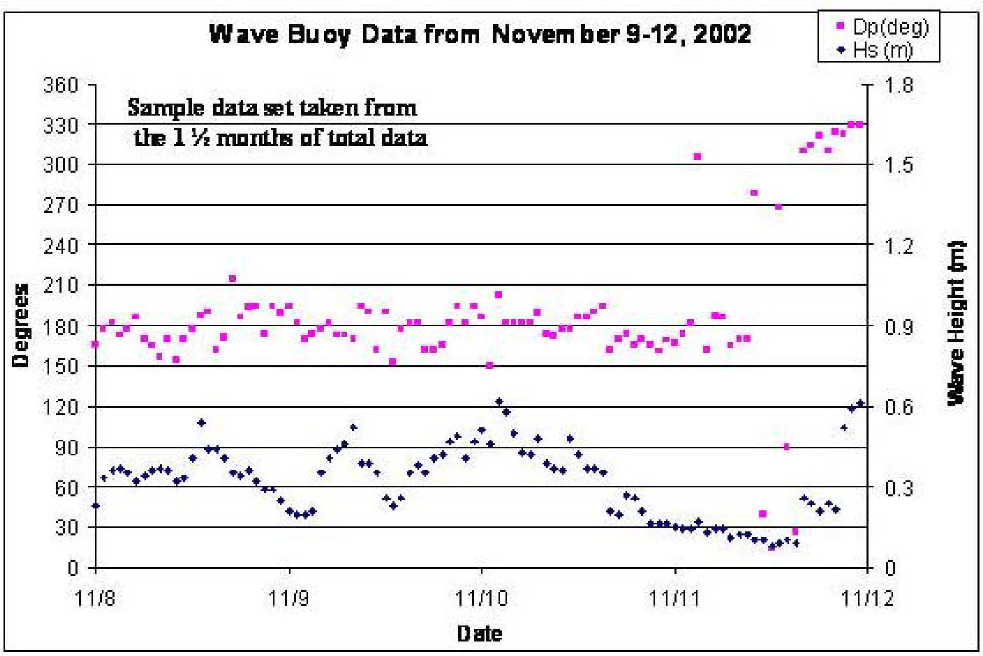

Figure 15. TriAxys wave buoy data typical for the entire data set describing direction and wave height.

Typically, this would not affect a normal coast-line. But because Barren Island's shoreline mimics a clay shelf with no slope, this high period wave tends to erode the fine grain material very quickly. Also, the shape of the Bay's bathymetry near Barren Island demonstrates a gradual slope from the shoreline to a sudden, deep natural channel near the center, inducing what is known as a wave-caustic or wave-reflecting boundary. Thus, large waves created by vessel travel, specifically large displacement boats – tankers, cargo, etc. - are reflected between the shoreline and the caustic, giving more opportunities for the same energy to be more destructive.

Data from the ADCP with WAVES software further supported the TriAxys' findings of high frequency waves induced by local winds. Scientists used the ADCP, a long known standard of NOAA currents specialists, to verify the newer TriAxys technology. Both instruments found that waves evolved from the northwest and the south. This correlated nicely to the long fetches of open water in each of these directions in relation to the Barren Island deployment site and restoration area. Almost 52% of waves affecting the Barren Island shoreline were from the northwest, which would mimic typical meteorological patterns for the area. Wind direction sensors on the tide gauge operating during the time of ADCP data collection point strongly to this occurrence. Another 21% of waves propagated from the south and most likely from the mouth of the Chesapeake Bay. Also found by the ADCP sensor, in conjunction with the water level station meteorological sensors, was a correlation between strong currents and high wind speeds to produce larger than typical wave fields affecting the island. **Figure 16** shows a snap shot of the currents and waves in parallel. The area currents are produced by the tidal influence of filling and draining near the Atlantic Ocean mouth of the Chesapeake basin. The data collected from these instruments will not only help baseline statistics but will be used in the construction of a new retention system for further restoration efforts.

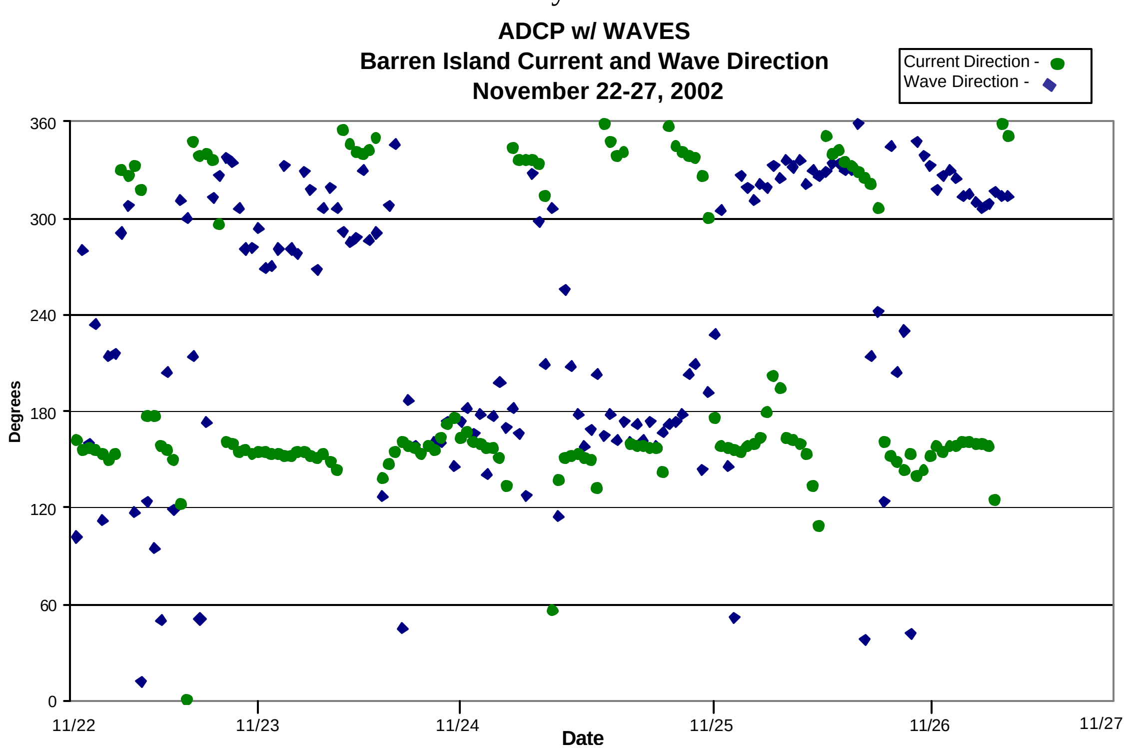

Figure 16. Correlation between wave direction and current direction for a 5-day period in November 2002.

Water-marsh surface intersection determination

After collection and processing, NOAA scientists used a Geographic Information System (GIS) platform to geo-locate and digitally integrate the various tidal, geodetic, and biological data types. It is important to note that this piece of analysis was done after restoration efforts had taken place, but will be used in the future as a tool. This assimilation of unique data allowed scientists to visualize more basic routines such as specifying zones of optimal growth for each of the two plant species, understand the layout of the restoration area vertically, and make estimates on future personnel/cost needs.

As previously mentioned, MHW and MLLW values were used to delineate areas in which both *Sp. alterniflora*, and *Sp. patens* would tend to thrive and take hold. Based on the digital integration of tidal and geodetic data, **Figure 17** illuminates what areas, color coded by species, would be best for planting of the marsh grass. Red zones (below MHW to the MLLW line) are the most beneficial for *Sp. alterniflora* and the blue zones (above MHW but below the MHHW) have the right amount of inundation for *Sp. patens.* Note the black zones; these are areas that received less than 2% of high water inundation over the 11-month data series collected on Barren Island and would likely be re-graded to match surrounding marsh heights, or considered 'no plant' zones. These areas are likely to be much too dry for anything other than high marsh plants. **Figure 18** shows the vertical relief of the restoration area, and how digital interpolations can benefit a wetland biologist or restoration specialist. One can see the severe slope from flat 'beach zone' to deep erosional-pond-portion consequently as a part of a geo-tube failure. This same feature is mimicked in the grass-optimization picture (**Figure15**) with tight bands where each grass would thrive. Also, a long natural berm running from north to south just behind the restoration site is evident in the 3-D rendering of the aerial photograph.

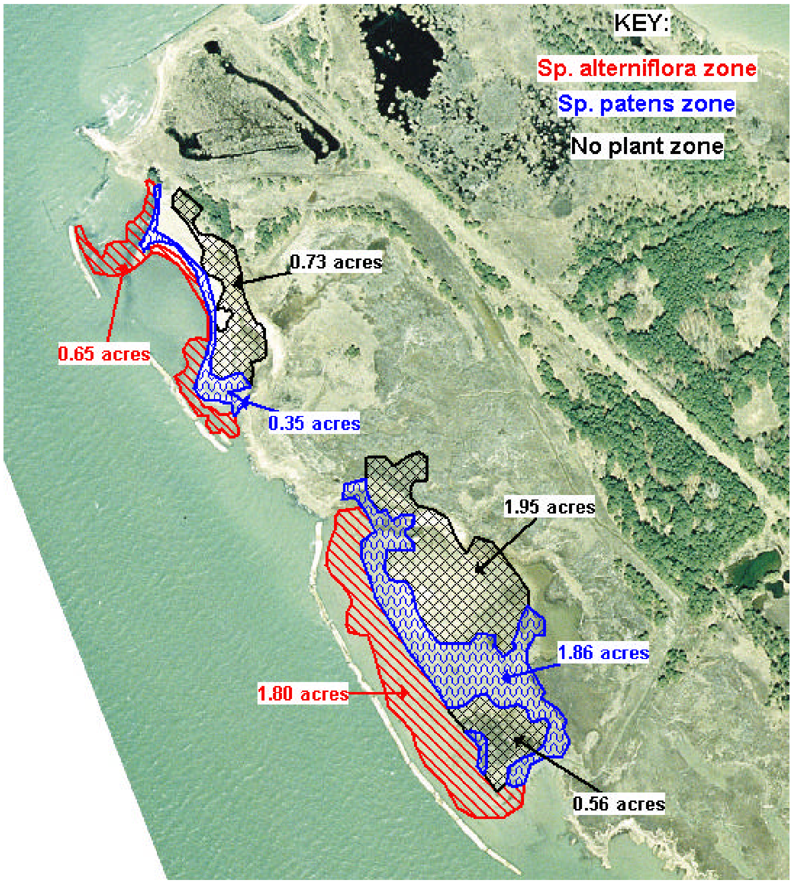

Figure 17. Optimal marsh grass tidal parameters overlayed onto an aerial photograph using KGPS

