State of Oregon
Department of Geology and Mineral Industries
Vicki S. McConnell, State Geologist

Open-File Report O-08-15

OREGON BEACH AND SHORELINE MAPPING AND ANALYSIS PROGRAM: 2007-2008 BEACH MONITORING REPORT

TECHNICAL REPORT TO THE OREGON DEPARTMENT OF LAND CONSERVATION AND DEVELOPMENT

By

Jonathan C. Allan[1] and Roger Hart[1]

2008

[1]Oregon Department of Geology and Mineral Industries, Coastal Field Office, 313 SW 2nd Street, Suite D, Newport, Oregon 97365

NOTICE

The results and conclusions of this report are necessarily based on limited geologic and geophysical data. At any given site in any map area, site-specific data could give results that differ from those shown in this report. **This report cannot replace site-specific investigations.** The hazards of an individual site should be assessed through geotechnical or engineering geology investigation by qualified practitioners.

Cover photo: A moderate storm on January 9, 2008, impacts oceanfront homes and condominiums in the community of Neskowin. An earlier storm (January 5) destroyed portions of the riprap wall and came close to destroying one home. Photo by Jonathan Allan.

Oregon Department of Geology and Mineral Industries Open-File Report O-08-15
Published in conformance with ORS 516.030

For copies of this publication or other information about Oregon's geology and natural resources, contact:

Nature of the Northwest Information Center
800 NE Oregon Street #5, Suite 177
Portland, Oregon 97232
(503) 872-2750
http://www.naturenw.org

or these DOGAMI field offices:

Baker City Field Office
1510 Campbell Street
Baker City, OR 97814-3442
Telephone (541) 523-3133
Fax (541) 523-5992

Grants Pass Field Office
5375 Monument Drive
Grants Pass, OR 97526
Telephone (541) 476-2496
Fax (541) 474-3158

For additional information:
Administrative Offices
800 NE Oregon Street #28, Suite 965
Portland, OR 97232
Telephone (971) 673-1555
Fax (971) 673-1562
http://www.oregongeology.org
http://egov.oregon.gov/DOGAMI/

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

This report describes and documents the Oregon Beach and Shoreline Mapping Analysis Program (OBSMAP) maintained by the Oregon Department of Geology and Mineral Industries (DOGAMI), with funding from the Northwest Association of Networked Ocean Observing System (NANOOS contract #449958), the Oregon Department of Land Conservation and Development (DLCD contract #PS07028), and the Oregon Parks and Recreation Department (OPRD contract #07-372). The objective of this monitoring program is to document the response of Oregon's beaches to both short-term climate variability (e.g., El Niños, extreme storms) and longer-term effects associated with the changing climate of the earth (e.g., increasing wave heights, changes to storm tracks, and sea level rise), that will influence the stability or instability of Oregon's beaches over the next century. Understanding the wide range of responses characteristic of the Oregon coast is critical for effectively managing the public beach both today and into the future.

Beach monitoring undertaken as part of the OBSMAP effort is based on repeated high-accuracy surveys of selected beach profiles using a Trimble 5700/5800 Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) mounted on either a backpack or on an ATV vehicle. The OBSMAP monitoring network currently consists of 119 beach monitoring sites, which include:

- Six sites along the Clatsop Plains (Seaside to the mouth of the Columbia River);
- Twenty-five sites along the Rockaway littoral cell (Cape Meares to Neahkahnie Mountain);
- Fifteen sites in the Neskowin cell (Cascade Head to Cape Kiwanda);
- Fifteen sites in the Beverly Beach cell (Yaquina Head to Otter Rock); and,
- Fifty-eight sites in the Newport littoral cell (Yachats to Yaquina Head).

This report focuses specifically on coastal changes along the Rockaway and Neskowin littoral cells, with emphasis on measured responses following the extreme December 2-3, 2007, winter storm. Our beach monitoring efforts completed thus far have identified the following large-scale beach responses:

- The cumulative effect of the 1997-1998 and 1998-1999 winters resulted in extensive erosion along the Rockaway littoral cell; to date, some of the largest erosion responses measured on the Oregon coast. Nevertheless, the degree of change observed and the level of beach rebuilding that has taken place since then varies along the shore:
    - Erosion continues to plague much of the Rockaway subcell, which has continued to recede landward up to the present. The area presently experiencing the highest beach erosion changes is occurring north of Tillamook Bay and south of the Rockaway High School.
    - North of Rockaway High School and south of the Nehalem jetties, beaches have been slowly gaining sand and, hence, are gradually rebuilding following the extreme storms of the late 1990s.
    - Erosion continues to affect the southern half of Bayocean Spit, while the northern third of the spit has effectively been rebuilt and is now beginning to prograde (advance) seaward.
    - Similarly, erosion continues to plague the southern half of Nehalem Spit, while the northern third has gained some sand.
    - The beaches along the Rockaway littoral cell remain in a state of net deficit compared to 1997, with the loss of sand for the period 1997–2002 estimated to be about 1,439,600 m^3 (1,883,000 yd^3). Given that much of the Rockaway subcell has continued to erode and lose sand, we estimate that as of March 2008 the net sand loss from the cell is likely to be on the order of 2 million cubic meters of sand (2.6 million cubic yards). Whether the beaches recover fully and how long it takes remain important scientific and management questions, which in time will be answered by continued beach monitoring.

  - Post-storm recovery has been slow, limited to the lower beach face, and restricted to parts of Bayocean Spit, Nedonna Beach, and at the north end Nehalem Spit. The lack of significant sand accumulation high on the beach face in recent years suggests that the present climate may not be conducive for transporting sand landward from the beach face.
- In contrast to the Rockaway cell, measured beach changes on the Clatsop Plains indicate that although this section of shore was also affected by the extreme storms of the late 1990s, the degree of impact was much less; the beaches fully recovered within 1 to 2 years.
  - The exception is shoreline change taking place just south of the south jetty. Repeated beach surveys at the Eastjetty profile site has revealed that the beach has been slowly eroding landward. Given its narrow foredune width, it is likely that parts of this dune system could be breached in the near future.
  - The main foredune has steadily gained sand over the past several years. We estimate that the net sediment volume gain for the period 1997 to 2008 is about 3.4 million cubic meters (4.5 million cubic yards) of sand.
- The 2007-2008 winter caused severe erosion at selected sites in the Rockaway subcell (south end of the cell) and north of the town of Rockaway; erosion and damage to facilities at Cape Lookout State Park (including significant damage to the dynamic revetment constructed there to protect the park); damage to riprap revetments at multiple locations on the north coast but most notably at Neskowin; and exhumed cannons at Cannon Beach and a boat near Coos Bay. In most cases, the erosion was enhanced due to formation of rip embayments, allowing waves to break close to the shore with little loss in incident wave energy.
- An analysis of wave and water levels associated with the 2007-2008 winter indicates that events during this winter was not as extreme as past events. However, several major storms that occurred in winter 2007-2008 when the beaches of Oregon remained in a generally degraded state (i.e., beaches were narrower and had less sand volume), enabled the waves to cause significant damage to infrastructure along the coast.

INTRODUCTION

Over the past century, the Oregon coast has undergone several periods of major coastal erosion in which the mean shoreline position retreated landward, encroaching on homes built atop dunes and coastal bluffs, and in several cases resulted in the destruction of homes. The most notable of these events took place in 1934, 1939, 1958, 1960, 1967 (Dicken and others, 1961; Stembridge, 1975), the winters of 1972-1973, 1982-1983 (Komar, 1997), in 1997-1998, 1999 (Allan and others, 2003), and most recently in December 2007. Of these, it is generally thought that the winter of 1938-1939, and specifically a storm in January 1939, was probably the worst on record (Dr. Paul Komar, personal communication, 2006). This storm resulted in extensive coastwide erosion (e.g., Netarts Spit was breached at several locations), along with the flooding inundation of several communities (e.g., Seaside, Cannon Beach, Rockaway, and Waldport), as ocean waves accompanied high water levels (Stembridge, 1975). Although the effects of the January 1939 storm were captured in the 1939 suite of aerial photographs flown by the U.S. Army Corps of Engineers (USACE), the fact that these photos have never been orthorectified makes it difficult to interpret the true extent of the storm's impact on the coast.

An assessment of how the beaches of Oregon respond to storms could not be fully documented until the late 1990s, when a joint venture between the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA), used Light detection and ranging (lidar) technology to measure the topography of U.S. coastal beaches. On the Oregon coast, the results of such surveys have been published in several papers (Revell and others, 2002; Revell and Marra, 2002; Allan and others, 2003, 2004; Allan and Hart, 2005; Allan and Komar, 2005). However, while lidar provides an unprecedented amount of quantitative information that may be used to assess beach morphodynamics, on the Oregon coast such data sets have been collected infrequently (only on three occasions: 1997, 1998, and in 2002), with no additional measurements scheduled until 2009; given the present high costs, the expectation is that lidar will only be flown approximately every five years. As a result, the temporal scale of the lidar surveys is presently insufficient to adequately characterize short-term and to a lesser extent long-term trends of beaches.

The purpose of this report is to describe the Oregon Beach and Shoreline Mapping Analysis Program (OBSMAP) maintained by the Oregon Department of Geology and Mineral Industries (DOGAMI), with funding from the Northwest Association of Networked Ocean Observing System (NANOOS), the Department of Land Conservation and Development Agency (DLCD), and the Oregon Parks and Recreation Department (OPRD). The objective of the OBSMAP effort is to develop a comprehensive beach observation program, capable of providing high-quality quantitative data on the response of Oregon's beaches at a variety of time and space scales that are of most value to coastal resource managers and the public at large. OBSMAP data have been supplemented through analyses of lidar data measured along the Oregon coast in 1997, 1998, and 2002, and are now beginning to yield important new insights on how the beaches of Oregon respond to storms, El Niños, and climate change.

MANAGEMENT NEEDS AND MONITORING OBJECTIVES

Management of beaches and dunes in Oregon falls under the jurisdiction of the OPRD, the Coastal Management Program of DLCD, and local jurisdictions through their comprehensive plans and land-use ordinances. OPRD has jurisdiction over the active beach up to the statutory vegetation line (surveyed in 1967; Oregon Revised Statute 390.770) or the existing vegetation line, whichever is located most landward, and thereby controls the permitting of structures used to protect ocean shore property. DLCD works with the planning departments of local jurisdictions to preserve Oregon's beaches and dunes by ensuring that they apply the standards for siting development as required by specific statewide planning goals that are incorporated into their local comprehensive plans. The department provides technical assistance to local jurisdictions in the form of model ordinances, as well as support for the improved and updated mapping and inventories.

The permitting of new ocean shore development by state and local jurisdictions is based on the best available knowledge and, in some cases, site investigations of specific locations. Although the information collected through these efforts meets the standards required by agencies, at times the information is piecemeal and does not always reflect an adequate understanding of the processes affecting the property for making sound decisions (i.e., site-specific studies on dune-backed beaches tend to be too narrowly focused, effectively ignoring issues that may influence the site at larger spatial or longer time scales). Specifically, the information presented often does not fully take into account the high-magnitude episodic nature of North Pacific extratropical storms, the long-term processes that may impact the property, the manner in which the proposed alterations might affect the system, or the effect those alterations could have on adjacent properties. State and local agencies are therefore relegated to making decisions about ocean shore development with only a partial understanding of their potential impacts. Those decisions will affect not only the relative level of risk posed to that development but also the long-term integrity of ocean shore resources and a variety of public recreational assets. Improved baseline data and analysis of beach morphodynamics will enable state agencies and local governments, and the geotechnical community, to better predict future shoreline positions and will provide the quantitative basis for establishing scientifically defensible coastal-hazard setback lines.

New baseline data repeated at appropriate time intervals (e.g., seasonal to annual surveys) and space scales (hundreds to thousands of meters) in conjunction with periodic detailed topographic information derived from lidar and ground surveys will help coastal managers resolve short- and long-term specific planning issues by providing an improved understanding of the following:

- The spatial and temporal responses of beaches to major winter storms in the Pacific Northwest (PNW) and to climate events such as El Niños and La Niñas.
- The time scales required for beach recovery following major winter storms, El Niños', or from persistent El Niño conditions that characterize the warm phase of the Pacific Decadal Oscillation. Under the present climatic regime and given uncertainties over future climate conditions, an important question is how long does it take for beaches to fully recover following a major storm(s)?
- The long-term implications of climate change to Oregon's beaches that result from increased storminess, larger storm wave heights (and hence greater wave energy), and changes to the predominant tracks of the storms and sea level rise.

Several important questions that may also be addressed from repeated ongoing monitoring of Oregon beaches include:

- What are the cumulative effects of increased storm wave heights, increased armoring of shorelines, and possible accelerated sea level rise on erosion rate predictions for bluffs and dunes? Is past practice of using historical data (e.g., aerial photos, ground surveys) to predict future shoreline or bluff toe/top locations defensible? If not, what quantitative approach should take its place? Can a numerically based model be developed that adequately handles all of the forcing that affects coastal change in the PNW?
- How can we improve existing process/response models so they adequately account for the erosion of PNW beaches? Present models were developed mainly for United States East Coast wave and

sediment transport conditions rather than for the significantly different conditions in the PNW. The wave climate in the PNW is far more severe, and, unlike the unidirectional longshore movement of beach sediment typical of the U.S. East and Gulf coasts, Oregon's beach sand oscillates from south to north, winter to summer, within its headland-bounded littoral cells.

- What are the spatial and temporal morphological characteristics of rip embayments on PNW beaches? What are the "hotspot" erosion impacts of rip embayments on dunes and beaches? How often do rip embayments occur at a particular site on the coast and what is the long-term effect on bluff erosion rates?
- How has the morphology of Oregon's beaches changed since the 1960s (i.e., when the coastline was last surveyed)?
- The loss of large volumes of sediment from several littoral cells on the northern Oregon coast in recent years (e.g., Netarts and Rockaway) raises the obvious questions: why are they eroding, where has the sand gone, and will it return?

Integral to answering many of these questions and for making informed decisions based on technically sound and legally defensible information is an understanding of the scales of morphodynamic variability within the coastal zone. Comprehensive beach monitoring programs have enhanced decision-making in the coastal zones of populous states such as Florida (OBCS, 2001), South Carolina (Gayes and others, 2001), Texas (Morton, 1997), Washington state (Ruggiero and Voigt, 2000), and in the United Kingdom, where the UK government recently endorsed the expansion of a pilot beach and bluff monitoring to extend around the bulk of the English coastline (Bradbury, 2007). These programs typically include the collection of topographic and bathymetric surveys, remote sensing of shoreline positions (aerial photography or lidar), and measurements of environmental processes such as currents, waves, and sediment transport. Over time such data sets prove critical in calibrating predictive models of shoreline change, in the design of shore-protection measures, and in determining regional sediment budgets (Gayes and others, 2001).

The general purpose of this study is to continue to document the response of Oregon's beaches using real-time kinematic differential global positioning system (RTK-DGPS) technology. Although the OBSMAP program now spans several littoral cells, this report will focus primarily on the measured responses in the Rockaway and Neskowin littoral cells, particularly as a result of the December 2-3, 2007, extreme storm and the problems that have arisen as a result of that event. The specific tasks associated with completing this ongoing study include the following:

1. Undertake quarterly (spring, summer, fall, and winter) surveys of the Neskowin (15 sites), Rockaway (25 sites) and Clatsop Plains (6 sites) beach monitoring network, Figure 1, in order to provide ongoing documentation of the response of Oregon's beaches to North Pacific winter storms, El Niños, and climate change.
    - Surveys were undertaken during the following months (approximately): March 2007; May/June 2007; September/October 2007; December 2007; March/April 2008.
2. Maintain and update the existing OBSMAP website (http://www.oregongeology.org/sub/nanoos1/index.htm). Continue to develop new data products that may be of value to coastal resource managers, and to improve the readability and usability of the website;
3. Disseminate beach state/change data and products among coastal managers and regulatory authorities in appropriate formats. Specific products produced as part of this monitoring effort include the measured beach profile responses, and the response of the beach at specific contour intervals. For the purposes of this study, we use the 6.0-m (20 ft) and 5.0-m (16 ft) contour changes to account for changes that may be occurring adjacent to the dune toe (i.e., caused predominantly by storms, El Niños, and long-term shoreline responses), while the 3.0-m (10 ft) contour reflects those changes near the Mean Higher High Water (MHHW) line (i.e., seasonal to interannual to longer-term changes); and,
4. Develop a report that summarizes the latest findings for each of the littoral cells.