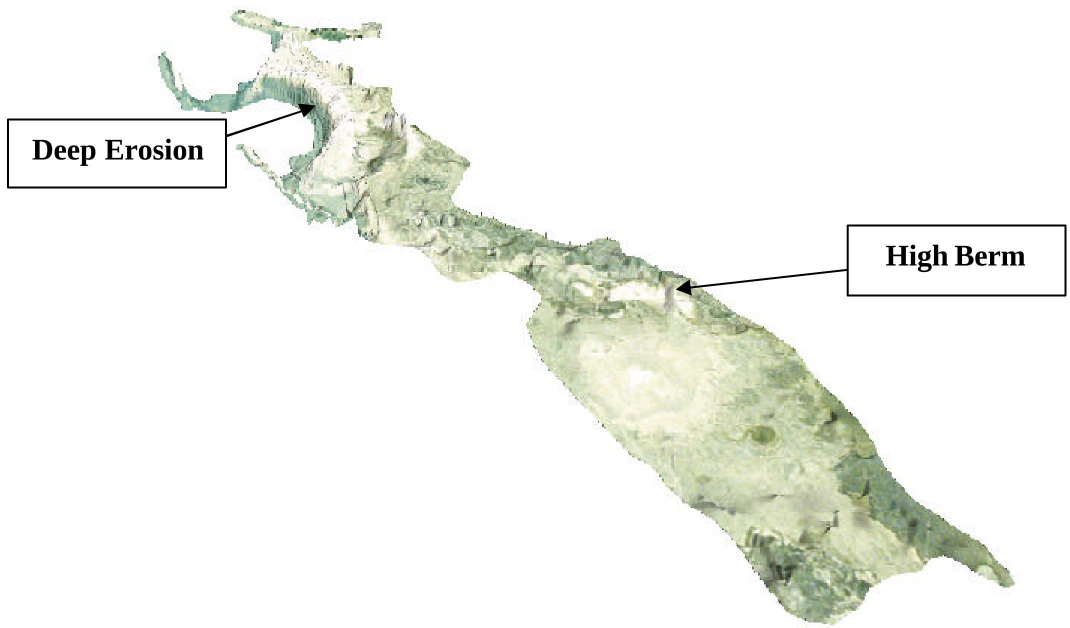

Figure 18. Aerial photograph digitized to show 3D heights of KGPS data collection.

Conclusions

NOAA's Beaufort Laboratory of the National Centers for Coastal Ocean Science and NOAA's Restoration Center are working with the National Aquarium, USACE, and USFWS and NGS on a large scale marsh restoration project that is demonstrating the beneficial use of dredged material. The USACE is dredging from a nearby navigation channel and placing it on marsh face and surface being quickly eroded away by waves. Geotubes have been placed along the western side of the island to help protect it from erosion and to contain the dredged material. The island is subjected to severe erosion. One of the original geotubes failed, and you can see the scalloping that occurred. Tidal information was collected, and NGS conducted KGPS surveys to determine the present marsh surface topography. Wave and current measurements were collected offshore and will help the USACE decide how to place new, protective infrastructure. For example, if the waves and currents are coming from the north, they might want to orient the infrastructure differently than if they are coming from the west. The elevation data will help in determining where to plant in the future, how much and where to place dredged material on the subsiding marsh and how high to make the protective infrastructure. USACE will be building out Barren Island over the next several years and will be building a large levee system. Elevations and high water analyses have been provided so that they can be used in designing and building these future protective structures.

This project has demonstrated the capabilities of tidal and geodetic measurement integration with high water analyses and analyses of wave and current data, to provide much needed baseline information required by coastal engineers and marsh restoration scientists.

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Fort McHenry Wetlands Restoration Project

- Critical Issues:
  - Reestablish and enhance existing small wetlands in an urban setting
  - Provide elevation topography for wetlands design and construction
- Preliminary Analysis/Instrumentation:
  - Tidal datums were transferred to the site from the nearby tide station bench marks
  - Geodetic datums were transferred to the site from nearby bench mark elevations
  - Frequency and duration of inundation analyses were run on historical data from the nearby long-term tide station
- Data Analysis:
  - Kinematic GPS (KGPS) survey provided basis for Digital Elevation Model (DEM)
  - The DEMs and tidal datum relationships were used to develop engineering design
  - Wetlands construction has begun and plans for planting are proceeding in Spring 2004

Introduction/Background

In the past two decades, creation and restoration of tidal wetlands has become a required form of mitigation. This is also the case for many areas in the Chesapeake Bay such as the wetlands adjacent to the Fort McHenry National Historic Monument and Shrine. These wetlands were originally constructed in 1982 as mitigation for the Interstate 95 highway tunnel construction. The wetlands are now being reconstructed from mitigation credits for filling in a nearby port slip. This will allow more containers to be offloaded. **Figure 1** is a photo overlook view of the marsh, and **Figure 2** is an aerial photograph of Fort McHenry wetlands and vicinity, showing where the wetlands are relative to the Fort.

When originally constructed in 1982, this wetland had three small culverts through the riprap that encircled the site. The culverts allowed tidal exchange with adjacent harbor waters. These culverts have since mostly silted in, largely cutting off tidal exchange and resulting in the degradation of natural salt marsh function at the site. The purpose of the proposed modifications to the site is to promote regular, natural tidal flooding to the site, control debris accumulation, and enhance its habitat value to plant and animal species.

The restriction of tidal flow has resulted in several deleterious effects that should be reversed if normal tidal exchange can be restored. Primary among these is invasion by the common weed, *Phragmites australis*. *Phragmites* tends to invade and successfully colonize salt marshes that lose their source of tidal salt water. This process can be exacerbated by the presence of fresh water runoff to the site, which the wetland at Ft. McHenry has. The proposed modifications will result in the physical removal of several

Monday, March 22, 2004 – 3:00 pm EST

Figure 1. Photograph showing visual overview of the Ft. McHenry Wetlands

Figure 2. Location of Ft. McHenry Wetlands Restoration Project

existing *Phragmites* stands, which will either be replaced with planted native vegetation (e.g. *Spartina alterniflora*, *Spartina patens*, smooth cordgrass) or will be converted to intertidal creek habitat. The return of tidal salt water to the site via the proposed inlets and network of created creeks also has the potential to confer a benefit to the entire site by minimizing its susceptibility to continued *Phragmites* expansion.

The current system of mostly silted-in culverts also prevents juvenile migratory fish (e.g. *Morone saxatilis*, striped bass; *Leiostomus xanthurus*, spot; Alosa spp., river herrings) from utilizing the site as nursery habitat. The proposed plan will produce two inlets to the harbor allowing fish access to the created creek network in the marsh. Tidal creeks are known to be high-quality foraging habitat for the juveniles of many fish species. It should also be noted that many juvenile fish use the flooded marsh surface as foraging habitat during higher high tides (spring tides). As the proposed plan will return tidal flooding to the marsh surface of the entire site during spring tides, it also has the potential to confer benefits to fish that will extend across the entire marsh. Other resident marsh fauna, including small fish and benthic invertebrates, as well as birds and other larger animals that prey on these species, will also likely benefit by the return of natural tidal flooding to the created creeks and the marsh surface.

The National Ocean Service (NOS) is working in partnership with the National Aquarium in Baltimore (NAIB) to ensure that the restoration of the Fort McHenry wetland is successful. The NOS Center for Operational Oceanographic Products and Services (CO-OPS) and the NOS National Geodetic Survey (NGS) are performing the tide and geodetic work described in this case study. A formal Memorandum of Agreement (MOA) has been established between NOS and the Maryland Port Authority (MPA) to transfer funds to cover costs for a new tide station installation.

Plan/Approach

Perry *et al* (2001) provide a discussion of wetlands restoration and the creation of salt marshes within the Chesapeake Bay. Among the many considerations for design and construction is the knowledge of the elevation and gradient of the substrate relative to high water datums and mean sea level. Information on the time-varying nature of inundation and drying is also required. The physiographic range of the associated species of vegetation is generally related to the elevation of Mean High Water (MHW) for use in guidance of where to plant. Other considerations include how often marsh surfaces are irregularly flooded due to storm tides and maximum astronomical tides. Long-term viability of functioning marshes is dependent upon proper accretion rates and sediment accumulation in response to local sea level rise. Stevenson *et al* (1989) discuss this linkage.

Executing the construction plan will entail breaching the existing riprap at three locations to allow tidewater to enter the site unobstructed, and excavating a network of creek channels that will tie into the existing creeks at several locations. The proposed creek network includes primary creeks that communicate directly with the harbor via the inlets, and smaller second-order creeks branching off the primary creeks. After the plan is implemented and the site matures, third order and smaller creeks may form as natural erosion forces shape the site. This would be desirable since fully-functioning wetlands are characterized by a complex, dendritic channel network.

The technical approach for this project has been to:

- Transfer tide and geodetic datums to the site from the nearby existing control, rather than establishing a new control
- Conduct a topographic survey of the wetlands surface using Kinematic GPS (KGPS), and develop a DEM surface
- Provide the DEM and the tidal datum relationships to the wetlands design engineers
- Design and construct the new wetlands using the reference information
- Establish a tide station on-site after construction for monitoring purposes, and conduct a new post-construction DEM.

Analyses

Tide and Geodetic Datums: The Fort McHenry wetlands are in very close proximity to the long-term NOAA National Water Level Observation Network (NWLON) station at Baltimore (located on a U.S. Army Corps of Engineers pier just north of the Fort and the marsh – see **Figure 2**). Given this proximity, the tidal characteristics, tidal analyses, and tidal datums were transferred directly to the wetlands from the observations at this long-term station. The accepted tidal datums at the tide station have been computed over the 19-year National Tidal Datum Epoch (NTDE) of 1960-78 (see http://tidesandcurrents.noaa.gov/, "Bench Marks for Baltimore," and CO-OPS, 2001). Elevations of the tidal datums have been referenced to geodetic datums using leveling and GPS surveys from the tidal bench marks to the National Spatial Reference System (see www.ngs.noaa.gov). North American Vertical Datum (NAVD88) is the geodetic datum being used as the vertical reference datum for the wetlands restoration project. **Figure 3** is a stick diagram showing the elevation relationships of the tidal datums to NAVD88. Knowing these relationships was fundamental to the project design.

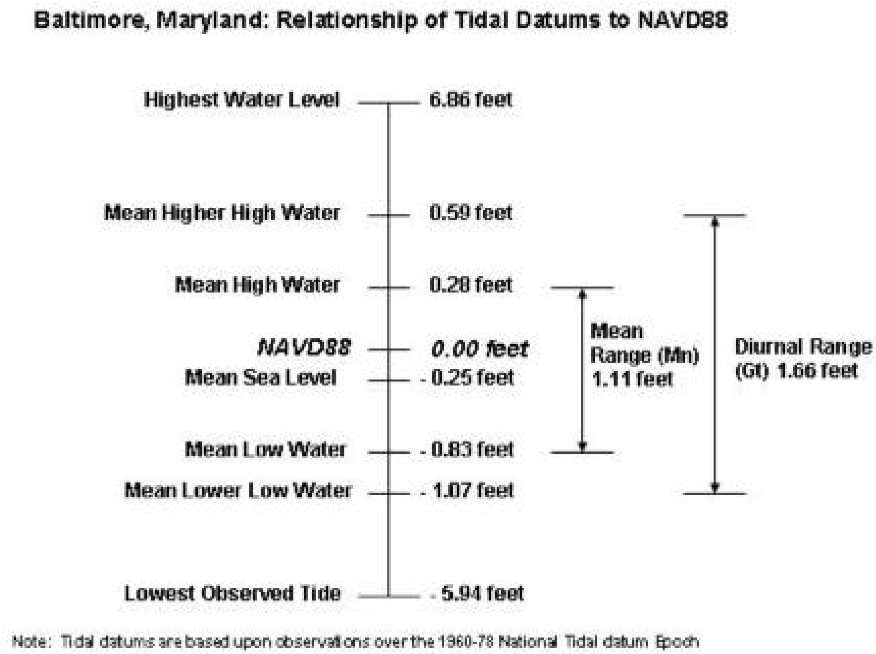


Figure 3. Tide and Geodetic Datum Relationships at the Baltimore NWLON station.

Digital Elevation Model: NOS/National Geodetic Survey (NGS) conducted KGPS surveys of the site to obtain existing wetlands surface elevations. The KGPS survey was conducted by establishing a base station over one of the existing bench marks with known precise geodetic datum elevation, and by "walking" the wetlands using a portable backpack KGPS unit. Topographic elevations in the existing sloughs (under water) were made using a small boat and inserting the GPS pole down to the bottom. **Figure 4** is a diagram showing the KGPS measurement paths. The elevations, referenced to NAVD88, were then used to develop the DEM (**Figure 5**).

Wetlands Engineering Design: The DEM in **Figure 5** was then used by MPA's engineering consultants to design the new wetland in a construction elevation drawing **(Figure 6). Figure 7** shows the newly designed wetlands topography relative to the tidal datum of Mean Higher High Water (MHHW). The ability to overlay various elevation surfaces in this manner was critical to the final design elevations.

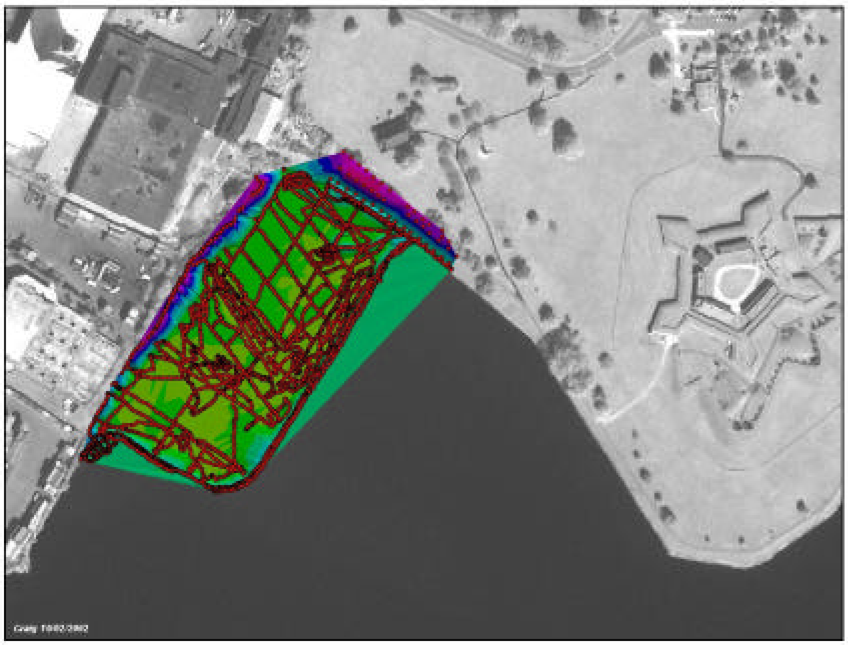


Figure 4. The Ft. McHenry Kinematic GPS Survey

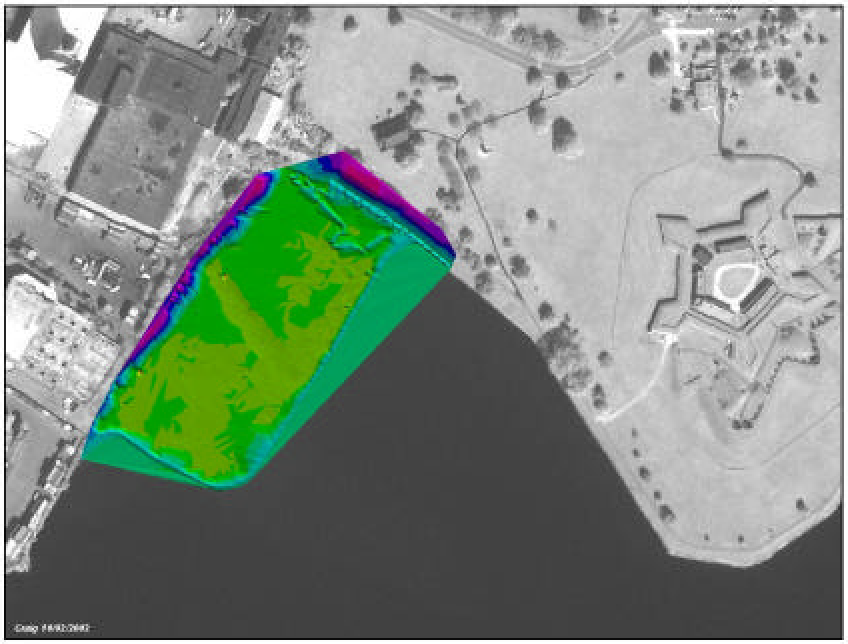


Figure 5. The Ft. McHenry Pre-construction Digital Elevation Model (DEM)