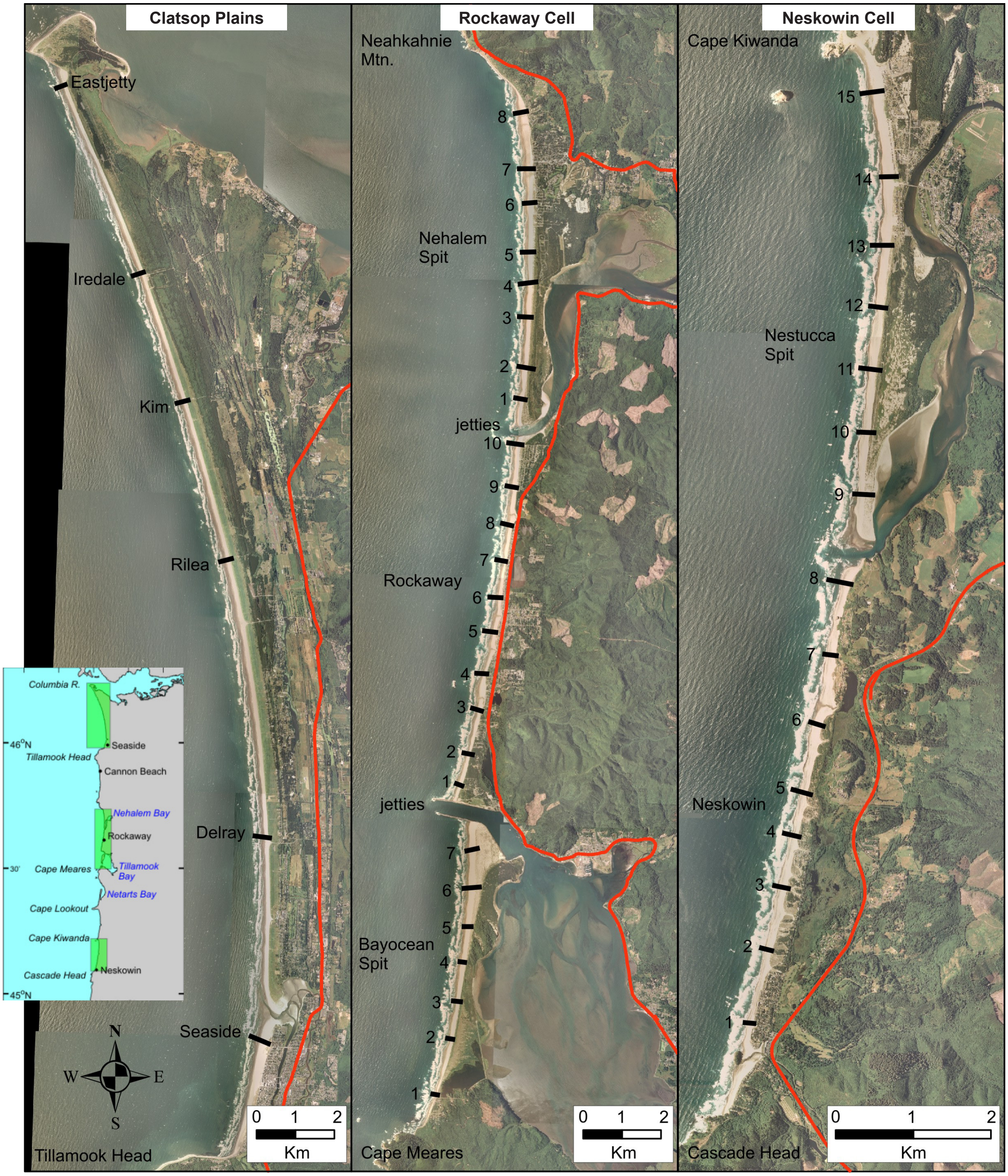


Figure 1. Location maps of Oregon Beach and Shoreline Mapping and Analysis Program (OBSMAP) beach monitoring stations (locations shown by black bars) established on the northern Oregon coast and overlaid on 2005 ortho-imagery (OGIC; http://gis.oregon.gov/DAS/EISPD/GEO/data/doq.shtml). Red line is U.S. Highway 101.

BACKGROUND

Beaches composed of loose sediments are among the most dynamic and changeable of all landforms, responding to a myriad of complex variables that reflect the interaction of processes that drive coastal change (waves, currents, and tides), and the underlying geological and geomorphological characteristics of the beaches (sediment grain size, shoreline orientation, beach width, sand supply, losses, etc.). These factors have a threefold role in contributing to the morphology and position of the beach:

1. Promoting the supply of sediments to the coast for beach construction;
2. Transferring sediments through the system; and ultimately,
3. Removing sediments through the process of erosion.

Because beaches are composed of loose material, they are able to respond and to adjust their morphology rapidly in intervals of time ranging from seconds to days to years (Figure 2) in response to individual storm events, and enhanced periods of storm activity and increased water levels (e.g., the 1982-1983 and 1997-1998 El Niños).

Beginning with the 1997-1998 El Niño, the Oregon coast experienced a series of 20 unusually severe storms in which the deep-water significant wave heights exceeded 6 m (20 ft) for 9 hours or longer. Prior to the 1997-1998 winter the largest number of major storms experienced in a single season was 10 to 12, which occurred in the early 1980s (1982–1986). Furthermore, on the basis of wave data up through 1996, researchers (Ruggiero and others, 1996) had calculated the 100-year storm waves to be around 10 m (33 ft) for the Oregon coast. However, an event on November 19-20, 1997, exceeded that projection, and wave conditions were far worse the following winter, 1998-1999, when 22 major storms occurred, four of which generated deep-water significant wave heights over 10 m, the largest having generated wave heights of 14.1 m (47 ft). When wave energy of this magnitude (approximately proportional to the square of the wave height) is expended on the low sloping beaches characteristic of the Oregon coast, especially at times of elevated ocean water levels, these storms have the potential for creating extreme hazards to developments in foredunes and atop sea cliffs backing the beaches. For example, the cumulative impact of these recent extreme storms along the Neskowin and Netarts littoral cells in Tillamook County resulted in the foredune retreating landward by, on average, 11.5 m (38 ft) to 15.6 m (49 ft) respectively, and as much as 55 m (180 ft) in some locations, damaging properties fronting the eroding shore (Allan and others, 2004). In response to the erosion, property owners have resorted to the placement of riprap to safeguard their properties. Following erosion there is usually a period lasting several years to a few decades during which the dunes rebuild, until later they are eroded by another storm (Allan and others, 2003). How long this process takes is not known for the Oregon coast.

Longer-term adjustments of the beaches may also result from changes in sediment supply or mean sea level. However, attempts to quantify these processes suggest that erosion due to rising sea level is considerably lower compared with the effects of individual storms or from storms in series.

The monitoring of two-dimensional beach profiles over time provides an important means of understanding the morphodynamics of beaches and the processes that influence the net volumetric gains or losses of sediment (Morton and others, 1993; Ruggiero and Voigt, 2000). Beach monitoring is capable of revealing a variety of information concerning short-term trends in beach stability, such as the seasonal response of a beach to the prevailing wave energy, responses due to individual storms, or hotspot erosion associated with rip embayments. Over sufficiently long periods, beach monitoring can reveal important insights about the long-term response of a particular coast, such as its progradation (seaward advance of the mean shoreline) or recession (landward retreat), attributed to variations in sediment supply, storminess, human impacts, and ultimately as a result of a progressive increase in mean sea level.

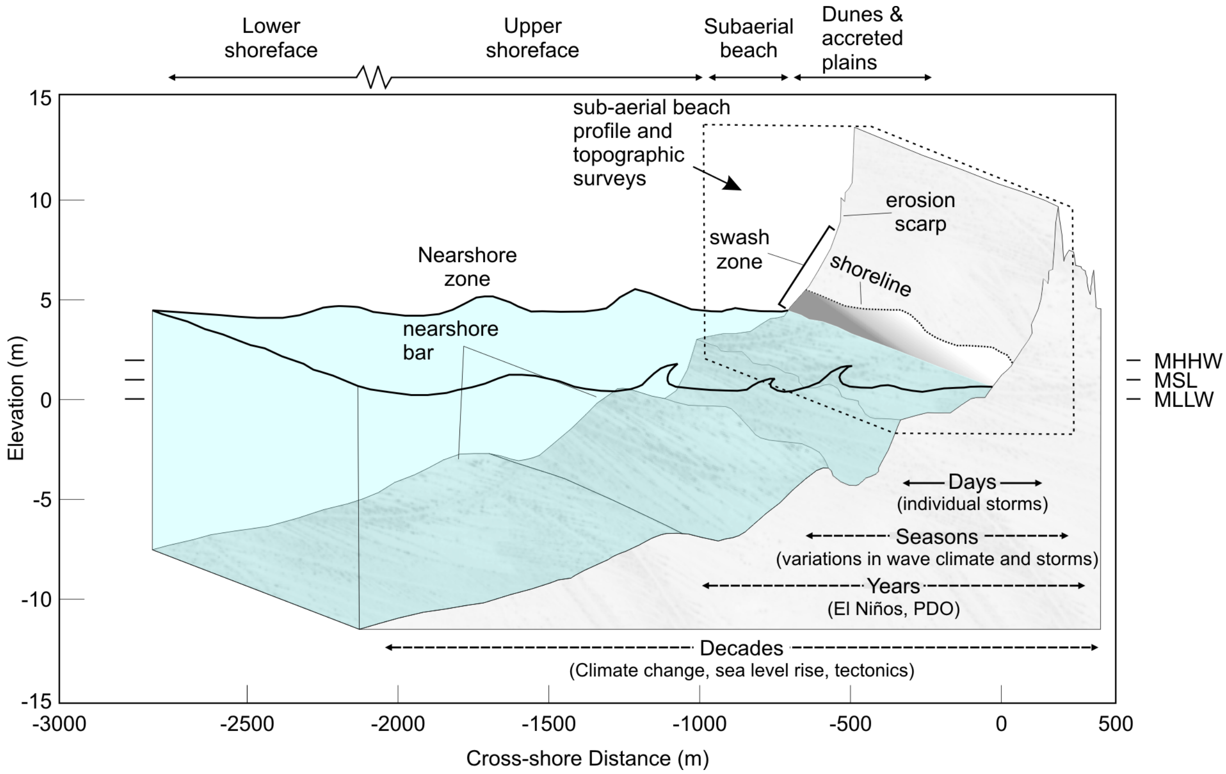


Figure 2. Conceptual model of beach and shoreline changes that occur over various time and space scales (after Ruggiero and Voigt, 2000). Dashed box indicates the portion of beach measured as part of OBSMAP. MHHW is mean higher high water; MSL is mean sea level; MLLW is mean lower low water; PDO is Pacific Decadal Oscillation.

METHODOLOGY

Beach profiles that are nominally orientated perpendicular to the shoreline (Figure 1) can be surveyed using a variety of approaches, including a simple graduated rod and chain, surveying level and staff, Total Station theodolite and reflective prism, lidar, and RTK-DGPS technology.

Traditional techniques such as leveling instruments and Total Stations are capable of providing accurate representations of the morphology of a beach but are demanding in terms of time and effort. For example, typical surveys undertaken with a Total Station theodolite may take anywhere from 30 to 60 minutes to complete, which reduces the capacity of the surveyor to develop a spatially dense profile network. At the other end of the spectrum, high-resolution topographic surveys of the beach derived from lidar are ideal for capturing the three-dimensional state of the beach over an extended length of coast within a day; other forms of lidar technology are now being used to measure nearshore bathymetry but are dependent on water clarity. However, the technology remains expensive and is impractical along small segments of shore. More importantly, the high cost of lidar effectively limits the temporal resolution of the surveys and hence the ability of the end-user to understand short-term changes in the beach morphology (Bernstein and others, 2003). Within this range of technologies, the application of RTK-DGPS for surveying the morphology of both the subaerial and subaqueous portions of the beach has effectively become the accepted standard (Morton and others, 1993; Ruggiero and Voigt, 2000; Bernstein and others, 2003; Ruggiero and others, 2005).

The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations, originally developed by the U.S. Department of Defense. In its simplest form, GPS can be thought of as triangulation with the GPS satellites acting as reference points, enabling users to calculate their position to within several meters (e.g., by using off-the-shelf hand-held units [note that the vertical error is typically about twice the horizontal error]), while survey-grade GPS units are capable of providing positional and elevation measurements that are accurate to a centimeter.

At least four satellites are needed to determine mathematically exact position, although more satellites are generally available. The process is complicated because all GPS receivers are subject to error, which can significantly degrade the accuracy of the derived position. These errors include the GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere and multipath effects (where the signals bounce off features and create a noisy signal). For example, hand-held autonomous receivers have positional accuracies that are typically less than about 10 m (<~30 ft), but can be improved to less than 5 m (<~15 ft) using the Wide Area Augmentation System (WAAS). This latter system is essentially a form of differential correction that accounts for the above errors, which is then broadcast through one of two geostationary satellites to WAAS-enabled GPS receivers.

Greater survey accuracies are achieved with differential GPS (DGPS) using two or more GPS receivers to simultaneously track the same satellites, thus enabling comparisons to be made between two sets of observations (Figure 3). One receiver is typically located over a known reference point and the position of an unknown point is determined relative to the reference point. With the more sophisticated 24-channel dual-frequency RTK-DGPS receivers, positional accuracies can be improved to the subcentimeter level when operating in static mode and to within a few centimeters when in RTK mode (i.e., as the rover GPS is moved about).

Survey benchmarks

Allan and Hart (2007) fully describe the procedures used to establish survey benchmarks and the beach profiles established in the Neskowin cell, while Ruggiero and Voigt (2000) describe procedures used to establish the beach monitoring network on the Clatsop Plains. Here we briefly describe our earlier efforts to establish a dense GPS beach monitoring network in the Rockaway cell, located in Tillamook County. It is important to note that this effort was originally undertaken in the summer/fall of 2004 and was funded in part by DLCD and through the initial NANOOS pilot project.

Twenty-five beach profile sites and survey benchmark locations were initially identified in a Geographical Information System (GIS). These sites were then

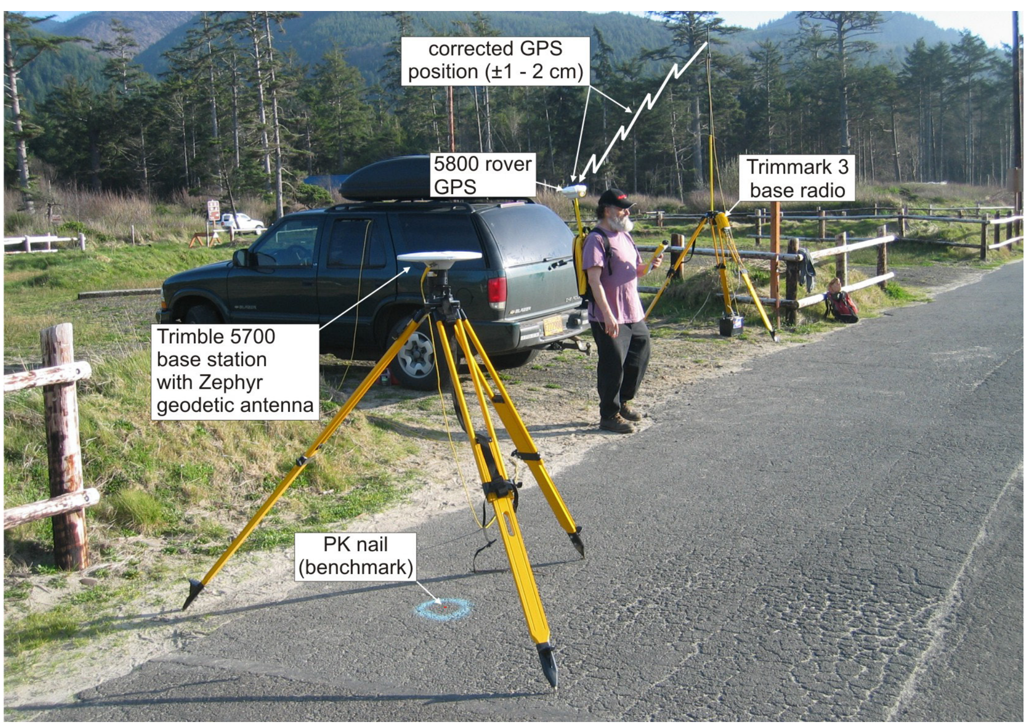


Figure 3. The Trimble 5700 base station antenna located over a known reference point at Cape Lookout State Park, Oregon. Corrected GPS position and elevation information is then transmitted by a Trimark III base radio to the 5800 GPS rover unit.

assessed in the field to refine the benchmark locations and to make sure that the sites would have an unobstructed view of the sky. The benchmarks consisted of either:

- aluminum sectional rods (Figure 4A) hammered approximately 12–24 ft into the ground and capped with a 2½" aluminum cap. The ends of the rods and caps are concreted into the ground; or,
- 2½-ft deep holes that include a 4- to 6-ft-long galvanized steel earth anchor (with a 6" helix screw) screwed into the hole to provide additional support and rigidity and then backfilled with concrete (Figure 4B). These latter benchmarks are characterized by brass survey caps.

All survey caps are stamped with an Oregon Department of Geology designation *but currently do not have an ID number on them*.