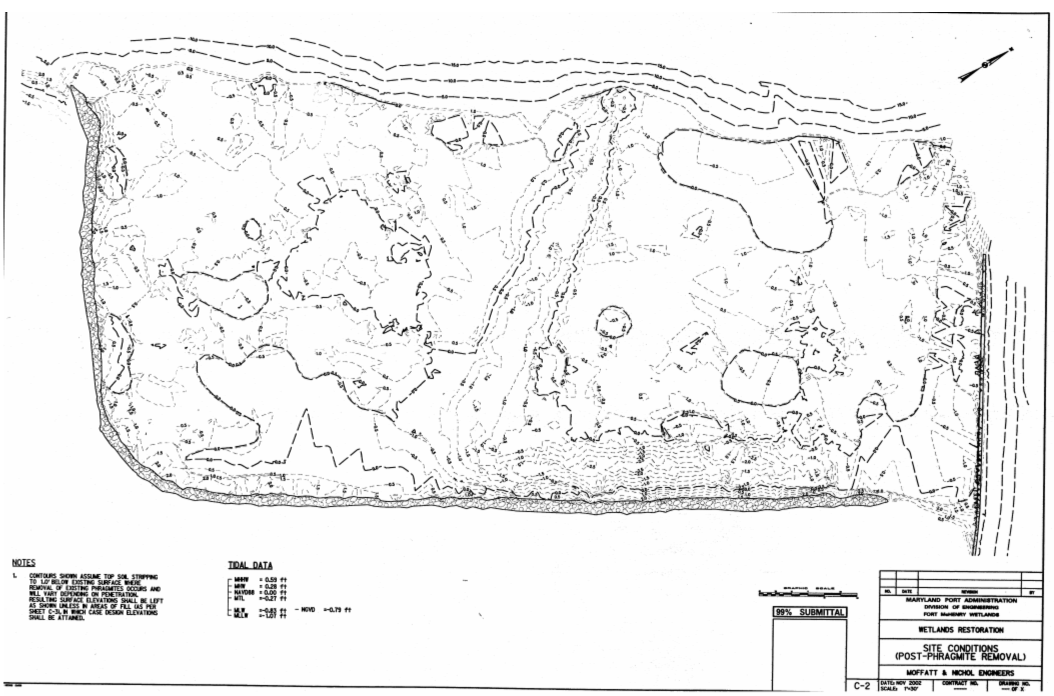


Figure 6. Pre-construction Engineering Drawing

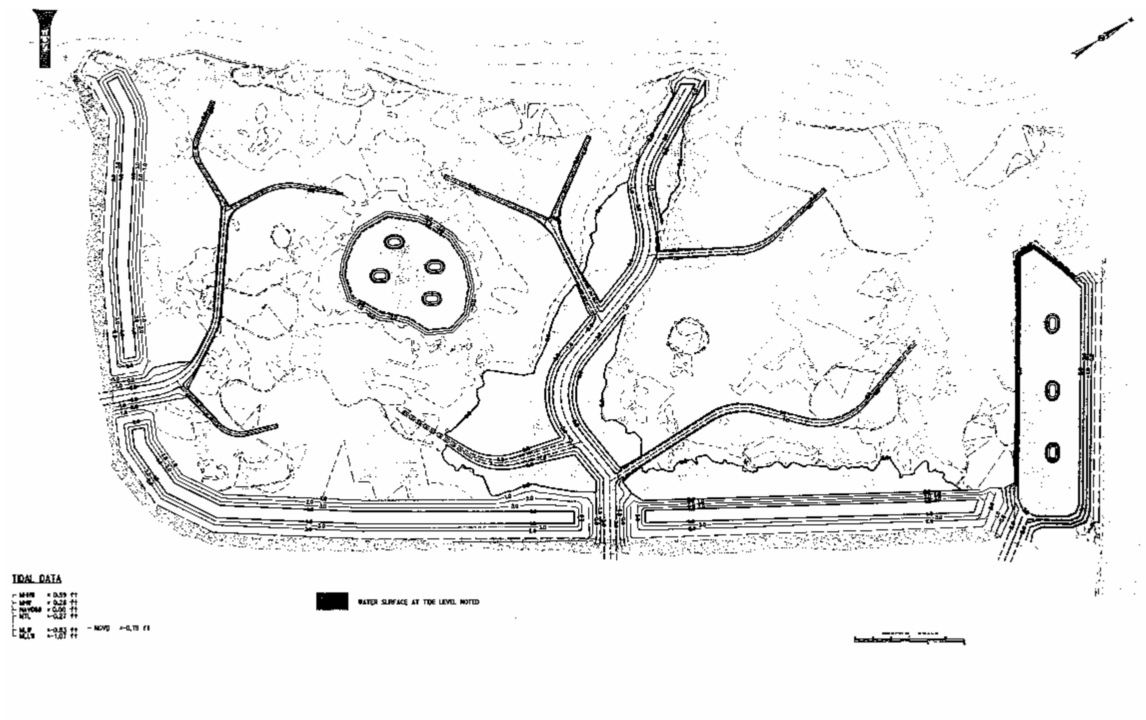
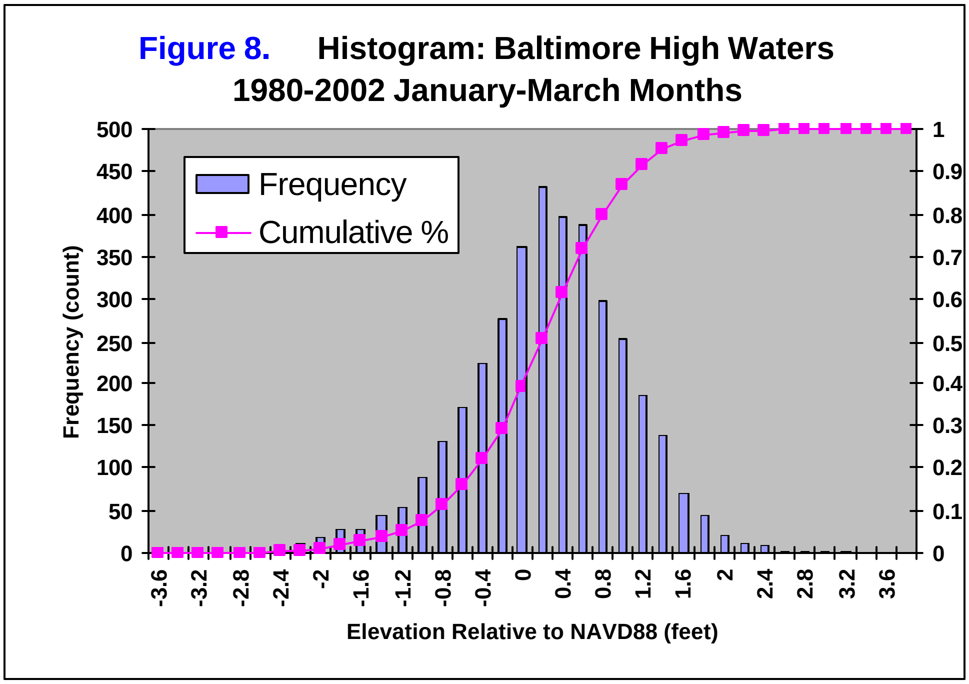
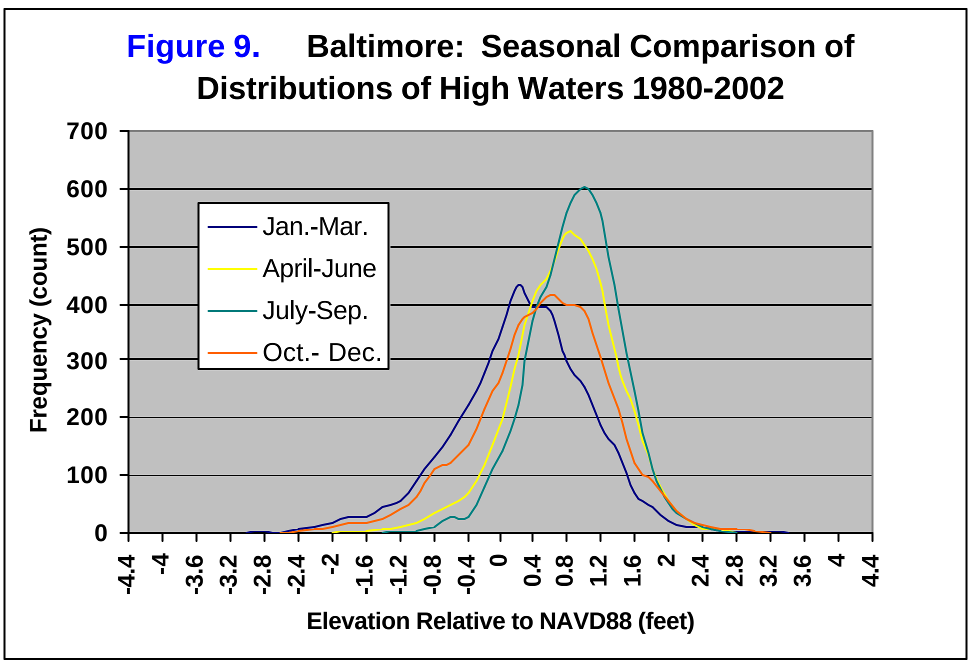


Figure 7. Newly Designed Wetlands Engineering Drawing at MHHW

<u>Frequency and Duration of Inundation Analyses:</u> Frequency and duration of inundation analyses of the high waters for the site were obtained by analyzing the data from the long-term NWLON station at Baltimore. NAIB biologists have used this information to determine where and when to plant different species marsh vegetation. Using information from the observed times and heights of the high and low waters from 1980 through 2002, frequency analyses of the high tides are shown in **Figure 8** for the January through March time period. The frequency histogram is a count of high waters contained in various elevation bins relative to NAVD88. The histogram also shows the associated cumulative percentage curve that is used to estimate inundation probabilities for given elevations. **Figure 9** is a comparison of four histogram curves that illustrate the seasonal variations in the elevations of the high tides. The distribution curves for January through March and October through December are similar in shape. They are broader and shorter than the two curves for April through June and for July through September. In addition, the distributions for the latter time periods are shifted more toward the higher elevations above NAVD88.





A plot of the duration of inundation for calendar years 1994-2003 is shown in **Figure 10**. The duration of inundation, or the elapsed time that the water elevation was at or above

NAVD88 for each high water, was estimated using the 6-minute interval data before and after the time of each high water. The plot reveals a tiered effect of the duration of inundation dependence on the elevation of the high waters. A distinct tier from the elevation of NAVD88 at time intervals of multiples of 12 hours is readily apparent. Less defined tiers are found above 60 hours. There were several extremely long durations of greater than 90 hours. The data point to the far right on the plot is from Hurricane Isabel. Although extremely high in amplitude, the duration of inundation was not extreme due to the fast moving nature of the storm inland. This tiered effect is attributed to the effects of weather on the water levels of the upper Chesapeake Bay for extended time periods, greater than one day. It is appropriate to expect that the wetlands surface will often be inundated for more than 12 hours.

This information, along with the frequency statistics in **Figures 8 and 9**, is important because certain plant species can only survive limited durations of inundation. The engineering of the wetlands surface, the depths of the sloughs and the elevation of the berms must also take into account these statistics.

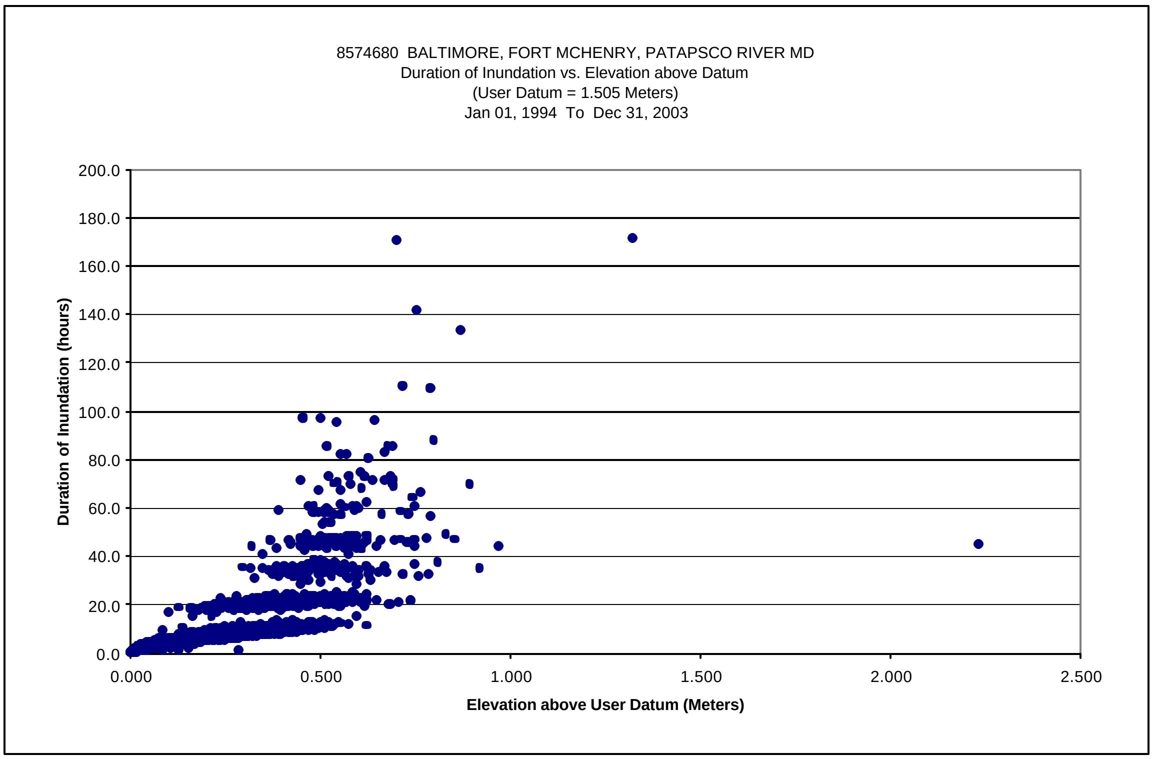


Figure 10. Duration of inundation curve for Fort McHenry from NWLON station at Baltimore, MD.

Construction Phase

The wetlands construction phase began in Feburary 2004. Initial construction phases are shown in **Figures 11 through 13.** A leveling transit is used to bring the desired marsh elevations into the project. The elevations are based on the engineering drawings and tide and geodetic datum relationships. The photograph in **Figure 11** shows the leveling transit used for this project. **Figure 12** shows the use of a leveling rod to estimate the depth to which the ponds and sloughs are to be sculpted by the heavy machinery. **Figure 13** shows the extent of some of the surface grading using the heavy machinery.

Figure 11. Photograph showing the use of the leveling transit to control the marsh surface.

Figure 12. Photograph showing the use of leveling rod to determine depth of one of the ponds being sculpted by the heavy machinery.

Figure 13. Photograph showing the grading of the surface of the wetlands.

Post-Construction Activities

NOS has installed a tide gauge that will operate for one year at the wetlands site, and has connected it to the existing bench mark network nearby. Simultaneous comparisons between the long-term station and the short-term station will be made to compute tidal datum elevations at the wetlands site. These elevations will be compared to those brought in from the nearby long-term tide station using levels. Frequency and duration of inundation analyses will be performed from the short-term (one-year) station as well. NAIB will use this station as part of the public relations and education aspects of the restoration effort.

Figure 14. The one-year tide station at Ft. McHenry Wetlands showing the equipment shelter and GOES antenna and solar panel towers.

This particular tide station configuration uses a "bubbler" pressure sensor located several yards off shore (to the right of the picture in **Figure 14**) in which the water level pressure is digitized from an air-vented pressure transducer inside the instrument shelter. The nitrogen bubbler tubing is buried under the beach and connected to the orifice securely mounted to the bottom offshore. The equipment was installed on a raised platform designed to be higher than the expected highest tides.

Figures 15, a – d show some of the features of the newly constructed wetlands surface, as of March, 2004. The photographs were taken during an extreme low water stand. The photos show some of the features shown in the engineering diagrams found in **Figures 6 and 7**. Inflatable barriers protect tidal slough entrances so that debris will not choke the entrances. Debris will still be a problem during extreme high water events.

Figures 15 a – d. Post construction wetlands surface before planting.

NOS has started to perform a post-construction KGPS survey of the wetlands surface to update the DEM (see **Figure 16**). The performance of the newly planted marsh grass and the hydraulic performance and stability of the tidal sloughs and ponds will be closely monitored for the next several years**.** The effectiveness of the wetlands design will be evaluated continuously and some minor construction changes are anticipated. NAIB will be doing precise photo time-lapse monitoring and is going to install Sediment Erosion Table (SET) equipment to measure marsh accretion and subsidence. Long-term sea level trends observed at the nearby NOAA NWLON station will be used to estimate relative sea level trends at the restoration site.

Figure 16. Running a post-construction KPGS survey at Ft. McHenry Wetlands.

The elevation of the extreme, 100-year event storm surge was recently recorded at the wetlands during Hurricane Isabel. The debris line left by the hurricane was several feet above the wetlands surface, and caused some erosion to the high berm located upland of the wetlands. A strong front blew water up into the Bay, and then out of the Bay the following day. The effects of that extreme high water event followed by the extreme low water event were captured on March 20 and 21 following the passage of the front. **Figures 17, a – d** show the contrast from photographs taken from the same vantage points each day. **Figure 18** shows how high and low the extremes were relative to predicted tides. **Figure 19** (same as **Figure 10**) shows the event in the context of the duration of inundations over the longer time period.

Figures 17, a-d. The Ft. McHenry Wetlands during an extreme high water (left photos) followed by an extreme low water event (right photos).

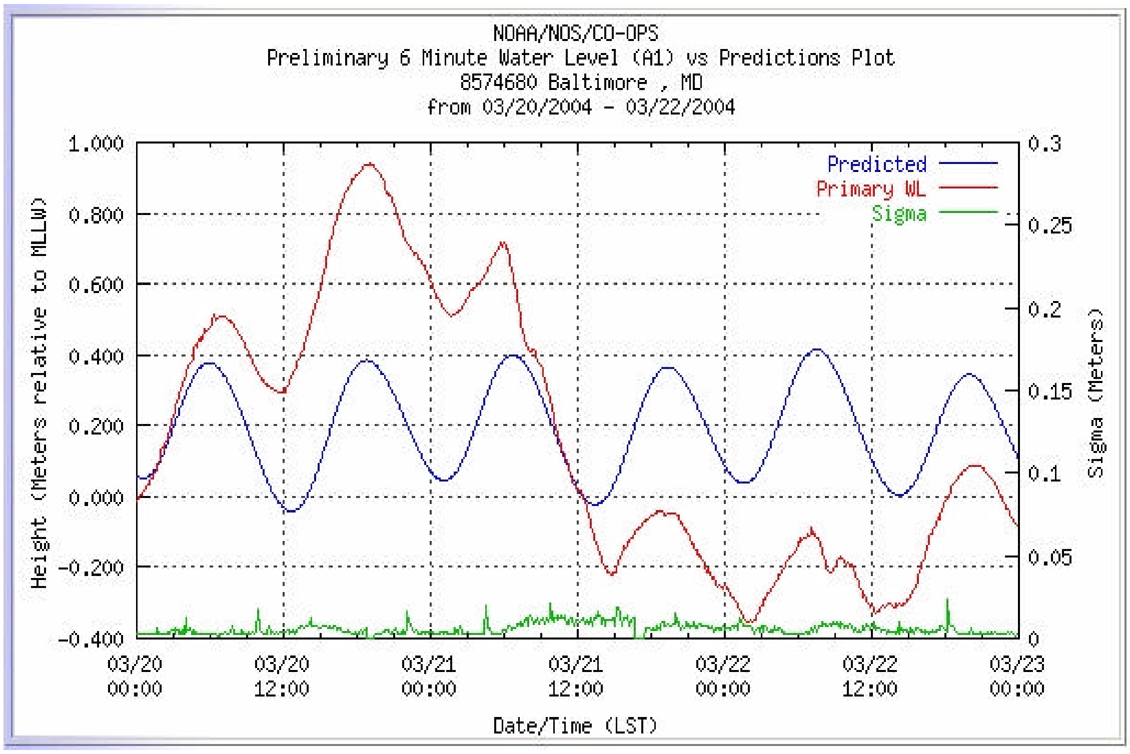


Figure 18. The time series plot of the extreme high water/low water event on March 20 and 21, 2004

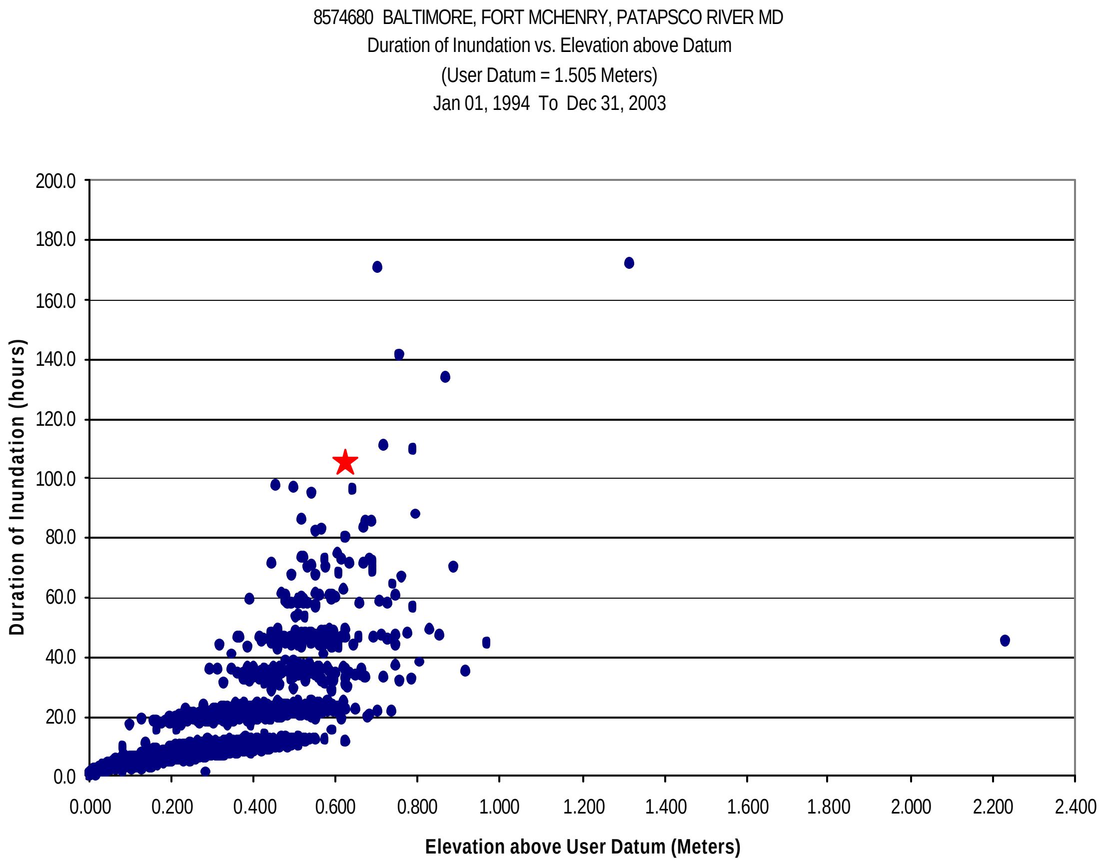


Figure 19. The duration of inundation plot putting the March 20 and 21'st event (Red Star) into context with the historical record.

Conclusions

The wetlands adjacent to the Ft. McHenry National Historic Monument and Shrine have been degraded by the removal of regular tidal flushing to the site and by accumulation of anthropogenic debris from tidal waters. The wetlands restoration will have direct benefits to the proportion of the site that is either converted to new aquatic habitat or re-vegetated with native wetlands vegetation. In addition, the entire site will likely benefit as a natural tidal flooding regime and hydroperiod is restored.

The Ft. McHenry Wetlands Restoration Project is already considered a success from a planning and implementation perspective. This is because the water-level analyses as well as the tide and geodetic datum information were applied up front, in the planning and in the actual engineering drawings. They were also applied during wetlands construction and to the strategy for planting the new marsh grass. The new wetlands are presently under construction and the wetlands surface is taking shape. **Figures 20 and**

21 are the post-construction remote sensing imagery taken just before planting. Planting activities were started in April, 2004.

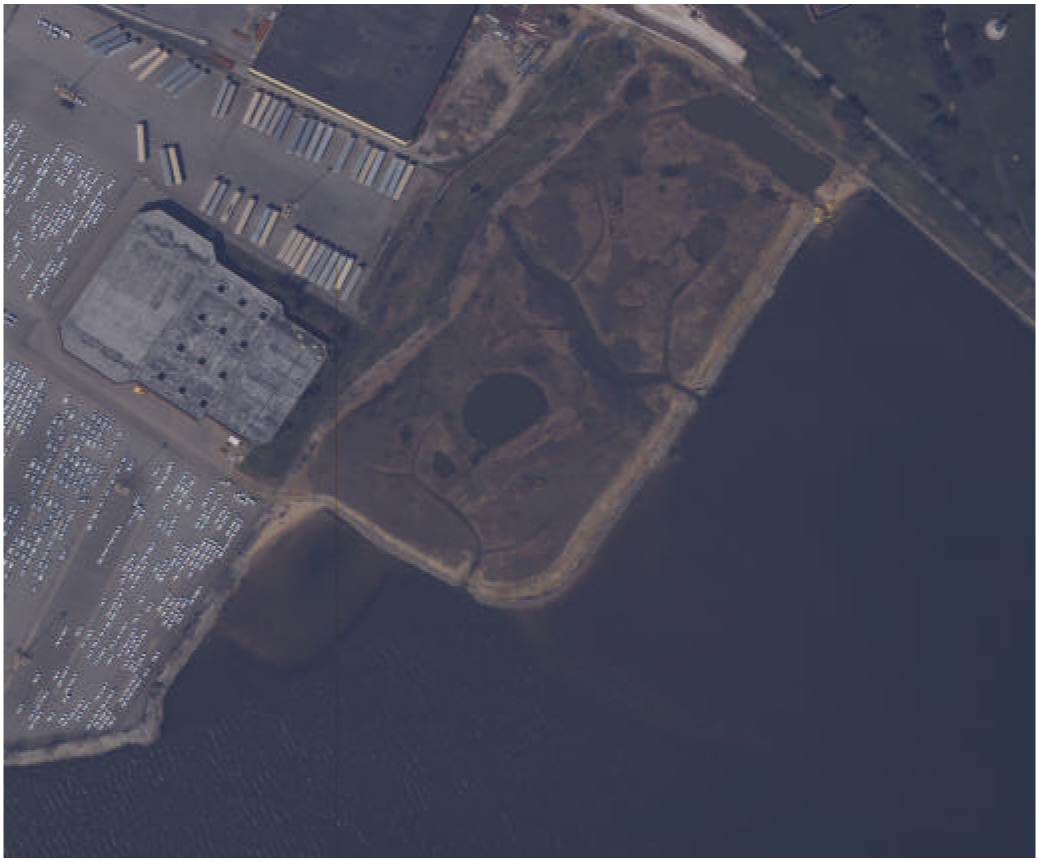


Figure 20. Aerial photographic image of the wetlands after completion of construction.