Precise coordinates and elevations were determined for the Rockaway beach and shoreline network by the Tillamook County Surveyor's Office using several GPS units. The GPS units were mounted on fixed height (2.0 m) survey rods and located over known geodetic survey monuments to establish precise survey control. Surveys of the new monuments were then undertaken and typically involved occupation times of 20 minutes or more. This approach enabled multiple baselines to be established from known survey benchmarks points to the unknown monuments, which produced excellent survey control. Coordinate information for each of the benchmarks were determined in both geographic coordinates and in the Oregon State Plane (northern zone, meters) coordinate system. All elevations are expressed in the North American Vertical Datum of 1988 (NAVD88). All benchmark information can be accessed via the web at: http://www.oregongeology.org/nanoos1/Benchmarks/benchmarks.htm

Figure 1 shows the general layout of the final Rockaway cell survey network, which consists of seven profiles sites between Cape Meares and the Tillamook estuary mouth, ten sites located between Tillamook and Nehalem bays, and eight sites between Nehalem bay and Manzanita in the north. Surveying of beach

Figure 4. A) Sectional aluminum rod capped by a 2½" aluminum cap serves as a benchmark at Rock8 in the Rockaway subcell. B) Where rods are not used, a 5-ft-long helix anchor screw is inserted into an 8" diameter hole (3 ft deep) and filled with concrete. The monument is then capped with a 2½" brass cap. Example shown is for the Bay2 monument located on Bayocean Spit.

profiles commenced on October 26, 2004, using a Trimble® 5700/5800 Total Station GPS (Figure 3). This system consists of a GPS base station (5700 unit), Zephyr Geodetic™ antenna, TRIMMARK™ 3 radio, and 5800 "rover." The 5700 base station was mounted on a fixed height (2.0 m) tripod and located over a known geodetic survey monument followed by a site calibration on the remaining benchmarks to precisely establish a local coordinate system (Figure 5). This step is critical to eliminate various survey errors. For example, Trimble reports that the 5700/5800 GPS system results have horizontal errors of approximately ±1-cm + 1-ppm (parts per million × the baseline length) and ±2-cm in the vertical (Trimble Navigation Limited, 2005). These errors may be compounded by other factors such as poor satellite geometry, multipath, and poor atmospheric conditions, combining to increase the total error to several centimeters. Thus, the site calibration process is critical to minimize these uncertainties (Ruggiero and others, 2005).

Once the local site calibration was completed, cross-shore beach profiles were surveyed with the 5800 GPS rover unit mounted on a backpack (Figure 6). This process was typically undertaken during periods of low tide. The approach was to walk a straight line from the landward edge of the primary dune, over the dune crest, down the beach face, and out into the ocean to approximately wading depth by navigating along a predetermined line perpendicular to the shoreline and displayed on a hand-held Trimble TSCe computer, connected to the 5800 rover. The computer shows the position of the operator relative to the survey line and indicates the deviation of the GPS operator from the line. The horizontal variability during and between subsequent surveys is generally minor, approximately 1 m (3 ft) (i.e., about ±0.5 m either side of the line), and typically results in negligible vertical uncertainties due to the wide gently sloping beaches characteristic of much of the Oregon coast (Ruggiero and others, 2005). The surveys were repeated on approximately a quarterly basis and/or after major storms. According to previous research, this method can reliably detect elevation changes on the order of 4-5 cm, that is, well below normal seasonal changes in beach elevation, which typically varies by 1–2 m (3–6 ft) (Shih and Komar, 1994; Ruggiero and others, 2005).

Figure 5. Static GPS occupations were used as part of a site calibration on selected benchmarks to derive a local coordinate system in the Rockaway littoral cell. GPS site calibration procedures involved occupying a benchmark for 180 epochs (typically at least 3 minutes or longer) and then processing the data in Trimble Geomatics Office software.

Figure 6. Profile survey undertaken near Neskowin using a Trimble 5800 GPS rover mounted on a backpack.

The collected GPS data were subsequently processed using the Trimble Geomatics Office™ suite of software. The first stage involved a re-examination of the site calibration undertaken on the TSCe computer. A three-parameter least-square fit was then applied to adjust all data points collected during the survey to the local coordinate system established for the particular study area in order to reduce any errors that may have occurred as a result of the GPS units. The reduced profile data were then exported for subsequent analysis.

Analysis of the beach survey data involved several stages. Data were first imported into the Mathworks MATLAB® computer programming environment using a customized script. A least-square linear regression was then fit to the profile data. The purpose of this script is to examine the reduced data and eliminate data points that exceed a ±0.5-m threshold on either side of the predetermined profile line. The data were then exported into a Microsoft Office Excel™ database for archiving purposes. A second MATLAB script was applied to the Excel profile database to plot the latest survey data (relative to the earlier surveys) and to output the generated figure as a Portable Network Graphics (.png) file. A third script examined the profile data and quantified the changes that occurred at selected contour elevations; for this study, temporal trends were developed for all contours between the 1-m and 6-m elevations and for all available data. Finally, the reduced contour data were plotted against time and exported as a .png file for additional analysis. After data analysis, the graphic images were displayed on the OBSMAP website for online viewing (http://www.oregongeology.org/sub/nanoos1/index.htm).

RESULTS

A variety of approaches may be used to view and analyze beach morphology measured by surveys. In the traditional approach, one simply examines the temporal and spatial variability of graphed beach profiles. Other approaches include examining changes at specific contour elevations (also known as excursion distance analysis, or EDA), undertaking volumetric calculations, or examining alongshore changes that occurred.

Beach profiles provide the most important information concerning the spatial variability in the shape of a beach section over time. The information derived from repeated surveys provides a measure of the response of the beach to variations in the wave energy (e.g., winter versus summer wave conditions), which is reflected in accretion of the beach during the summer and erosion in winter. These data may also contain important information on how the beach responds to major storms, such as during the extreme 1997-1998 and 1998-1999 winters, including dune or bluff erosion (i.e., how much dune or bluff retreat occurred), data that are extremely useful when designating hazard zones along the coast. Given the short period in which beach changes in the Rockaway cell have been monitored, information derived from lidar topographic surveys has been used to supplement the beach monitoring data, extending the data set back to at least October 1997. Along the Rockaway cell, airborne lidar data were obtained in October 1997 (pre El Niño), April 1998 (post El Niño), and in September 2002 (Allan and Hart, 2005). When combined, the lidar and RTK-DGPS data provide almost a decade of information on beach changes in the Rockaway littoral cell.

Results presented here focus primarily on changes that have taken place in the Rockaway cell and on the Clatsop Plains during the past decade. (A similar assessment was previously undertaken for the Neskowin cell by Allan and Hart [2007].) This report concludes with an examination of beach changes that took place over the 2007-2008 winter, particularly in response to the extreme December 2-3, 2007, event and another event on January 5, 2008, and the associated beach responses that took place at Neskowin and in Rockaway and at Twin Rocks.

Rockaway cell beach changes

The Rockaway littoral cell extends from Cape Meares in the south to Neahkahnie Mountain in the north. The length of the cell is about 26 km (16 mi), and can be further subdivided into three subcells that include Bayocean Spit, Rockaway, and Nehalem spit, with each of the subcells separated at the mouths of Tillamook and Nehalem bays. Within this cell, the most concentrated area of coastal development occurs along the Rockaway subcell (i.e., the area includes the towns of Twin Rocks, Rockaway, and Nedonna Beach). Intense development is also occurring in the north at Manzanita.

Bayocean Spit

The Bayocean Spit subcell extends from Cape Meares in the south to the south jetty that bounds Tillamook Bay. Site Bay1, located at the south end of Bayocean Spit is characterized by a wide (~50 m wide [164 ft]) low-lying (5.8 m high [19 ft]) barrier berm comprised of pebbles and cobbles, which extends from the Cape Meares headland in the south to about 270 m (900 ft) north of Bay 1. North of Bay1, the shore is backed by a high (10 to 12 m [33 to 39 ft]) frontal foredune (primary dune) that extends from Bay2 to Bay5. North of Bay5, the foredune decreases in height to about 8 m (26 ft) in elevation. Between Bay4 and Bay5, the backshore is characterized by a remnant parabolic dune and transverse dunes that have been truncated due to the erosion of Bayocean Spit following construction of the north Tillamook jetty in the early 1900s (Cooper, 1958; Komar, 1997). South of Bay3 and north of Bay1, the backshore is low lying and is characterized by a wetland and lake that formed from the breaching of Bayocean spit in 1952. Seaward of the cobble berm and foredune, the beach is wide and gently sloping (tan β = 0.021). Grain-size statistics determined by Peterson and others (1994) indicate that the mean grain size is 0.167 mm (i.e., fine sand).

Beach morphological changes for four of the study sites located along Bayocean Spit are presented in Figure 7. The measured changes indicate that over the past decade the beach has been relatively stable. In the far south at Bay1, the beach has experienced little change (Figure 7), a testament to the resilience of the cobble beach that protects the community of Cape Meares. Nevertheless, due to its relatively low crest elevation (~ 5 to 6 m [16 to 20 ft]) this particular shore section is periodically overtopped by ocean waves, carrying flotsam and cobbles landward of the cobble berm. Hence, this section of shore remains subject to major hazards associated with ocean flooding (storm surge plus high wave runup) that may accompany large storms, as well as from ballistics associated with the transport of cobbles and tree trunks inland against the houses that have been built parallel to the beach.

In response to the extreme winter storms of 1997-1998 and again in 1998-1999, parts of the spit did experience some erosion, particularly along the south-central section of the spit (north of Bay1 and south of Bay3), with the foredune eroding landward by about 5 to 7 m (16 to 23 ft) (Figure 8). However, since those events the monitoring data indicate that the Bay2 site has been gradually recovering, while the Bay3 site has not. In contrast, monitoring data from the remainder of the spit (north of Bay4) indicate that the upper part of the beach and frontal foredune have been aggrading (building vertically) over time, causing the beach-dune face (measured at an elevation of about 6 m [20 ft]) to advance (prograde) seaward by about 31.6 m (104 ft) at Bay5 and 37.8 m (124 ft) at Bay 7 at the north end of the spit (Figure 8). Much of this phase of beach building and dune growth has occurred since 2002. Although beach building has occurred at higher elevations on the beach face, the position of the lower beach face near the MHHW mark (~ 3 m [9 ft] elevation) has continued to erode landward over time, north of Bay2 and south of Bay5, causing the beach in the central part of the spit to steepen over time. For example, beach changes measured at the peak of the 2007-2008 winter revealed the beach in its most eroded state since monitoring commenced. In contrast, the beach along the northern one third of the spit revealed little to no change on the lower beach face. Nevertheless, as can be seen in Figure 8, the lower beach face at Bay7 was generally in the positive (i.e., had more sand on it relative to previous years).

Rockaway

The Rockaway subcell extends from Tillamook Bay in the south to Nehalem Bay in the north. Along much of its shore, significant property development has occurred, particularly in the areas of Twin Rocks, Rockaway, and Nedonna Beach. As a result of these developments having been allowed to be built too close to the beach, and because of the relatively narrow beach widths present in this subcell (compared with other

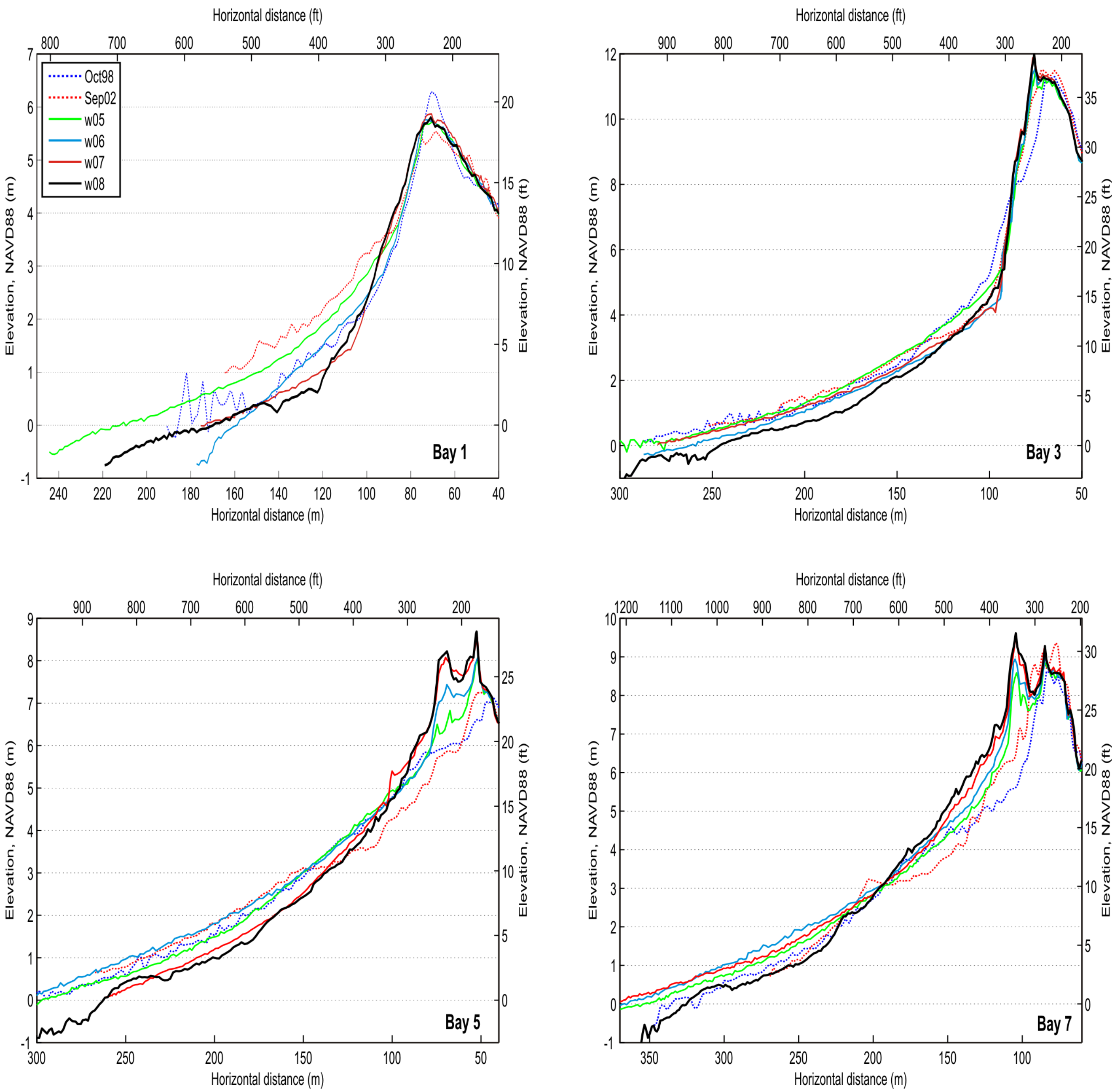


Figure 7. Measured beach morphological changes carried out between 1997 and 2008 along Bayocean Spit. Morphological changes shown in the figure are based on only the winter surveys undertaken in each year. Note: w in the legend signifies winter; beach surveys typically occurred in March. NAVD88 is North American Vertical Datum of 1988.

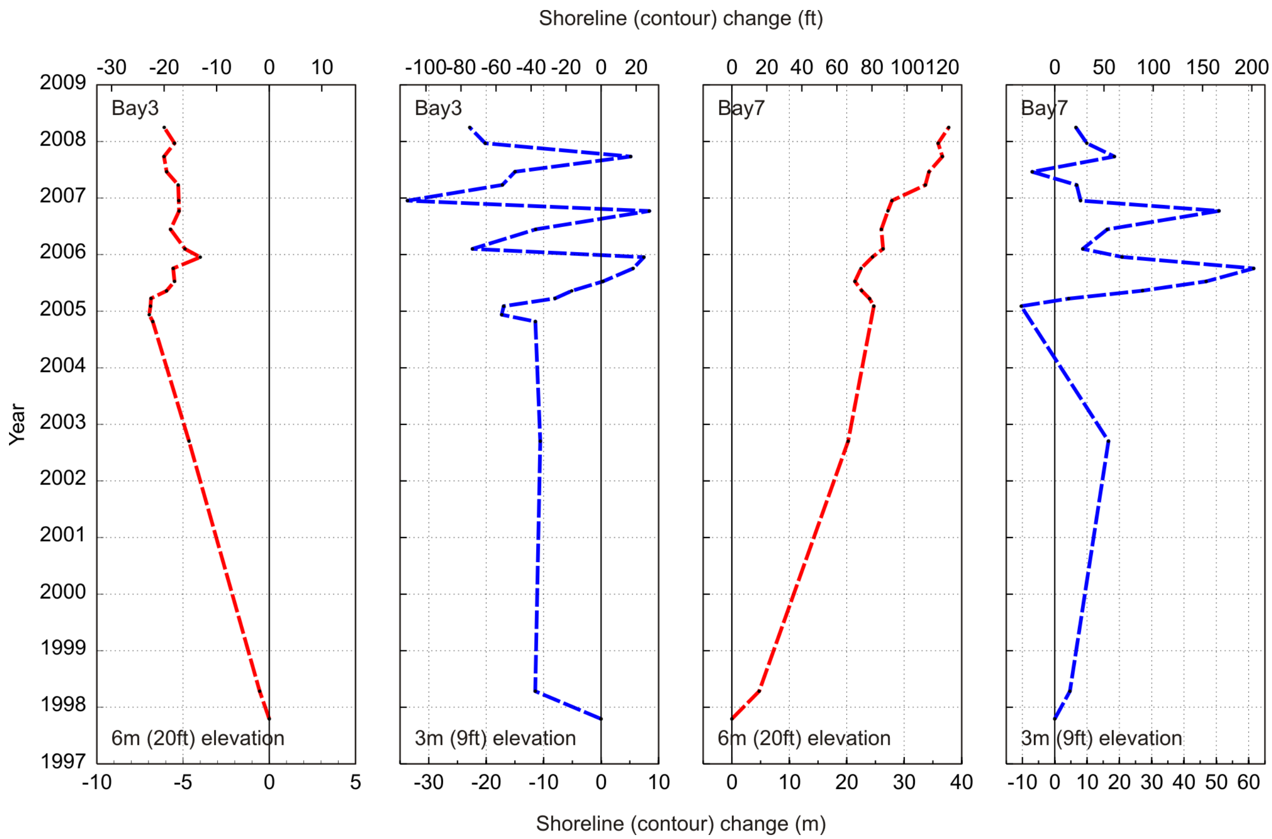


Figure 8. Shoreline "contour" changes determined for the upper (red) part of the beach at the 6 m (20 ft) elevation and for the lower (blue) beach face (3 m [9 ft] elevation) near the mean higher high water (MHHW) mark. Data presented here incorporate all the measured responses. Negative values indicate erosion, positive values indicate accretion, and zero indicates no change. Note figure top indicates units in feet, while the units on the bottom of the plot are metric.

beach sites), the Rockaway subcell has become one of several erosion "hotspots" on the Oregon coast, requiring expensive coastal engineering (riprap revetments) to combat the beach and dune erosion that has taken place in recent years. In particular, riprap structures have been constructed along much of the township of Rockaway, north of profile Rck5 and south of Rck8, as well as in the south between Rck2 and Rck3 (Figure 1).