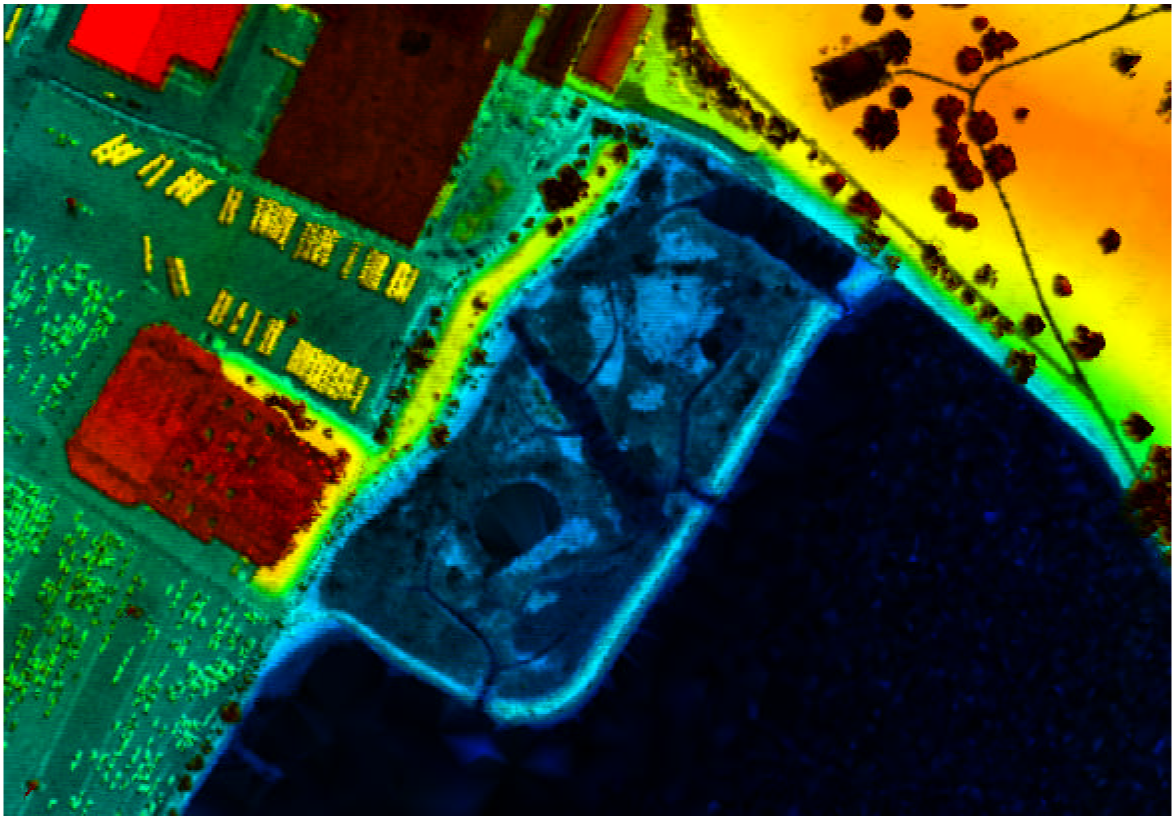


Figure 21. Light Detection and Ranging (LIDAR) Imagery of the wetlands taken after completion of construction.

The success of the wetlands restoration will only be known over time, however the application of the tide and geodetic information has made the planning and construction phases more effective. The full suite of capabilities in tide and water level analyses, Kinematic GPS surveys, Digital Elevation Modeling, and LIDAR have been used in support of this effort, and their application to programs other than traditional hydrographic and shoreline mapping have been successfully illustrated.

References

Perry, J.P. et al. 2001. Creating Tidal Salt Marshes in the Chesapeake Bay. *Journal of Coastal Research*, Special Issue NO. 27, Winter 2001.

Stevenson, J.C. et al. 1989. Marsh and Mangrove Responses to Changes in Sea Level and Sediment Inputs, *Estuaries*, Dedicated Issue, Vol. 12, No. 4, December 1989.

V. Appendices

Appendix A: References

Geodetic Control

The mission of NOAA's National Geodetic Survey (NGS) is to ensure that the United States has the consistent, high-accuracy geodetic reference framework it needs to support these fundamental activities. As such, NGS establishes and maintains the National Spatial Reference System (NSRS). See:
http://www.ngs.noaa.gov/INFO/OnePagers/NSRS.pdf

The NGS-led National Height Modernization Initiative addresses the issue of establishing accurate heights in a very efficient, cost-effective manner with Global Positioning System (GPS) technology. See: http://www.ngs.noaa.gov/initiatives/height_modernization.shtml

Guidelines have been established by NGS for Height Modernization surveys; publication NOS NGS-58. Using NOS NGS-58, Guidelines for Establishing GPS-Derived Ellipsoid Heights, geodetic control can be established at marsh resoration sites with accuracies in the height component of 2 cm at the 95% confidence level. See:
http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html

The data from the field is then processed and adjusted in accordance with Procedures described in Input Formats and Specifications of the National Geodetic Survey, known as the "NGS Blue Book" procedures. See: http://www.ngs.noaa.gov/FGCS/BlueBook/

Ongoing NGS activities on restoration projects and development of applied tools can be found at:
http://ngs.noaa.gov/TOOLS/
http://www.ngs.noaa.gov/PROJECTS/Wetlands/

Additional sources for geodetic information can be found from sources such as:

Federal Geodetic Control Subcommittee
& GPS Interagency Advisory Council:
http://www.ngs.noaa.gov/FGCS/

Wisconsin State Cartographer's Office
http://www.geography.wisc.edu/sco/geodetic/geodetic_control.html

California Geodetic Control Committee:
http://www.rbf.com/cgcc/

Arizona State Cartographer's Office
http://sco.az.gov/geodetic.htm

Topography:

Discovering Topography
http://earthview.sdsu.edu/trees/topqest.html

NOAA.gov
http://www.noaa.gov/topography.html

Land Information New Zealand
http://www.linz.govt.nz/rcs/linz/pub/web/root/core/topography/index.jsp

NOAA Data and Information Services
http://www.esdim.noaa.gov/story/ngdc_state.html

Digital Elevation Models:
http://rmmcweb.cr.usgs.gov/elevation/dpi_dem.html
http://www.ngdc.noaa.gov/seg/topo
http://www.geog.ucsb.edu/~good/176b/a13.html

Tides and Water Levels:

Programmatic information of NOAA's tides and water levels program can be found at:
http://tidesandcurrents.noaa.gov/about2.html

General information on standards and procedures for conducting tidal studies can be found at:
http://tidesandcurrents.noaa.gov/publications/
http://www.nos.noaa.gov/education/tides/welcome.html
http://www.hydrographicsociety.org/Publications/Subject/tide2.htm

Specific information on tides and tidal datums and their computation are found in:
http://tidesandcurrents.noaa.gov/publications/Computational_Techniques_for_Tidal_Datums_handbook.pdf

http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf

Preliminary and observed water level data, tidal datums, bench mark elevations, and sea level trends can be obtained at:
http://tidesandcurrents.noaa.gov/data_res.html

Bathymetry:

General information on NOAA marine surveying and mapping programs are found at:
http://www.nos.noaa.gov/topics/navops/marinenav/welcome.html

Historical charts and information are found at:
http://chartmaker.ncd.noaa.gov/csdl/ctp/abstract.htm
http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html

Further references and information are located at:
http://chartmaker.ncd.noaa.gov/staff/Library.htm
http://walrus.wr.usgs.gov/infobank/programs/html/definition/bath.html
http://coastal.er.usgs.gov/projects/topics/bathymetry.html

Other related information sources on habitat and marsh restoration:

Hydrologic and Hydraulic Analysis
Hydrology for the Meteorologist
http://meted.ucar.edu/hydro/hyd2/index.htm

The Columbia Encyclopedia
http://www.bartleby.com/65/hy/hydrolog.html

Advisory Commitee on Water Information
http://water.usgs.gov/wicp/acwi/hydrology/Frequency/

EPA
http://www.epa.gov/owow/watershed/wacademy/wam/hydrology.html

Sedimentation and Substrate Analysis

NOAA
http://response.restoration.noaa.gov/cpr/sediment/sediment.htm

Findarticles.com
http://www.findarticles.com/cf_dls/m2120/1_81/59555940/p8/article.jhtml?term=

Tropical Lagoon Sedimentation
http://www.jcn.net/cjordan/freebies/lagoon.html

Vegetation Analysis

SFWMD.gov
http://www.sfwmd.gov/org/erd/ecp/etweb/main_template/veg.html

http://nsm1.nsm.iup.edu/rwinstea/quant-veg.shtm

http://alpha.marsci.uga.edu/coastalcouncil/Presentations/franklin_compressd_files/frame.htm

Contaminant Concerns

Household Contaminants
http://www.hsh.com/pamphlets/hazards.html

Drinking Water Contaminations
http://www.epa.gov/safewater/mcl.html

Oil Contamination on/in ground
http://www.heimer.com/frameset/offsite.asp?url=http://www.epa.gov/OUST

Oil Spill Contamination
http://www.epa.gov/oilspill/effects.htm

COE Manuals

http://www.wetlands.com/regs/tlpge02e.htm
http://www.wes.army.mil/el/wetlands/pdfs/wrpre21/wrpre21.pdf

Appendix B: Hydrologic and Hydraulic Analysis and Modeling

Understanding and predicting the hydrology and hydraulics of a dynamic coastal habitat is fundamental to restoration activities. Analysis and modeling of a site's hydrologic and hydraulic regime forms the context for developing restoration alternatives that will restore persistent function and habitat, and address economic and safety concerns. Hydrologic analysis generally refers to the properties and distribution of surface and subsurface water, while hydraulic analysis generally comprises the specific characteristics of fluid (in this case water) dynamics. Some restoration sites require only cursory analysis of hydrology or hydraulics, while others are entirely driven by the effect of alteration of the sites hydraulics (e.g. modification of a beach to reduce wave erosion and promote re-vegetation).

Analysis and modeling

Generally speaking, hydrologic modeling provides decision makers with a quantitative and potentially spatial and temporal representation of the current hydrologic regime, in addition to building a platform to ask predictive questions. For example, if a wetland restoration project entails creating a marsh wetland by breaching a dike or restoring hydraulic connectivity to an isolated historic streambed, it will be very important to predict what type of flow and water levels can be expected. Will the flooded marsh encroach upon adjacent properties during a 10-year flood event? What about the effect on water level due to coincident high tides and storm events? Hydrologic and hydraulic modeling and analysis of restoration sites ranges from conceptual site models of a watershed to complex hydrodynamic simulations of an estuary, all of which helps decision makers choose restoration alternatives.

The type and extent of data necessary to characterize a restoration sites' hydrology and hydraulics will depend on the restoration project goals, available historical data, modeling needs, and resources. A first step in data collection will likely be to establish what type and scope of modeling is required for the project. This may entail research and review of what has been done in the past (and may be available to build upon), and identification of Federal, Tribal, State, local and educational institutions that are repositories of data.

Data collection

If the restoration site is located in a tidally influenced area, establishing a tidal record will be of great importance. It would be ideal to have a tide gauge with continuous water elevation for as long as possible at the restoration site. However, it is more likely that there is a moderate to long tidal record at a gauge that is within several miles of the restoration site. Depending on the level of precision required for the restoration site, analyses should be performed to correlate the best proximate tidal record available with a gauge set up at the restoration site. Ideally, the local gauge should collect data for as long as possible (over several seasons). This dataset is useful in performing predictive hydrologic modeling of the restoration site. The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) will likely be the best place to start.

In addition to tidal records, surface water flow (stream/river gauge); rainfall ground water flow, and drainage basin delineations are examples of potentially available datasets that may be an input to 1, 2, or 3 (or more) dimensional modeling. This type of data can be acquired from the USGS, a regional (basin or watershed) planning group, a local University, or a municipality. Some hydrologic and hydraulic models incorporate chemical processes in the water column, while others focus on sediment/water interface interactions. The type and complexity of modeling that you intend to do will drive these data needs.

Many of these datasets have geospatial and temporal components that enable integration with models and GIS layers. Issues such as datum, projection and precision should be addressed in the coordination and planning phases of the restoration project. If possible (and desirable), the collection of monitoring data can be used to calibrate and refine models and analysis. This type of on-going monitoring is also useful in evaluating the effectiveness of predictive models and modifying the model. Long term management goals can also be supported by incorporating feedback from monitoring into modifications or trend evaluation.

Some other physical measurements that may already exist or will potentially be part of field data collection efforts are:

- Stream Morphology (Channel survey)
- Coastal/Estuary survey
- Wave dynamics
- Lidar
- Conventional topographic survey
- Vegetation Analysis
- Substrate analysis
- Flow rates
- Current
- Salinity gradients
- Temperature
- Ground water flow parameters (direction/rate/aquifer characteristics)
- Rainfall (Hydrograph)

Some Agencies within NOS involved in modeling and analysis of restoration (there are too many State and Local groups to mention):

NOAA

- Coastal Protection and Restoration Division (NOS)
- Damage Assessment and Restoration Program (NOS)
- CO-OPS (NOS)

- Office of Coast Survey (NOS)
- Restoration Center (NOAA Fisheries)

Other Federal Agencies involved in hydrologic and hydraulic modeling…

- USFWS
- USGS
- USACOE
- USEPA
- USDOT
- USDOI

Appendix C: Morphologic and Sedimentologic Characteristics of Tide-Dominated Estuaries

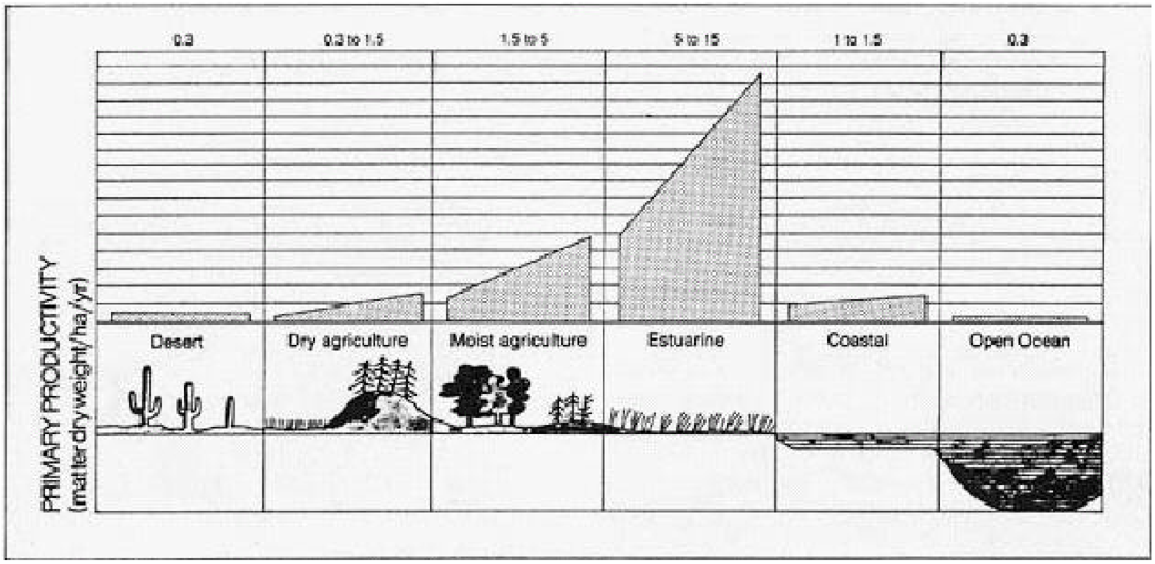
Authored by Athanasios (Thanos) N Papanicolaou, Professor, Washington State University, e-mail: apapanic@wsu.edu

Estuaries are among the most productive areas, when compared with other biological zones. Scientists say they produce four times more plant matter than fertile farmland, and are 20 times more productive than the open sea. Estuaries grow a wide variety of plants, which provide food for crustaceans, fish, birds and animals. In estuaries, most of the primary production occurs in the marshes and mudflats where wetland plants such as sedges and rushes, mangroves, bottom-dwelling algae, sea lettuce and eelgrass grow in abundance.

Herbivores only manage to eat a small part of the plants produced in the estuary. The rest (over 90 percent) dies down to become food for a host of bacteria, fungi, protozoa and other micro-organisms. These in turn become food for larger consumers such as crabs, bivalves, snails and fish. This is an example of the complicated food chains that form a food web in the estuary. Each organism is dependent on others for survival, with all of them linked. Estuaries support up to five times as many bird species as an equivalent area of native bush.

A Northland study has shown that about 30 species of marine fish use estuaries at some stage of their life history. These sheltered havens are an important breeding and nursery area for snapper, flatfish, kahawai and whitebait. Many fish enter the estuary to take advantage of the rich food supply found in eelgrass beds and intertidal sandflats.

Studies overseas have shown that more than 90 per cent of marine species can be found in mangrove estuaries during one or more periods in their life cycles. 80 per cent of fish caught commercially, were linked to mangrove-dependent food chains.



Estuaries are one of the most productive ecosystems on earth. Much of this productivity comes from coastal wetlands (From Knox, 1980)

Figure 1: Qualitative assessment of productivity in waterine environments (after Knox,1980)

The productivity and water quality in most estuaries of the world are influenced (to some degree) by tides. Tidal currents serve as a mechanism for mixing both river-mouth and estuarine waters, for resuspending and transporting sediments, creating bedforms, scouring channels, and redistributing pollutants. The role of tides is complex and less well studied than many aspects of estuarine processes. We know that when converging to smaller cross-sectional areas, the tidal currents become progressively more asymmetric in both current velocity and duration. It is difficult to unravel the role of tides in sedimentation patterns and morphologic development because of the differences in source, distribution, and nature of both fine and coarse sediments found within estuaries. This is true even when generalizations and simplifying assumptions are made.

This chapter summarizes the important processes and attributes, as we presently understand them, in the class of estuaries referred to as tide-dominated estuaries. Basic physical processes such as sediment entrainment and transport are reviewed, while some examples of tidal-dominated estuaries are described.

PHYSICAL PROCESSES IN THE TIDE-DOMINATED ESTUARIES

Strong tidal effects destroy vertical stratification, create bi-directional currents, produce high shear stresses at the bed, and lead to time-velocity asymmetry in flow (velocity time series have a time-lag from location to location). The periodic rise and fall of tide at the mouth of a river results in the temporary storage of large volumes of sea water in the estuary at high tide, followed by drainage at low tide. Tide-dominated estuaries typically have a tidal prism at least an order of magnitude greater than river discharge. The ratio between tidal and freshwater discharge constitutes a surrogate measure of the degree to which tidal mixing prevents vertical density stratification (Ippen and Harleman, 1966) which, in turn, affects estuarine recirculation and sediment dispersion. The most prominent effects of tidal currents are the production of bi-directional currents and high shear stresses during peak flows. In a first approximation, maximum current (velocities) are determined by the cross-sectional area of the estuary relative to the tide range. If frictional effects are neglected, constrictions will always accentuate currents. **Figure 2** illustrates an example of the first approximation relations that are typically are employed in a tidal estuarine environment. This is done by correlating (via linear regression) changes in tide withthe maximum current velocity. This plot is constructed based on recent measurements performed by Papanicolaou and Strom in the Tacoma Narrows vicinity.

FLOOD
WSU measured velocity as function of WSU measured change in watersurface elevation

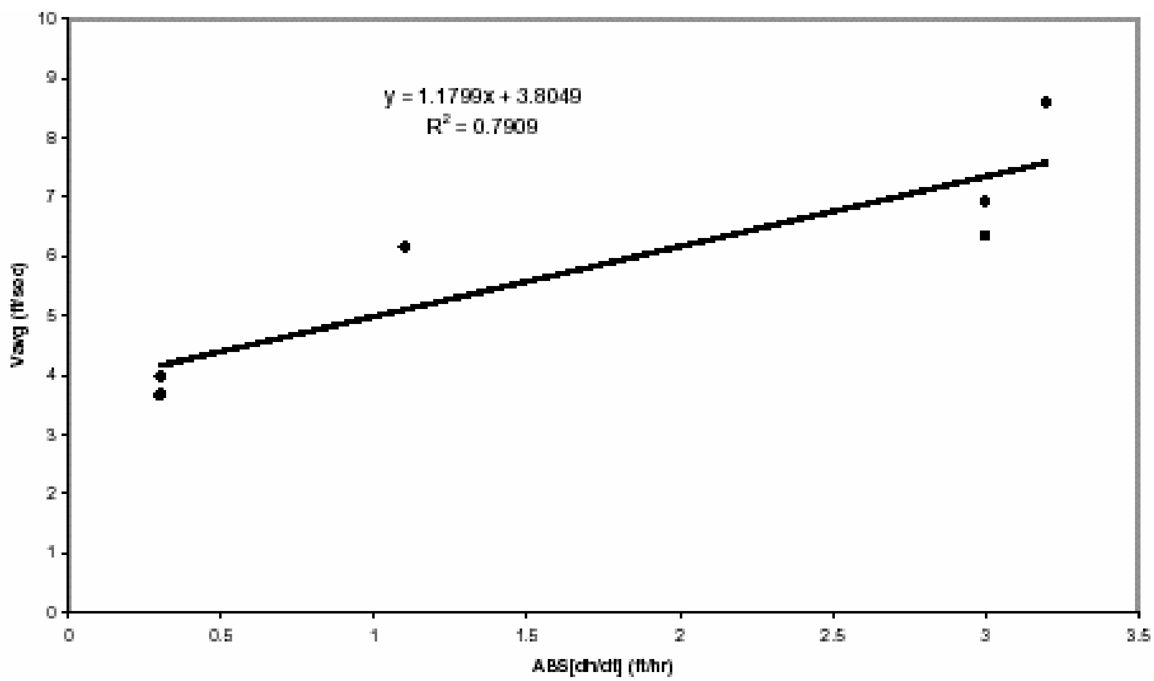


Figure 2. Current velocity (y-axis) vs. tidal height change (x-axis) at the Tacoma Narrows for the event of May 27th, 2002.