Grain-size statistics indicate that the mean sand size is slightly coarser (0.21 mm) at Rockaway than at Bayocean Spit, but the sand is still classified as fine sand. Where creeks and streams flow out onto the beach, gravels can also be identified, though the quantities are very small. Due to the slightly coarser nature of the sediments, the beach in the Rockaway subcell tends to be generally steeper (tan β = 0.021) than Nehalem and Bayocean Spit beaches.

Since construction of the Tillamook and Nehalem jetties, the shoreline has changed considerably. In the south, the mean shoreline position has prograded seaward by up to 300 m (1000 ft) (Allan and Priest, 2001). Shore progradation also characterizes the beach response in the area of Nedonna Beach, which has been gradually accumulating sand since the late 1960s.

Figure 9 shows the responses of the Rockaway beach since the extreme storms of the late 1990s. Unlike the beach changes identified on Bayocean Spit, changes along the Rockaway subcell have been far more dramatic. Beach and dune erosion dominates the bulk of the shoreline, with the greatest amount of erosion having occurred north of the Tillamook jetties and south of about Rck8 (Figure 1). Without doubt, much of the erosion can be attributed to the extreme storms that impacted this section of the coast during the 1997-

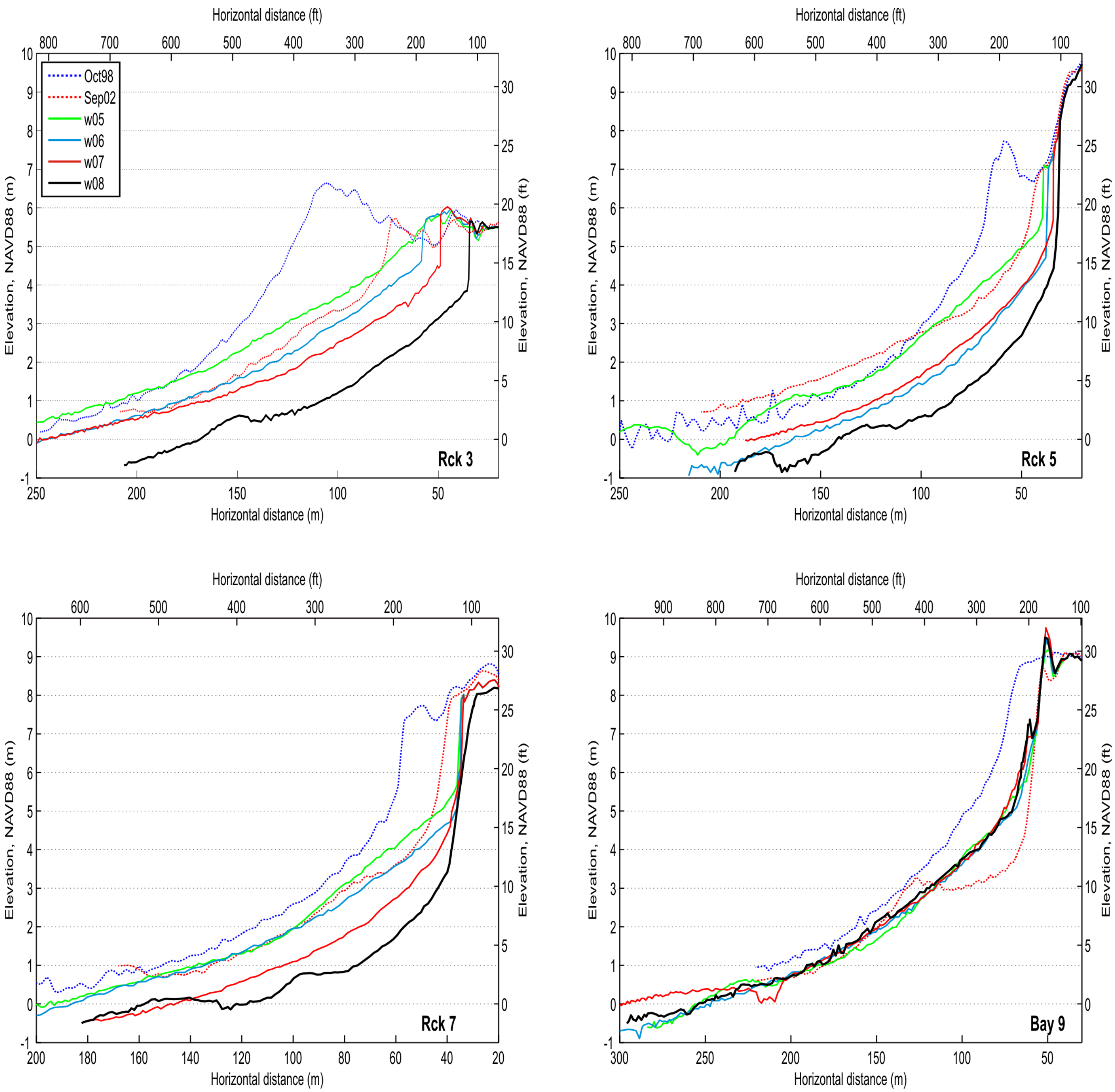


Figure 9. Measured beach morphological changes carried out between 1997 and 2008 along the Rockaway subcell. Morphological changes shown in the figure are based on only the winter surveys undertaken in each year. Note: w in the legend signifies winter; beach surveys typically occurred in March. NAVD88 is North American Vertical Datum of 1988.

1998 and 1998-1999 winters. For example, by the end of the 1998-1999 winter season the dune toe at Rck1 had receded landward by 38.2 m (125 ft). Recent beach monitoring efforts along this shore has revealed that this section of beach has continued to retreat landward, with Rck1 having now eroded by 46.9 m (154 ft) since 1997. It is likely that some of the beach erosion at the south end of the Rockaway subcell can be attributed to "hotspot" erosion effects that take place during major El Niños (Komar, 1998; Allan and others, 2003). Because the predominant storm tracks are shifted to the south during major El Niños, so that the storms cross the central/northern California coast, wave heights along the Oregon coast tend to be much larger. Furthermore, because of the proximity of the storm systems to the south, the arrival of waves on the Oregon coast tend to occur at strongly oblique angles relative to the shore, contributing to greater erosion at the south ends of the littoral cells (i.e., north of the headlands and jetties).

As shown in Figure 9, Rck3 has also experienced fairly significant beach and dune retreat. Between 1997 and 2002 (i.e., the period that spans the extreme storms of the late 1990s) the beach receded landward by 46.5 m (152.6 ft). Since 2002, the beach has eroded an additional 41 m (134.5 ft), bringing the total beach and shoreline retreat to 87.5 m (287 ft). Further north at Rck5, Figure 9, the beach eroded 26 m (85 ft) between 1997 and 2002. Our recent monitoring efforts have revealed that the Rck5 eroded an additional 5 m (16 ft) between 2002 and 2004, and was relatively stable up through early 2006. Since then, this section of Rockaway beach has retreated landward by an additional 7.9 m (26 ft), bringing the total amount of beach erosion since 1997 to 39.2 m (128.6 ft). Much of this recent phase of erosion can be attributed to a storm in early 2006, and most recently in December 2007. As can be seen in Figure 9, the erosion can be easily tracked over time, initially as small 1.2 m (3.9 ft) high erosion scarp that has increased in height (now about 4 m [13.1 ft]) over time as the dune has receded landward.

Similar changes can be identified for the Rck7 profile site, which retreated landward by about 20.6 m (-67.6 ft), between 1997 and 2002. By October 2004, when we commenced our surveys of the beach, the Rck7 site had eroded an additional 6.6 m (22 ft). While our other beach monitoring sites south of Rck7 continued to be characterized by ongoing beach and dune recession, the Rck7 site did not change much between 2004 and 2007. However, in January 2008 the beach cut back about 4 m (12 ft) (Figure 10); due to the close proximity of several homes to the beach, OPRD granted permission for emergency riprap to be installed. The

Figure 10. Dune erosion scarp that formed at Rck7 in January 2008. Note the two people having to use a ladder to get off the beach.

erosion that occurred at Rck7 was in fact exacerbated by the presence of a large rip embayment that formed over the winter. The presence of the rip embayment was identified in our summer survey; over the course of the winter, the embayment broadened and migrated north. Due to the presence of the rip embayment, large waves were able to break much closer to the shore in the throat of the channel, with minimal loss of energy. As a result of these processes as well as currents that form in response to circulation in the nearshore, the waves were able to rapidly lower the beach elevation and directly attack the dune face.

Finally, unlike south of Rck8, the Nedonna Beach area to the north has been relatively free of erosion problems. Although the Rck9 site shown in Figure 9 did experience fairly significant erosion between 1997 and 1998, since then the beach and dune has been gradually accreting. As a result, the dune has prograded seaward by about 4.4 m (14.4 ft). Such a response has likely been aided by the northward transport of sediments eroded from the beaches south of Rck8. Although the north end of the Rockaway subcell has gained new material over the past decade, the actual volume is relatively small compared with the total amount of sand that has been eroded from the beach south of Rck8. Further discussion of this is provided below.

Nehalem Spit

The Nehalem Spit subcell spans the region between the Nehalem jetties in the south and Neahkahnie Mountain in the north. The beach along Nehalem Spit is significantly wider than beaches in the Rockaway subcell, in part because this shore is appears to be presently gaining sand, albeit at slow rates, and because the Rockaway subcell has experienced so much erosion in recent years. Along much of the spit, the beach is backed by a high foredune that averages about 12 to 14 m (39.4 to 45.9 ft) in height, with a maximum height of 17.6 m (57.8 ft) at Neh4, located midway along the cell. North of Neh6, the foredune crest decreases in elevation to a low of 8.4 m (27.6 ft) at Neh8. While the bulk of the spit is managed by the OPRD, residential development has occurred in the northern portion of the cell, from just south of Neh6 all the way north to Neahkahnie Mountain. Like the beaches along Bayocean Spit and at Rockaway, the Nehalem Spit beaches are gently sloping and are characterized by a wide dissipative surf zone. Grain-size statistics determined by Peterson and others (1994) indicate that the mean grain size is 0.195 mm (i.e., fine sand).

Morphological changes for selected beach profile sites are shown in Figure 11. For the most part, the identified pattern of responses are consistent with changes observed on Bayocean Spit. Thus, in general, the beach south of and including Neh4 (Figure 1), experienced quite a bit of erosion during the extreme winter storms of the late 1990s. For example, the mean beach and dune retreat between 1997 and 2002 was 18.2 m (59.7 ft), while the maximum amount of erosion was 28.3 m (92.9 ft) measured at the Neh2 profile site. Since then, two of the sites (Neh1 and Neh4) have almost fully recovered, while the Neh2 and Neh3 sites continue to experience low beach volumes relative to their condition in 1997 prior to the major El Niño.

Neh5 marks the transition between the southern region that has been subject to erosional changes and the northern portion of the cell that has been steadily aggrading over time. As can be seen for Neh5 (Figure 11) this particular site has undergone some recent beach building. Between 2002 and 2008, the foredune aggraded vertically by about 2.5 m (8.2 ft) (Figure 12), the section of dune above about 8 m (25 ft) prograded seaward by about 21 m (68.9 ft), and the dune toe measured at the 6 m (20 ft) contour elevation advanced seaward by about 12.6 m (41.3 ft). These changes suggest that the bulk of the dune sand is accumulating up in the dune itself, probably aided by the presence of European beach grass that helps trap sand blown inland from the beach. In contrast, sand accumulation around the 6 m (20 ft) contour elevation is likely to be more ephemeral, as it is moved about by ocean waves and the wind. These types of responses are broadly similar to measured beach changes observed in the Neskowin littoral cell (Allan and Hart, 2007). Further north at Neh7 and Neh8, the measured beach responses indicate very subtle changes. While there has been some sand accumulation on the upper beach face at Neh7 and to a lesser extend Neh8, both sites indicate considerable variability on the lower beach face as the beach varies between erosion and accretion. In essence, neither of these sites has changed significantly in the last decade.

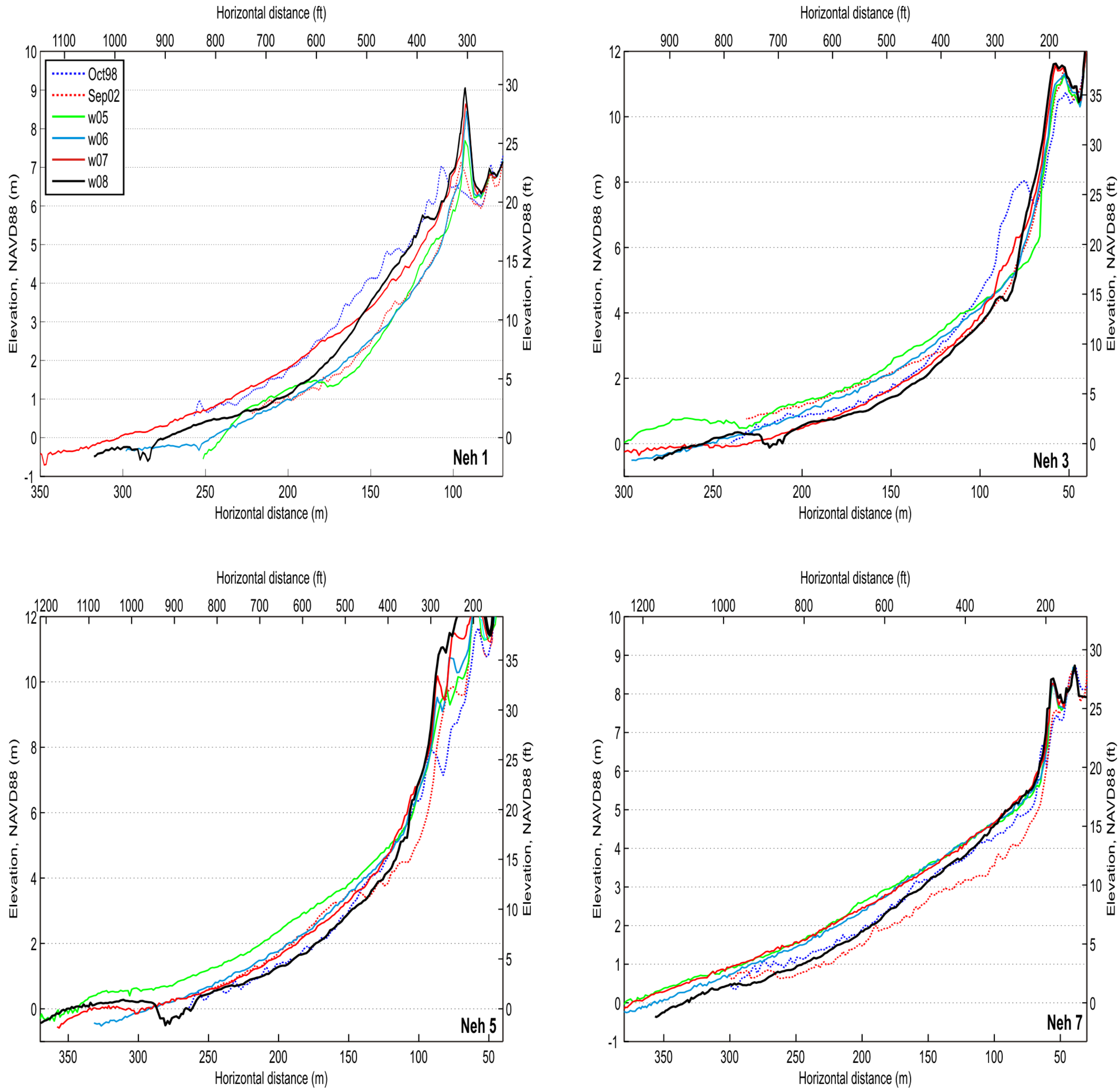


Figure 11. Beach morphological changes from surveys carried out between 1997 and 2008 along the Nehalem Spit subcell. Morphological changes shown in the figure are based on only the winter surveys undertaken in each year.
Note: w in the legend signifies winter; beach surveys typically occurred in March.
NAVD88 is North American Vertical Datum of 1988.

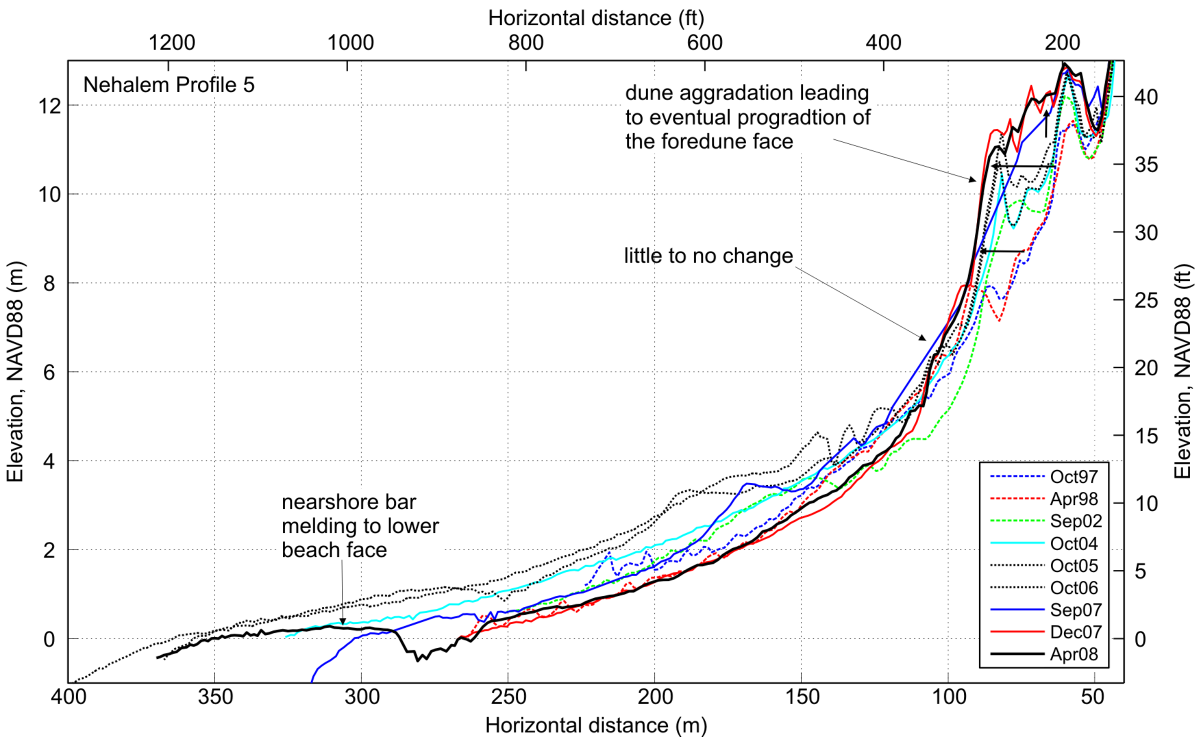


Figure 12. Summer beach profile measurements from surveys undertaken at site Neh5 on Nehalem Spit documenting buildup of sand on the foredune. NAVD88 is North American Vertical Datum of 1988.

Volume changes and alongshore responses

Analyses of volume changes along the Rockaway littoral cell indicate that the cumulative effect of the 1997-1998 El Niño and 1998-1999 winters resulted in considerable erosion along much of the cell (Figure 13). These changes were derived from an analysis of lidar data undertaken by Allan and Hart (2007), which were based on a GIS beach profile database spaced at 100-m (300 ft) intervals along the shore. As can be seen in Figure 13, greatest sand volume losses occurred at mid-cell, between Tillamook and Nehalem bays near the towns of Twin Rocks, Rockaway, and Nedonna Beach, and along the southern end of Nehalem Spit. In contrast, the northern end of Bayocean and Nehalem spits gained sand, probably due to some northward migration of the sand. Nevertheless, sediment volume gains in the north are offset by the substantial net losses observed along the bulk of the shore. Summing the volume changes along the entire littoral cell indicates that the cumulative erosion of the beach and dune as a result of both winters resulted in the removal of 1,439,600 m^3 (1,883,000 yd^3) of sand from the beaches, the bulk of which was probably carried offshore, with some sand possibly carried into the bays.

As described above, recent surveys of the beaches in the Rockaway littoral cell indicate that the shore continues to erode, primarily in the region between Tillamook and Nehalem bays. Figure 14 shows the alongshore response of the beach determined at the 5-m (16 ft) contour elevation, representative of the juncture between the dune face and the beach crest. Included in the plot are data for the period 1997 to 2002, essentially capturing those beach changes that took place during the extreme winter storms of the late 1990s. As can be seen in Figure 14, the upper portion of the beach face/dune toe area continues to recede landward, with the most significant changes having taken place along the southern half of the Rockaway subcell, between the north jetty and the Rck5 beach profile site. Erosion has also occurred north of Rck5 and south of Rck7 to such a degree that much of this section of shore has now been hardened with riprap. In contrast, beach changes talking place on Bayocean and Nehalem Spits suggest some level of beach recovery. For example, the 5-m (16

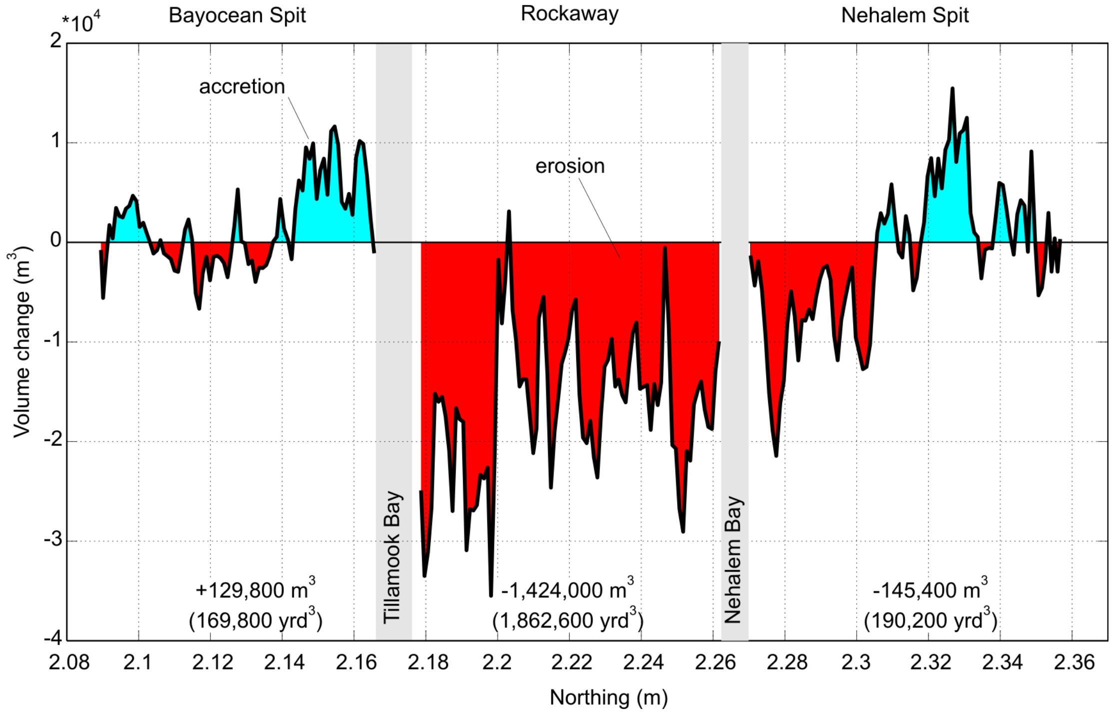


Figure 13. Alongshore beach volume changes (in cubic meters) derived from an analysis of available lidar data for the period 1997–2002. Data were derived from a re-analysis of lidar beach profile changes originally developed by Allan and Hart (2005, 2007). Red shading indicates erosion, blue shading indicates accretion.

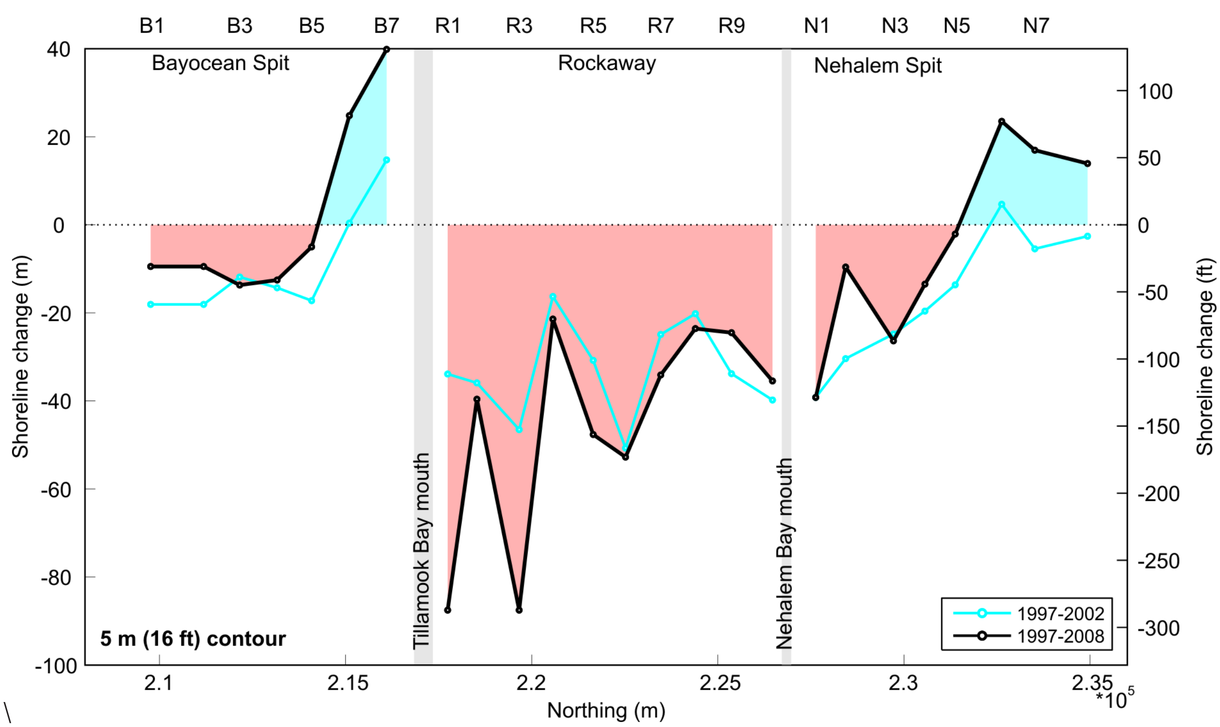


Figure 14. Alongshore variability in the response of the 5-m (16 ft) beach contour elevation for the periods 1997–2002 (derived from lidar) and 1997–2008 (lidar plus GPS surveys). Note the letters B, R, and N followed by a number denote the locations of profile sites. Red shading indicates erosion, blue shading indicates accretion.

ft) contour has begun to prograde seaward along the northern one third of Bayocean Spit, and the northern half of Nehalem Spit, with the sand tending to migrate up onto the dune face. From these ongoing changes, it is highly likely that the net volume of sand along the entire littoral cell remains in a state of net deficit compared to conditions in 1997, with the total loss of sand as of March 2008 estimated to be about 2 million cubic meters of sand (2.6 million cubic yards).

In summary, the measured responses identified by the combined lidar and RTK-DGPS survey data indicate that the beaches along the Rockaway subcell have continued to erode over time, with little to no evidence of recovery as of March 2008. Conversely, beaches along Bayocean and Nehalem Spits have recovered somewhat, while the northern ends of these two subcells have gained sand, relative to our lidar baseline measured in 1997. However, as was observed by Allan and Hart (2007), accretion in these two areas has been largely confined to a gradual buildup of sand on the primary frontal dune, raising its crest elevation over time. Thus, although these two sections of shore have accreted slightly over the past decade, the shoreline has not prograded seaward. Furthermore, the beaches along the littoral cell remain in a state of net deficit compared to their condition in 1997, with the estimated loss of sand as of March 2008 to be about 2 million cubic meters (2.6 million cubic yards) of sand. Whether the beach recovers fully and how long it takes remain important and interesting scientific and management questions, which can be answered only as the beaches continue to be monitored.

Clatsop Plains beach changes

The Clatsop Plains are an arcuate shaped coastline that extends from Tillamook Head in the south to the mouth of the Columbia River (MCR) (Figure 1). The plains form part of a smaller subcell (34 km long) located within the much larger Columbia River littoral cell (CRLC), a 165-km coastal system that extends from Tillamook Head, Oregon, to Point Grenville, Washington.

The coastline of the Clatsop Plains is characterized by wide surf zones and prominent longshore bars in the nearshore, while the beaches are backed by an extensive dune sequence (Cooper, 1958; Woxell, 1998). The frontal foredunes that immediately back the beaches range in height from several meters to over 16 m (up to 53 ft high). These dunes increase in height from Seaside to Kyle Lake, and then decrease in height toward Clatsop Spit (Ruggiero and Voigt, 2000). The beaches are gently sloping (mean slope [*S*] of 0.032 ± 0.007), and have a somewhat lower beach slope when compared with slopes identified along the Tillamook County coastline (Allan and Priest, 2001). The sediments that comprise the beaches range in size from 0.14 to 0.25 mm (classified as medium- to fine-grained sand).

For the past few thousand years, the shorelines of the CRLC, including the Clatsop Plains, have accreted, causing the coastline to prograde seaward by a few hundred to several thousand meters. This process is thought to have begun around 4000 years ago, as the rate of sea-level rise slowed (Woxell, 1998). Woxell (1998) estimated that the Clatsop Plains historically accreted at an average rate of 0.7 m/yr (2.3 ft/yr) from about 4000 years BP to AD 1700. Between 1700 and 1885, accretion rates along the Clatsop Plains fell slightly to around 0.5 m/yr (1.6 ft/yr). The year 1885 is significant because this was when construction of the south jetty began.

The seaward advance of the Clatsop Plains shoreline has continued throughout the past 120 years, but at rates exceeding several meters per year due to large supplies of sand from the Columbia River, and as a result of jetty construction at the MCR (Gelfenbaum and others, 1999). Of particular significance has been the construction and subsequent extensions of the south jetty, which caused a dramatic increase in the rate of shoreline advance. According to Woxell (1998), since the late 1800s accretion rates along the Clatsop Plains have ranged from 2.0 to 5.8 m/yr (6.6 to 19 ft/yr), with an average rate of 3.3 m/yr (10.8 ft/yr), with the highest accretion rates identified near the MCR. However, since about the mid-1920s the rate of coastal advance has slowed, while erosion has been the dominant shoreline response along the northern end of Clatsop Spit. These latter adjustments may suggest a change in the overall sediment budget of the Columbia River cell, which could have important implications to the future stability of coastal shorelines adjacent to the MCR.

To better understand the changes taking place within the CRLC, the Washington Department of Ecology (WDoE) and the U.S. Geological Survey (USGS) initiated a joint study, the Southwest Washington Coastal Erosion Study (SWCES), to examine the causes of erosion hotspots that had begun to appear along the CRLC.