In terms of sediment dynamics, one of the most important aspects of tide-dominated estuaries is the way in which tide propagates upstream. The speed at which tide moves up the axis of an estuary is governed by the equation for propagation of shallow water waves, and is therefore a direct function of water depth. Flood velocities will exceed ebb velocities, but be of shorter duration. Also, the period of high-water slack will become longer than that for low water.

Tides tend to increase in amplitude from upstream convergence. Decreases in depth and width resulting from the characteristic funnel-shaped geometry force the tidal wave through progressively smaller cross-sectional areas. However, frictional dissipation from the bottom and banks of the estuary occurs with convergence and tends to counteract it, thus decreasing the amplitude. If the effects of convergence exceed frictional dissipation, which is often the case in tide-dominated estuaries, then the system is referred to as hypersynchronous.

The reversals in tide that produce bi-directional currents also produce patterns of bidirectional bedload transport. Whereas much of sediment that is transported and trapped in microtidal estuaries consists of organic rich mud, many tidal-dominated estuaries are characterized by coarser sands transported from offshore, and in some cases from small to medium size gravel beds. In this case, bedload transport is the dominant mode of motion.

For example, based on a bed data survey that was conducted by Papanicolaou and Strom at the Tacoma Narrows area, it was found that there are 3 distinct gravel beds present. The size distribution of the smaller particle is shown in **Figure 3** while **Figure 4** shows a plan view image of the bed that was taken with an underwater camera.

Figure 3. Particle size distribution for frame 6fsmall

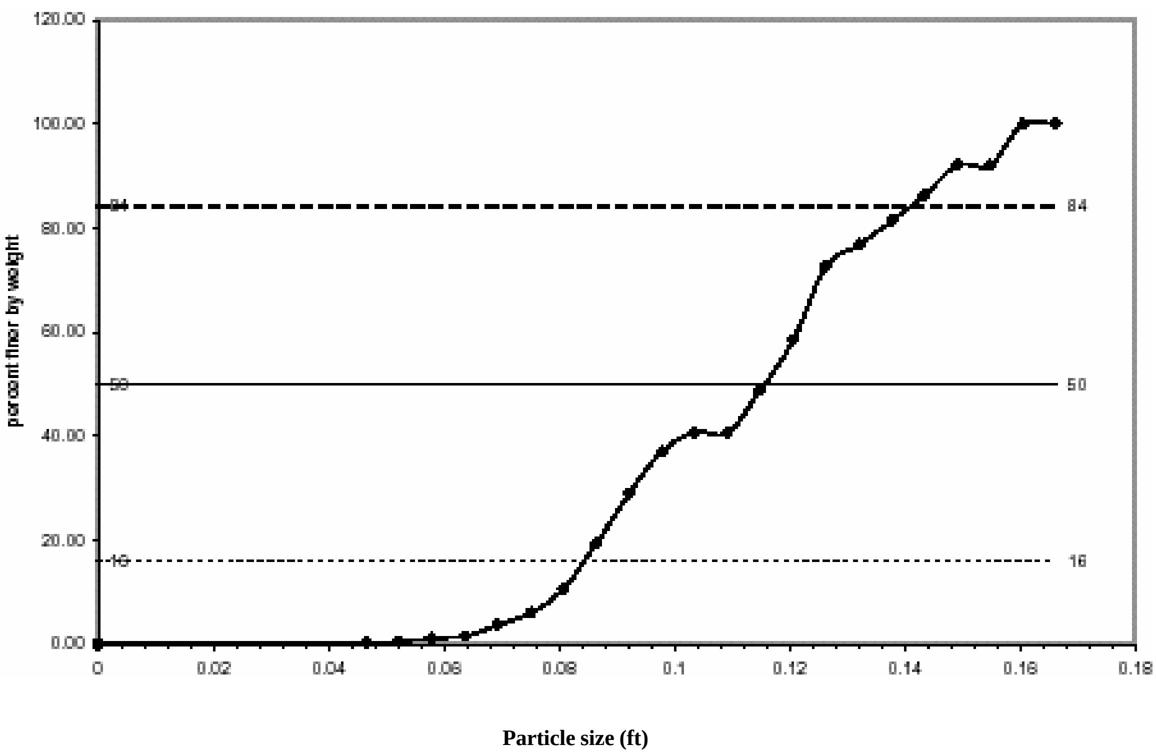


Figure 4. Example of “small” size particles (Image: 15asmall)

SEDIMENT SOURCE IDENTIFICATION IN A TIDAL ESTUARY

In estuaries there is also a significant quantity of fine sediments. The identification of sediment sources of fines has traditionally involved the establishment of sediment budgets within streams. With this approach, sediment source, entrainment, and deposition are identified for a specified stream reach and the sediment budget equation is expressed as

E=D* - ? *V

where, *E* denotes the sediment entrainment flux, and *D* is the sediment deposited flux and the storage term, ***V*** ? , is measured as the net difference between material entrained by the flow within the stream reach and the material deposited. While this simple method has been successfully employed in studies that are restricted to one land use practice (it does not provide accurate predictions of the storage term ***V*** ? in the case of multiple sediment sources, where knowledge of the sediment mineralogy and organic matter is important to predict accurately sediment deposition ***D*** and entrainment ***E***.

Where a simple identification of the source of sediments may suffice, the sediment properties of the material can be used to identify its origin. Simple indicators such as sediment color, zeta potential size, and water content have been used as natural tracers of sediment source. However, these indicators are less definitive that we might wish. Other techniques are needed.

Recently, tracers such as sterols and radionuclides have been used to determine the variation in sediment yield from a watershed. Specifically, the technique of Cs-137, a radioisotope created by atmospheric nuclear weapons testing principally between the years 1955 and 1966, has been employed by several researchers to predict sediment yield from farmlands into the streams. This method can accurately estimate the net input of eroded fine sediments into a stream, but it does not provide any information about the source of these sediments. For example, soil erosion studies using the Cs-137 method in the Palouse region of eastern Washington and Northern Idaho predict, with error less than 10%-16%, that the average erosion is about 11.6 t $ha^{-1}yr^{-1}$. What we do not know, though, is what proportion of this upland sediment (in the form of suspended or deposited matter) originated by farm, forest, cattle grazing, and urban activities in the Palouse watershed.

In the past decade, stable isotope technology has been employed to identify sediment sources in rivers and estuaries. Relatively large mineral clasts often retain the oxygen isotopic composition of their source rock. This is particularly true of minerals such as quartz, which are resistant to weathering and do not undergo low-temperature isotopic exchange. For example, Vennemann et al. (1992) used oxygen isotope compositions to determine sources of quartz pebbles in South Africa and Canada. In another study, Cushing et al. (1993) labeled natural fine particulate organic matter with ^{14}C and reinjected it into the stream to estimate transport distances in the water column and retention times in two Idaho gravel bed streams. Another stable isotope technique involves the use of stable carbon and nitrogen isotope compositions coupled with measurements of the weight ratio of organic carbon to total nitrogen (C/N) for identifying sources of instream sediments.

Appendix D: Contaminant Concerns (water, sediment, biota)

Contaminants enter the environment by a variety of sources, including: industrial and commercial facilities; oil and chemical spills; non-point sources such as roads, parking lots, and storm drains; wastewater treatment plants and sewage systems; and surface discharge of contaminated groundwater. Hazardous waste sites and industrial facilities that were contaminated decades ago are still polluting the aquatic environment and serve as an ongoing source. Contamination at potential coastal habitat restoration sites is a key factor in determining a restoration project's viability and expense. Elevated levels of contamination may significantly impact recovery rates at the site, and the cost of contaminant removal may make the project unfeasible. Therefore a thorough characterization of potential restoration sites is needed to identify chemicals of concern at the site, as well potential contaminant sources near the site. A proper site characterization can help to prioritize potential sites for restoration and increase the overall effectiveness of the project.

When selecting a site for potential restoration, modern source control and pollution prevention efforts can be effective and prevent further degradation in water quality. Unfortunately, many areas have sediment contamination due to the legacy of past practices and prior contamination and this contamination is often buried under cleaner sediment. These contaminants still pose an environmental threat because severe storms and biological activity can re-suspend contaminants and make them bioavailable. Once they are bioavailable, contaminants such as metals and polycyclic aromatic hydrocarbons can be highly toxic to the aquatic organisms that are the base of aquatic food webs. Other contaminants, which resist chemical breakdown, can bioaccumulate in the food chain and pose a threat not only fish and wildlife, but also humans who consume them.

Bioaccumulation is an increase in the concentration of a chemical in a biological organism over time, compared to the chemical's concentration in the environment; biomagnification occurs when the concentration increases through successive levels of the food chain. Organic contaminants, such as PAHs and PCBs are lipophilic or fat-soluble and are resistant to degradation. These compounds may accumulate in animal tissues and interfere with normal metabolic processes that affect growth, development, and reproduction. It is important to note that bioaccumulation varies between individual organisms as well as between species. Larger, long-lived organisms with slower metabolic rates will accumulate chemical compounds more readily than smaller, shorter lifespan organisms, even if they have the same site exposure. Because restoration sites can create recruitment habitats or serve as a nursery for many species the potential for contaminant bioaccumulation should be considered.

In order to more easily evaluate sediment contaminated with toxic chemicals, several sediment quality guidelines have been established to assist in determining ecological risk (Long et at. 1995; MacDonald et al. 1996). These guidelines are based on different evaluation methods and help to decide whether a certain concentration of toxic chemicals is likely to harm the ecosystem. Sediment quality guidelines are intended to serve as an initial screen for determining chemical concentration that may pose a threat to habitat resources. For more information on the use of these guidelines please refer to NOAA's CPRD website http://response.restoration.noaa.gov/cpr/sediment/sediment.html.

In an effort to reduce aquatic disposal of dredge materials, suitable materials may be used for the creation or restoration of wetland habitats. However, the beneficial re-use of dredge sediment during the restoration process may also serve as a source of contamination at the site. Generally the dredged material is used to create favorable drainage patterns, restore proper elevations for areas that have subsided, or to cover an existing substrate. Unfortunately, the movement of re-suspended and bottom sediments during the construction process also can serve as a mechanism for the transport of contaminants into cleaner areas. Therefore, the suitability for the beneficial re-use of dredge materials at a potential restoration site should be evaluated on a case-by-case basis.

References

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