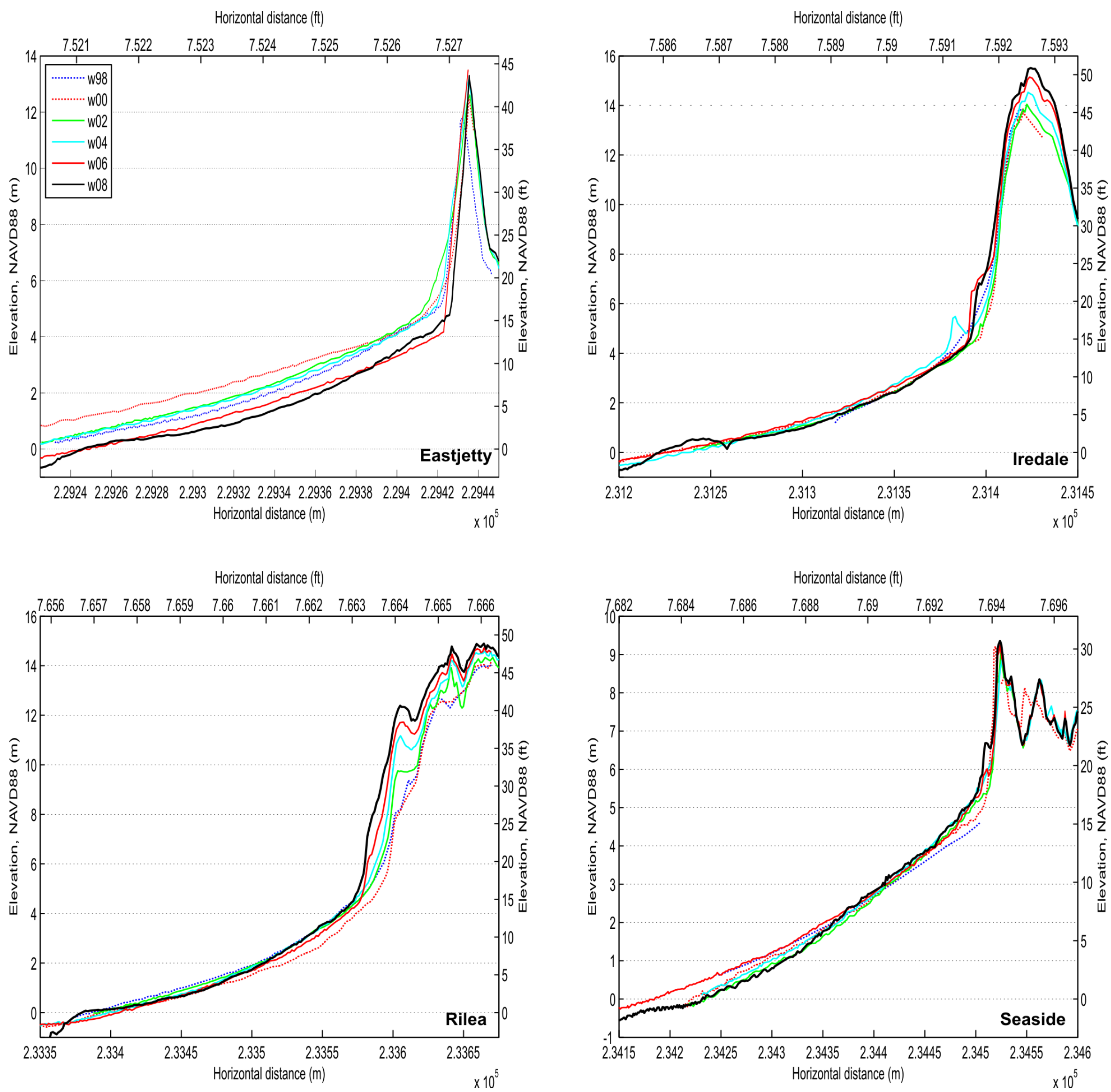


Figure 15. Beach morphological changes from surveys carried out between 1997 and 2008 along the Clatsop Plains subcell. Morphological changes shown in the figure are based on only the winter surveys undertaken in each year. Note: w in the legend signifies winter; beach surveys typically occurred in March. NAVD88 is North American Vertical Datum of 1988.

As part of this effort, the WDoE and the USGS developed and implemented a beach monitoring program along the full length of the CRLC. Within the Clatsop Plains subcell, six beach monitoring sites were established in 1997 (Figure 1) and have been surveyed on a seasonal basis since their inception. In 2005, a "technology transfer" was implemented between the WDoE and DOGAMI staff that resulted in DOGAMI staff taking over the monitoring of the beach profile sites.

Figure 15 shows the profile changes measured at four of the transect sites: Seaside, Rilea, Iredale, and Eastjetty. Beginning in the north at the Eastjetty site, Figure 15 indicates that the Eastjetty site eroded landward as a result of the storms of the late 1990s. One caveat here is that the winter 1998 survey is quite different from the other surveys and may reflect a survey that was carried out at the wrong location. By the late 2002 winter, the beach and dune had effectively rebuilt itself. However, since then the Eastjetty site has been steadily eroding (Figure 16), causing the foredune width to narrow over time. The current foredune width is 14 m (45.9 ft), down from 19 m (62.3 ft) in the winter of 2002. As a result, additional erosion of this shore section could easily breach the dune. Farther south at the Iredale site, morphological changes of the beach again indicate the impact of the storms of the late 1990s, which caused the beach to initially erode. However, since then the beach has been gradually rebuilding and by 2005 had essentially rebuilt itself. Probably the most significant change taking place at the Iredale site is the degree of aggradation occurring on the crest of the foredune (Figure 15). As can be seen in the figure, between 1997 and 2008 the foredune grew vertically by about 1.6 m (5.2 ft), resulting in a net gain of 90 m^3 of sand per meter of beach ($m^3 \times m^{-1}$) or 118 yd^3 per yard of beach. With progress south along the plains, aggradation on the foredune becomes even more significant, while changes on the beach face tend to be relatively minor. For example, net volume gains were measured at Kim (135 $m^3 \times m^{-1}$ [177 $yd^3 \times yd^{-1}$]), Rilea (259 $m^3 \times m^{-1}$ [339 $yd^3 \times yd^{-1}$]) and at Delray (159 $m^3 \times m^{-1}$ [208 $yd^3 \times yd^{-1}$)]). From these values and the length of shore between the transects a conservative estimate of the net sediment volume gain between 1997 and 2008 is 3.4 million cubic meters (4.5 million cubic yards) of sand. Given that the mean shoreline position at each of the beach profile sites has not changed substantially (i.e., prograded seaward), the bulk of the sediment gains reflect net gains on the foredune.

Figure 16. Surveying at the Eastjetty site on December 20, 2007. High waves associated with the December 2-3, 2007, storm eroded the dune toe, leading to its destabilization. Given the current foredune width of 14 m (45.9 ft), further erosion of this site will not take much to "punch" a hole through dune.

THE 2007-2008 WINTER STORMS

This section examines erosion and flood hazards that occurred over the 2007-2008 winter season. Here we briefly discuss changes that took place in the Neskowin and Rockaway littoral cells.

The 2007-2008 winter season was characterized by at least seven major storms (Figure 17), where a major storm is defined as an event in which the significant wave heights exceeds 6 m (20 ft) for a period of 9 hours or greater (Allan and Komar, 2000). By far the most significant of these events was the December 2-3, 2007, storm, which was the largest not only in terms of measured significant wave heights but also because the waves exceeded 10 m (33 ft) for a total period of 18 hours. As can be seen in Figure 17, the significant wave heights peaked at 14.6 m (47.9 ft) and are associated with a 1.1-m (3.6 ft) storm surge (the difference between the measured and predicted tides). Figure 17C also shows the estimated total water level for this event, which reflects the calculated wave runup plus the measured tide. The wave runup was determined using the Stockdon and others (2006) equation (19), which relies on knowledge of the deepwater wave height, peak spectral wave period, and beach slope. As shown in Figure 17C, the total water levels peaked at about 7.1 m (22.3 ft), effectively raising the mean shoreline elevation and thereby allowing the waves to attack the dunes directly and to erode them. GPS measurements of rack/strandline deposits along Neskowin beach indicated total water elevations on the order of 6.5 to 7.4 m (21.3 to 24.3 ft), increasing our confidence in the calculated total water levels shown in Figure 17. Also apparent is a second major storm that occurred January, 5, 2008. Although this event did not produce large waves (the waves were on the order of 9 m (29.5 ft) relative to the

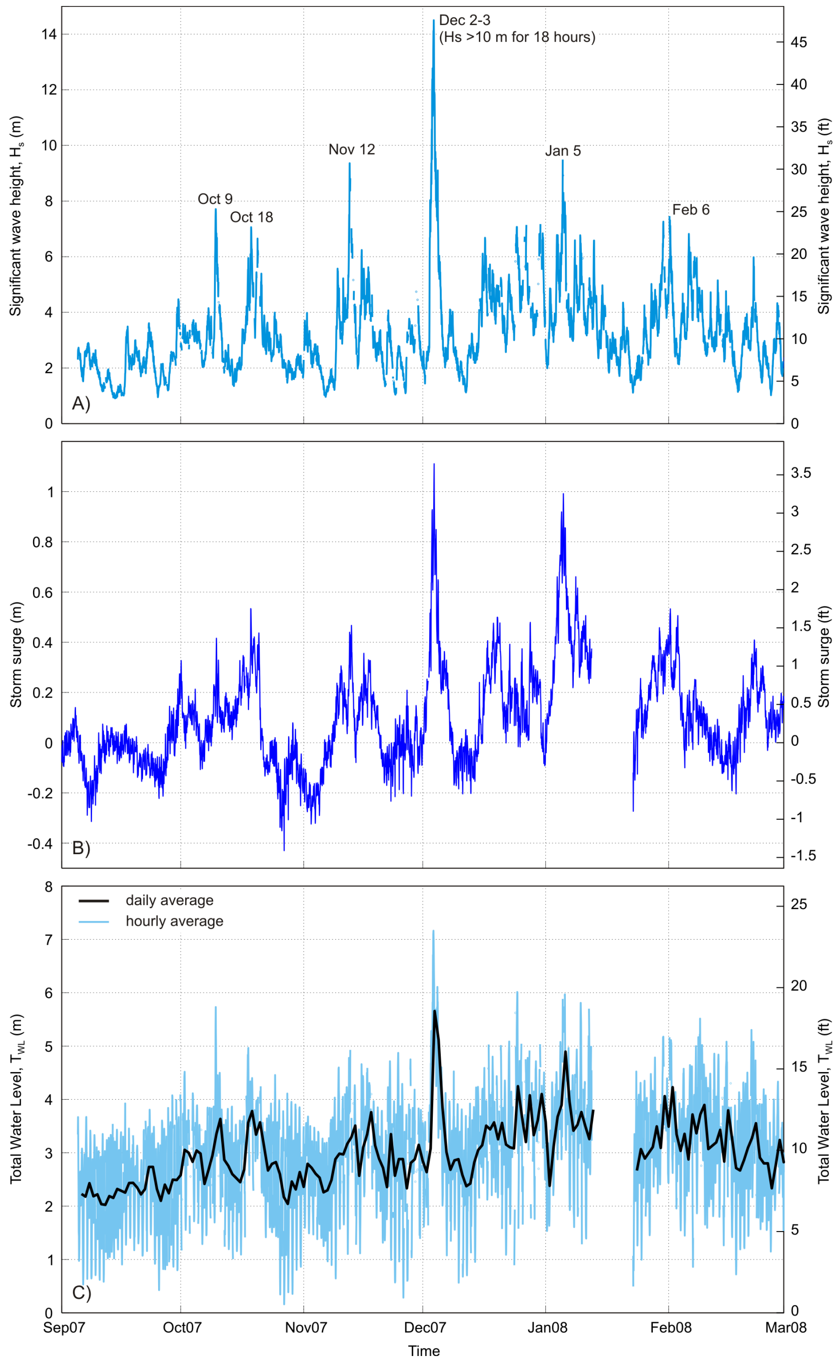


Figure 17. A) Significant wave heights measured by the Tillamook NDBC wave buoy (#46089) over the 2007-2008 winter. B) Storm surge derived by subtracting the predicted tide from the measured tide and based on the Garibaldi tide gauge. C) Hourly total water levels determined from the calculated wave runup plus the measured tide. Wave runup was calculated using the Stockdon and others (2006) equation (19) using a beach slope of 0.04.

December 2007 storm, the event did coincide with high tide that again helped to raise the elevation at which the wave swash could impact the shore. As a result, this event generated the second highest total water levels for the 2007-2008 winter, aided by the high storm surge (reaching 1 m [3.3 ft]) that characterized this event.

The effects of the 2007-2008 winter were widely felt along the Oregon coast, resulting in significant erosion in Neskowin, Netarts, Rockaway; the exhumation of a ship down on the north spit of Coos Bay and cannons at Cannon Beach; and erosion at Garrision Lake near Port Orford. At Neskowin, the storm contributed to as much as 25 m (82 ft) of dune retreat midway along the beach and north of the town of Neskowin. Slightly smaller erosion responses were observed to the north at Cape Lookout State Park, with the dune there retreating by 8.8 m (29 ft), eventually destroying a drain field constructed in the foredune that serves the park. At Neskowin, the formation of a rip embayment north of Proposal Rock during late summer 2007 broadened significantly over the course of the winter. In response to the combination of extreme waves, the high ocean water levels due to the occurrence of a storm surge, and the location of the rip embayment, wave breaking was able to occur close to shore, scouring down the beach face and eventually undermining the toe of a riprap structure and causing part of the structure to fail (Figure 18). Measurements of the beach elevation in April 2008 and obtained along the toe of the riprap indicated an extreme low beach elevation of 0.1 m (0.3 ft) above (mean lower low water (MLLW), while the beach elevation was typically less than 0.5 m (1.6 ft) along about 200 m (656 ft) of riprap. As a result, waves were able to impact the riprap wall at essentially all tidal elevations (Figure 19). During moderate wave events, green water was also observed to go over the top of the riprap wall, which has a crest elevation of 8.8 m (28.9 ft) affecting those properties built adjacent to the eroding shore (Figure 20).

Farther north in the Rockaway subcell, erosion issues were observed just south of Twin Rocks near an RV park built next to the ocean (Figure 21) as well as at the north end of Rockaway beach. In both cases, the problem was related to the presence of a rip embayment that lowered the beach elevation, decreasing its buffering capabilities. At the RV park, a survey of the shoreline

Figure 18. Erosion during a storm on January 5, 2008, eventually caused part of a riprap wall to fail in the town of Neskowin. (Photo courtesy of the The Breakers Condominiums, Neskowin, Oregon.)

Figure 19. Development of a rip embayment north of Proposal Rock in Neskowin removed much of the fronting beach that would otherwise have protected the riprap structure shown above. Extreme lowering of the beach elevation means that the structure is being impacted by ocean waves at all tidal elevations. (Photo taken at low tide by J. C. Allan on April 15, 2008.)

Figure 20. Overtopping of waves during the January 5, 2008, storm caused flooding and damage to ground floor condominium units located in Neskowin. Note that the crest elevation of the graded dune is 8 m (26 ft), while the condominium units are located approximately 6 to 10 m (20 to 30 ft) from the top of the riprap revetment. (Photo taken on January 9 at high tide.)

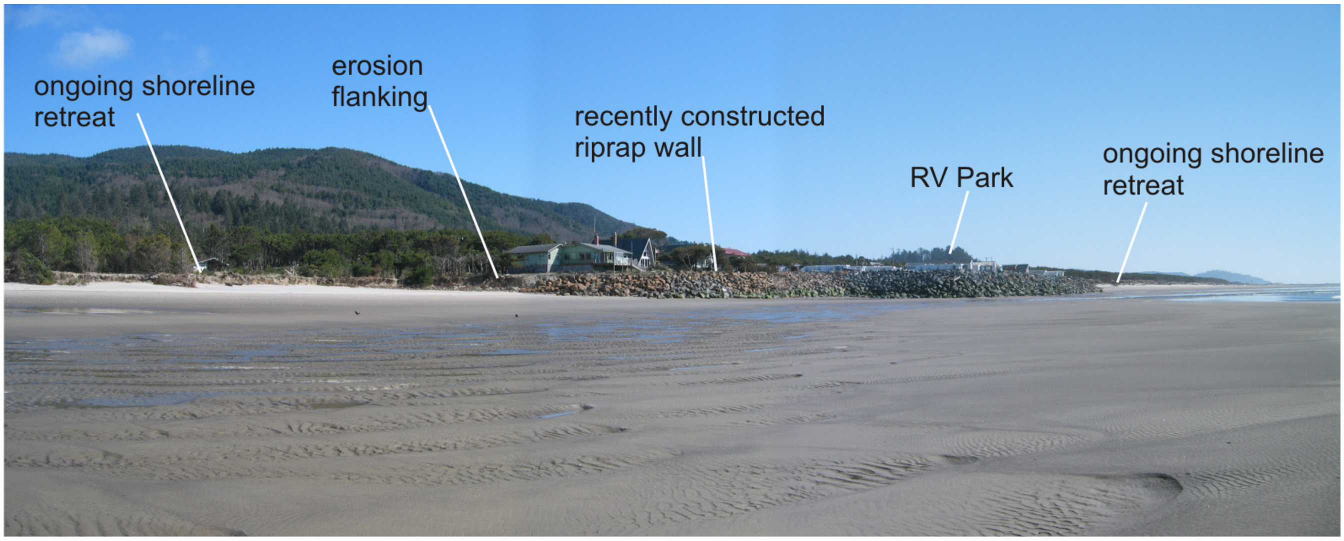


Figure 21. View south toward the RV park located south of Twin Rocks in the Rockaway subcell and erosion taking place to the north and south of the park.

undertaken at the end of the 2007-2008 winter highlights the changes that have taken place to the north and south of the RV park (Figure 22). As described previously, much of the Rockaway subcell has continued to erode landward following the extreme storms of the late 1990s. The erosion has been especially acute along the southern portion of the cell, south of about Rck4, including the area south of Rck4 and including the RV park shown in Figure 21. At the conclusion of the 2007-2008 winter, the RV park now stands out on the beach as the shoreline to the north and south of the park has receded landward (Figure 22). As can be seen in Figure 22, the beach north of the park receded landward by about 50 m (164 ft). In response to the erosion, an emergency permit for the construction and extension of a riprap revetment was issued for three homes north of the RV park. Since then, additional retreat of the shoreline north of northernmost home (Figure 21) has begun to flank the home (Figure 22). At this stage, the expectation is that the shore will continue to retreat to the north and south of these homes. Eventually, this could result in the need for these properties to be “ringed” by rock in order to protect the homes from erosion that is now occurring on all sides of the properties. The costs to maintain the riprap wall could become prohibitive and result in the property owner abandoning the site. At that point, all property owners would be at risk. This evolving situation also applies at several sites at Neskowin and at north Neskowin. Given the current state of low beach sand volumes along the much of the Neskowin and Rockaway shore, and ongoing concerns over climate change and more severe storms, the situation in these two areas alone remains extremely bleak.

To better understand the relative significance of the 2007-2008 winter compared with the previous 1998-1999 extreme winter, a wave-height frequency distribution analysis was performed. The wave-height data shown in Figure 23 were derived from the National Data Buoy Center (NDBC) buoy #46050 (average curve and 1998-1999 winter) and from the Tillamook buoy #46089 (2007-2008 winter) since buoy #46050 was out of commission. In all cases the waves heights analyzed reflect only the winter waves measured between October and March. The frequency values have been plotted on a log scale in order to emphasize the occurrence of the larger wave heights, which naturally have a much lower frequency of recurrence.

As can be seen in Figure 23, wave heights typically average about 3 m (9.8 ft) during winter, increasing to as much as 14 to 15 m for the most extreme storms. Of interest, conditions during the 2007-2008 winter averaged 3.4 m (11.2 ft), slightly above the long-term average, while the wave heights during the 1998-1999 winter averaged 3.8 m (12.5 ft). Of greater interest are the differences in the curves for the higher wave heights. As can be seen in Figure 23, measured wave heights during

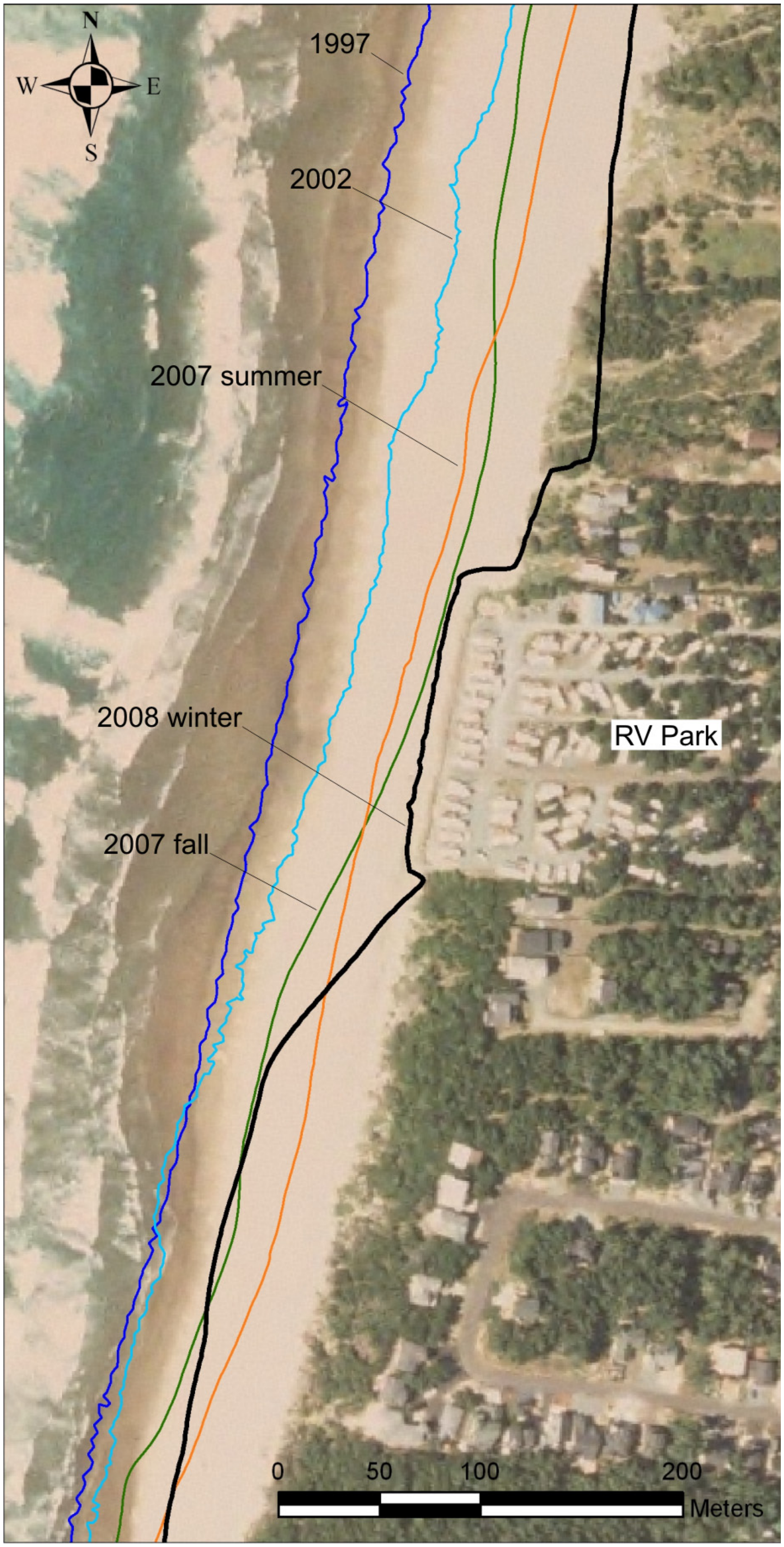


Figure 22. Plan view showing the extent of erosion along a portion of the Rockaway subcell. Mean Higher High Water (MHHW) shorelines derived from lidar (1997 and 2002) and from a Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) mounted on an ATV vehicle (post-2002) demonstrate the degree of erosion that has taken place at this site during the past decade. Total shoreline change at the RV park reflects approximately 300 feet of erosion.

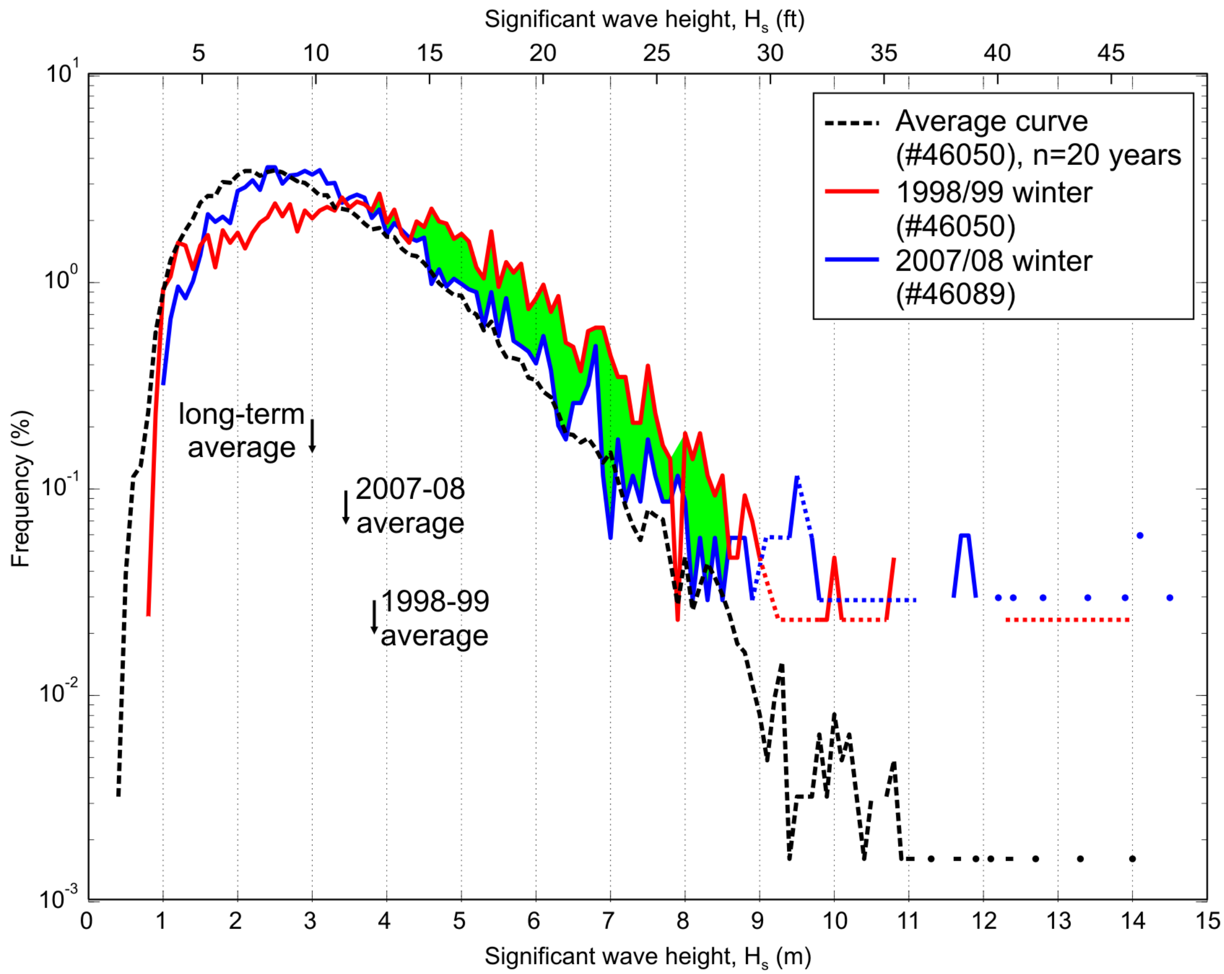


Figure 23. Comparison plot of 2007-2008 winter storm waves (blue) relative to the extreme 1998-1999 winter (red), and the long-term average curve for NDBC buoy #46050 (black). Green shading denotes a larger number of measured waves in the range of > 4 and < 9 m (>13 and < 29.5 ft) observed during the 1998-1999 winter, compared with the 2007-2008 winter.

the 1998-1999 winter well exceed the long term average curve, particularly for those wave heights > 4 and < 9 m (> 13 and < 29.5 ft). In contrast, 2007-2008 winter waves generally track close to the long-term average, and it is not until wave heights exceed 9 m (29.5 ft) that the curves begin to depart from the long-term average. These differences provide a stark reminder of the current level of risk facing many oceanfront property owners, particularly given that many of the beaches in Tillamook County have not recovered from the effects of past storms and hence the ability of the beaches to provide a buffering capacity against high waves is presently reduced. To that end, a worst-case scenario facing coastal communities in Tillamook County is a repeat of the 1998-1999 wave conditions, which would almost certainly result in significant damage to oceanfront property and infrastructure. Given the erosion responses observed in 2007-2008, and the state of the beach today, the prognosis remains bleak for beaches in Tillamook County for the immediate future.

CONCLUSIONS

This report has presented the results of a collaborative effort by DOGAMI and the DLCD to maintain a comprehensive beach monitoring program on the Oregon coast, with the surveys used to document short- and long-term responses of the beaches. The establishment and repeated monitoring of beach and shoreline observing systems such as the those established at Rockaway, Neskowin, the Clatsop Plains and, more recently, in the Newport littoral cell, are capable of providing critical information to scientists and coastal resource managers concerning the response of Oregon's beaches to major storms, the effects of climate events such as the El Niño Southern Oscillation (ENSO) phenomena, sediment transport patterns, variations in the beach sediment budget, and longer-term impacts associated with climate change and sea level rise.

A major aspect of this study and of a similar beach monitoring efforts underway on the Oregon coast (http://www.oregongeology.org/sub/nanoos1/index.htm) is that as the beach survey data are collected, the information is placed on DOGAMI's website for rapid access and viewing by other state agency officials, researchers, and the public at large. This approach has received considerable support and is rapidly gaining ground with members of the geotechnical community, who are beginning to use the measured information in their studies. In this respect alone, the beach monitoring effort has begun to pay off: officials are now able to respond to various beach erosion issues on the basis of on sound scientific information.

Our beach monitoring efforts completed thus far along the Rockaway and Clatsop littoral cell have identified a number of interesting aspects of large-scale beach responses:

- The cumulative effect of the 1997-1998 and 1998-1999 winters resulted in extensive erosion along the Rockaway littoral cell and reflects some of the largest erosion responses observed on the Oregon coast. The degree of change observed and the level of beach rebuilding that has taken place since then varies along the shore.
    - Erosion continues to plague much of the Rockaway subcell, which has continued to recede landward up to the present. The area presently experiencing the highest beach erosion changes is occurring north of Tillamook Bay and south of the Rockaway High School;
    - North of Rockaway High School and south of the Nehalem jetties, beaches have been slowly gaining sand and, hence, are gradually rebuilding following the extreme storms of the late 1990s.
    - Erosion continues to affect the southern half of Bayocean Spit, while the northern third of the spit has effectively been rebuilt and is now beginning to prograde (advance) seaward;
    - Similarly, erosion continues to plague the southern half of Nehalem Spit, while the northern third has gained some sand.
- The beaches along the Rockaway littoral cell remain in a state of net deficit compared to 1997, with the loss of sand for the period 1997–2002 estimated to be about 1,439,600 m^3 (1,883,000 yd^3). Given that much of the Rockaway subcell has continued to erode and lose sand, we estimate that as of March 2008 the net sand loss from the cell is likely to be on the order of 2 million cubic meters of sand (2.6 million cubic yards). Whether the beaches recover fully and how long it takes remain important scientific and management questions, which in time will be answered by continued beach monitoring.
- Post-storm recovery has been slow, limited to the lower beach face, and restricted to parts of Bayocean Spit, Nedonna Beach, and at the north end Nehalem Spit. The lack of significant sand accumulation high on the beach face in recent years suggests that the present climate may not be conducive for transporting sand landward from the beach face.
- In contrast to the Rockaway cell, measured beach changes on the Clatsop Plains indicate that although this section of shore was also affected by the extreme storms of the late 1990s, the degree of impact was much less; beaches fully recovered within a matter of 1 to 2 years. The one exception are those shoreline changes taking place at the north end of the subcell and just south of the south jetty. Repeated beach surveys at the East-jetty profile site has revealed that the beach has

been slowly eroding landward. Given its narrow foredune width, it is likely that parts of this dune system could be breached in the near future.

- Beach monitoring on the Clatsop Plains indicates that the main foredune has steadily gained sand over the past several years. We estimate that the net sediment volume gain for the period 1997 to 2008 is about 3.4 million cubic meters (4.5 million cubic yards) of sand.
- The 2007-2008 winter caused severe erosion at selected sites in the Rockaway subcell (south end of the cell) and north of the town of Rockaway; erosion and damage to facilities at Cape Lookout State Park (including significant damage to the dynamic revetment constructed there to protect the park); damage to riprap revetments at multiple locations on the north coast but most notably at Neskowin; and exhumed cannons at Cannon Beach and a boat near Coos Bay. In the majority of the cases, erosion was enhanced due to the formation of rip embayments in those areas, allowing waves to break close to the shore with little loss in the incident wave energy.
- An analysis of the wave and water levels associated with the 2007-2008 winter compared with the long-term average and past extreme winters indicates that the 2007-2008 winter was not as severe as past winter seasons (e.g., the 1998-1999 winter). Despite this difference, the 2007-2008 winter was characterized by one major storm and several minor events, which resulted in significant erosion at Neskowin, Cape Lookout State Park, and in Rockaway, with the degree of erosion accentuated due to the lack of any post-storm beach recovery at those sites. As a result, given that many beaches in Tillamook County have continued to see very little post-storm recovery in the intervening years between successive winters (i.e., beaches today are narrower and have less sand volume compared with beaches in the mid 1990s), the communities of Neskowin and Rockaway in particular remain at high risk of being affected by both coastal erosion and ocean flooding in the ensuing winter seasons.

As additional surveys are completed and analyzed, patterns of sand transport within the littoral cells will become clearer. Of importance, we now have a system in place that can be used to better document and understand the changing beach morphodynamics, including the tracking of large-scale sand movements within the cell, the effects of future storms, and any post-storm recovery. In time, such information can be used to further evaluate and refine coastal hazard “setback” zones that are being developed by DOGAMI.

Acknowledgments.

Funding for this study was kindly provided by the Department of Land Conservation and Development through their Coastal Management Program (DLCD #PS07028), the Northwest Association of Networked Ocean Observing System (NANOOS contract #449958), and the Oregon Parks and Recreation Department (OPRD contract #07-372). The authors acknowledge the assistance of Steve Williams (DLCD) throughout this study. We are also grateful to Paul Komar (Oregon State University) and Ian Madin (DOGAMI) for their constructive comments in developing the final report.

REFERENCES

Allan, J. C., and Hart, R., 2005, A geographical information system (GIS) data set of beach morphodynamics derived from 1997, 1998, and 2002 lidar data for the central to northern Oregon coast, Open-File Report O-05-09: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 16 p. + data on CD-ROM.

Allan, J. C., and Hart, R., 2007, Assessing the temporal and spatial variability of coastal change in the Neskowin littoral cell: Developing a comprehensive monitoring program for Oregon beaches Open-File Report O-07-01: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 27 p.

Allan, J. C., and Komar, P. D., 2000, Are ocean wave heights increasing in the eastern North Pacific?: EOS, Transactions of the American Geophysical Union, v. 81, no. 47, p. 561 and 566-567.

Allan, J. C., and Komar, P. D., 2005, Morphologies of beaches and dunes on the Oregon coast, with tests of the geometric dune-erosion model, Open-File Report O-05-08: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 34 p.

Allan, J. C., and Priest, G. R., 2001, Evaluation of coastal erosion hazard zones along dune and bluff backed shorelines in Tillamook County, Oregon: Cascade Head to Cape Falcon, Open-File Report O-01-03: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 126 p.

Allan, J. C., Komar, P. D., and Priest, G. R., 2003, Shoreline variability on the high-energy Oregon coast and its usefulness in erosion-hazard assessments: Journal of Coastal Research, p. 83–105.

Allan, J. C., Komar, P. D., and Priest, G. R., 2004, Coast hazards and management issues on the Oregon coast: Coastal workshop, Lincoln City, Oregon, field trip to the Oregon coast, 29 April 2004, Open-File Report O-04-18: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 26 p.

Bernstein, D. J., Freeman, C., Forte, M. F., Park, J.-Y., Gayes, P. T., and Mitasova, H., 2003, Survey design analysis for three-dimensional mapping of beach and nearshore morphology, *in* Davis, R. and Howd, P., Coastal Sediments 03: American Society of Civil Engineers, St. Petersburg, Fla., 12 p.

Bradbury, A. P., 2007, Application of a large-scale, long-term, regional coastal observation network to coastal management on the English-channel coast, Proceedings of Coastal Zone 07, Portland, Oregon, July 22-26, 2007, 5 p. Web: http://www.csc.noaa.gov/cz/2007/Coastal_Zone_07_Proceedings/PDFs/Tuesday_Abstracts/2527.Bradbury.pdf

Cooper, W. S., 1958, Coastal sand dunes of Oregon and Washington: Geological Society of America. Memoir 72, p. 169.

Dicken, S. N., Johannessen, C. L., and Hanneson, B., 1961, Some recent physical changes of the Oregon coast: Eugene, Oreg., University of Oregon, Department of Geography, 151 p.

Gayes, P. T., Balwin, W., Van Dolah, R. F., Jutte, P., Eiser, W. C., and Hansen, N., 2001, Systematic coastal monitoring: The S. Carolina coast (USA), *in* Proceedings of Coastal Dynamics, '01: ASCE, Lund, Sweden, p. 868–877.

Gelfenbaum, G., Sherwood, C. R., Peterson, C. D., Kaminsky, G. M., Buijsman, M. C., Twichell, D. C., Ruggiero, P., Gibbs, A. E., and Reed, C., 1999, The Columbia River cell: A sediment budget overview, *in* Proceedings of Coastal Sediments '99: Hauppauge, Long Island, New York, American Society of Civil Engineers, p. 1660–1675.

Komar, P. D., 1997, The Pacific Northwest Coast: Living with the shores of Oregon and Washington: Durham and London, Duke University Press, 195 p.

Komar, P. D., 1998, The 1997-98 El Niño and erosion on the Oregon coast: Shore & Beach, v. 66, no. 3, p. 33–41.

Morton, R. A., 1997, Gulf shoreline movement between Sabine Pass and The Brazos River, Texas: 1974 to 1996: Geological Circular 97-3: Austin Tex., Bureau of Economic Geology, The University of Texas at Austin, 46 p.

Morton, R. A., Leach, M. P., Paine, J. G., and Cardoza, M. A., 1993, Monitoring beach changes using GPS surveying techniques: Journal of Coastal Research, v. 9, no. 3, p. 702–720.

Office of Beaches and Coastal Systems (OBCS), 2001, Statewide coastal monitoring program: Florida Department of Environmental Protection Report, 7 p. Web: http://www.dep.state.fl.us/beaches/publications/pdf/monplan.pdf

Peterson, C. D., Darienzo, M. E., Hamilton, D., Pettit, D. J., Yeager, R. K., Jackson, P. L., Rosenfeld, C. L., and Terich, T. A., 1994, Beach-shoreline database, Pacific Northwest Region, USA, Open-File Report 0-94-2: Portland, Oreg., Oregon Department of Geology and Mineral Industries, 29 p.

Revell, D., Komar, P. D., and Sallenger, A. H., 2002, An application of lidar to analyses of El Niño erosion in the Netarts littoral cell, Oregon: Journal of Coastal Research, v. 18, no. 4, p. 792–801.

Revell, D. L., and Marra, J. J., 2002, An application of lidar to multiple scales of shoreline change in Oregon, *in* Ewing, L. and Wallendorf, L., eds., Solutions to Coastal Disasters '02: ASCE, San Diego, Calif., p. 596–610.

Ruggiero, P., and Voigt, B., 2000, Beach monitoring in the Columbia River littoral cell, 1997-2000, Publication No. 00-06-026: Olympia, Wash., Coastal Monitoring and Analysis Program, Washington Department of Ecology, 113 p.

Ruggiero, P., Komar, P. D., McDougal, W. G., and Beach, R. A., 1996, Extreme water levels, wave runup and coastal erosion, *in* Proceedings of the 25th Conference on Coastal Engineering: ASCE, Orlando, Fla., p. 2793–2805.

Ruggiero, P., Kaminsky, G. M., Gelfenbaum, G., and Voight, B., 2005, Seasonal to interannual morphodynamics along a high-energy dissipative littoral cell: Journal of Coastal Research, v. 21, no. 3, p. 553–578.

Shih, S.-M., and Komar, P. D., 1994, Sediments, beach morphology and sea-cliff erosion within an Oregon coast littoral cell: Journal of Coastal Resarch, v. 10, no. 1, p 144–157.

Stembridge, J. E., 1975, Shoreline changes and physiographic hazards on the Oregon coast: Eugene, Oreg., University of Oregon, Ph.D. thesis, 202 p.

Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H., 2006, Empirical parameterization of setup, swash, and runup: Coastal Engineering, v. 53, p. 573–588.

Trimble Navigation Limited, 2005, Trimble 5700 GPS Receiver Datasheet, 2 p. Web: http://www.trimble.com/5700_ds.asp

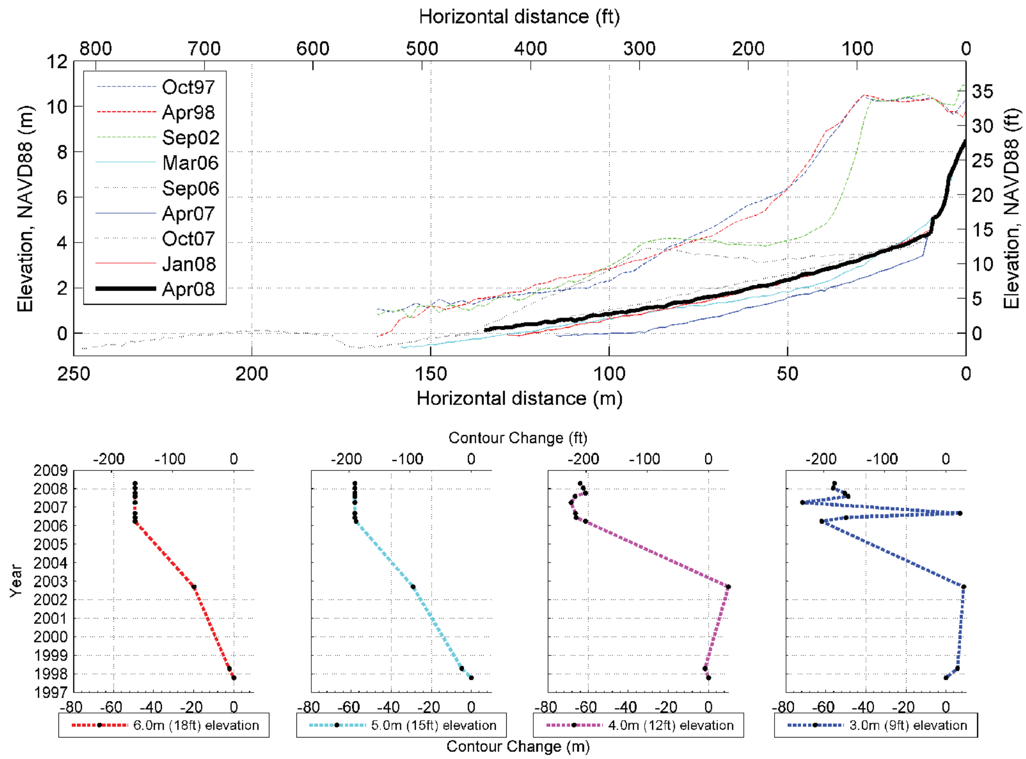
Woxell, L. K., 1998, Prehistoric beach accretion rates and long-term response to sediment depletion in the Columbia River littoral system, USA: Portland, Oreg., Portland State University, M.S. thesis, 206 p. Web: http://nwdata.geol.pdx.edu/Thesis/FullText/1998/Woxell/

APPENDIX A:
COMBINED BEACH PROFILE AND EXCURSION DISTANCE ANALYSIS "CONTOUR" PLOTS

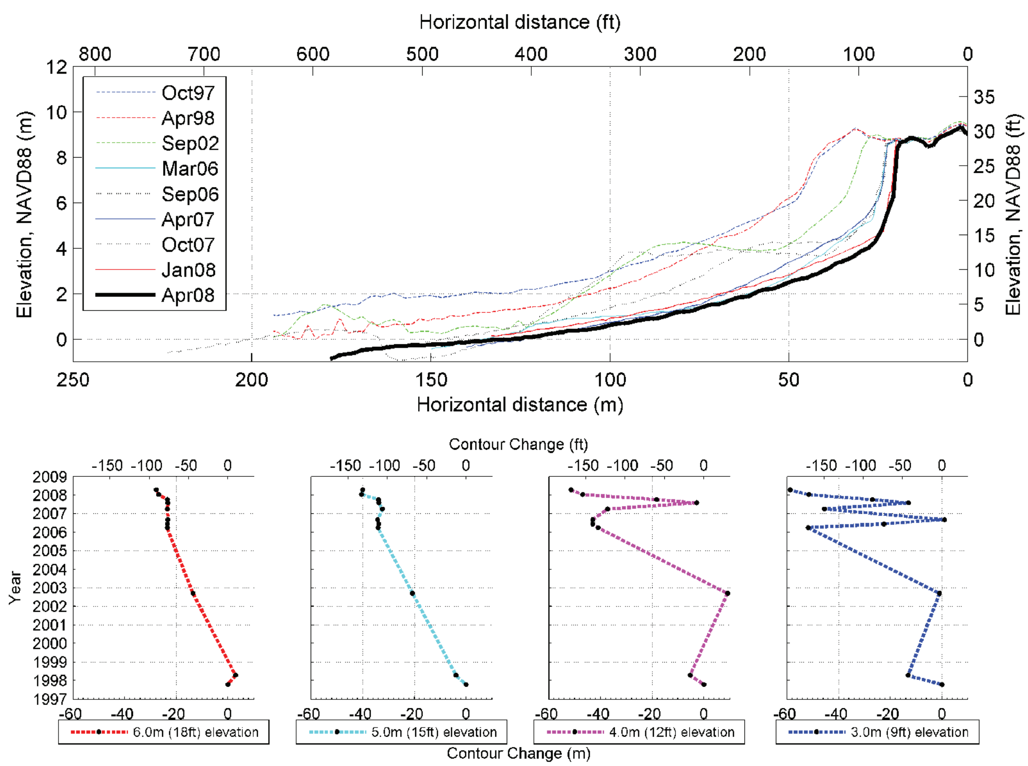
For each site shown, the upper plot is a conventional beach profile plot, which depicts the two-dimensional response of the beach to variations in the incident wave energy. The four lower plots reflect contours of greater interest due to their proximity to the dune toe (e.g., the 6.0-m and 5.0-m contours) or to Mean Higher High Water (MHHW) mark (e.g., the 3.0-m contour). The 1997 data have been used in the four lower plots as a baseline as this reflects the first comprehensive survey of the shape and position of the beach.

Neskowin sites

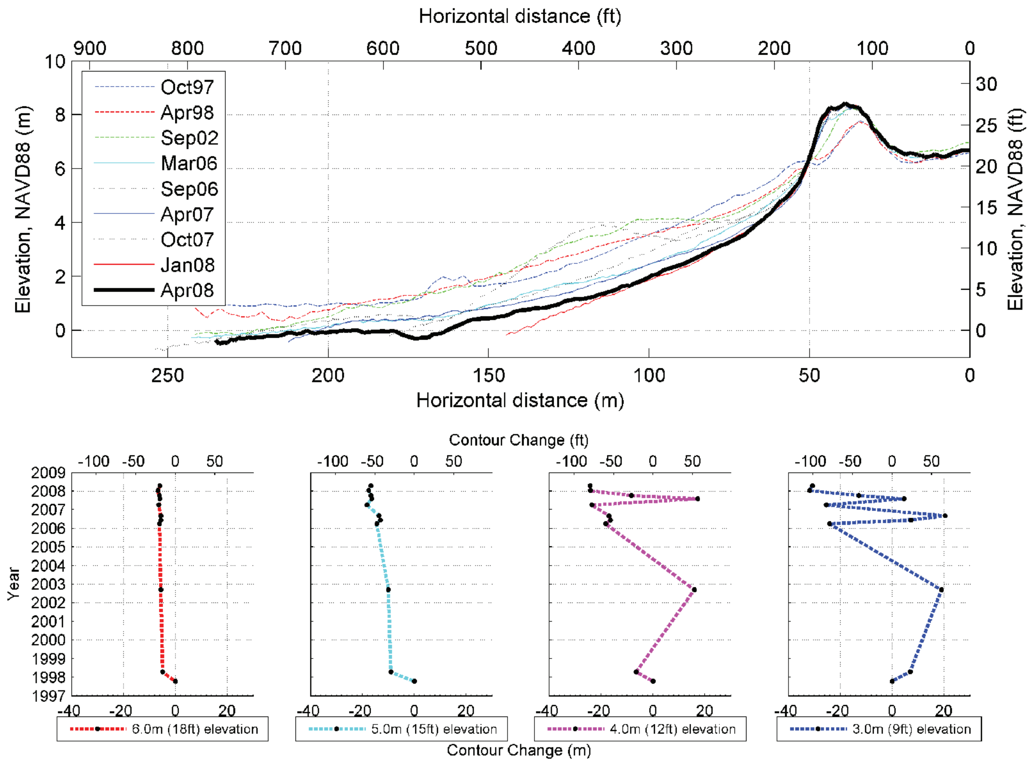
Nesk1:



Nesk2:

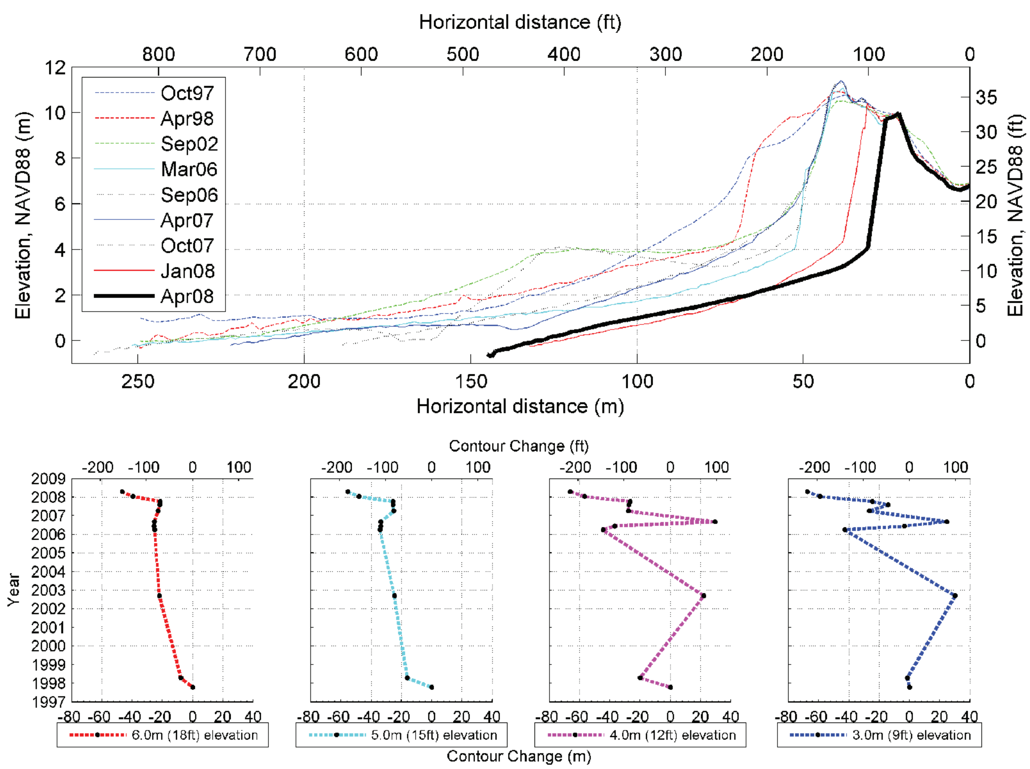


Nesk3:



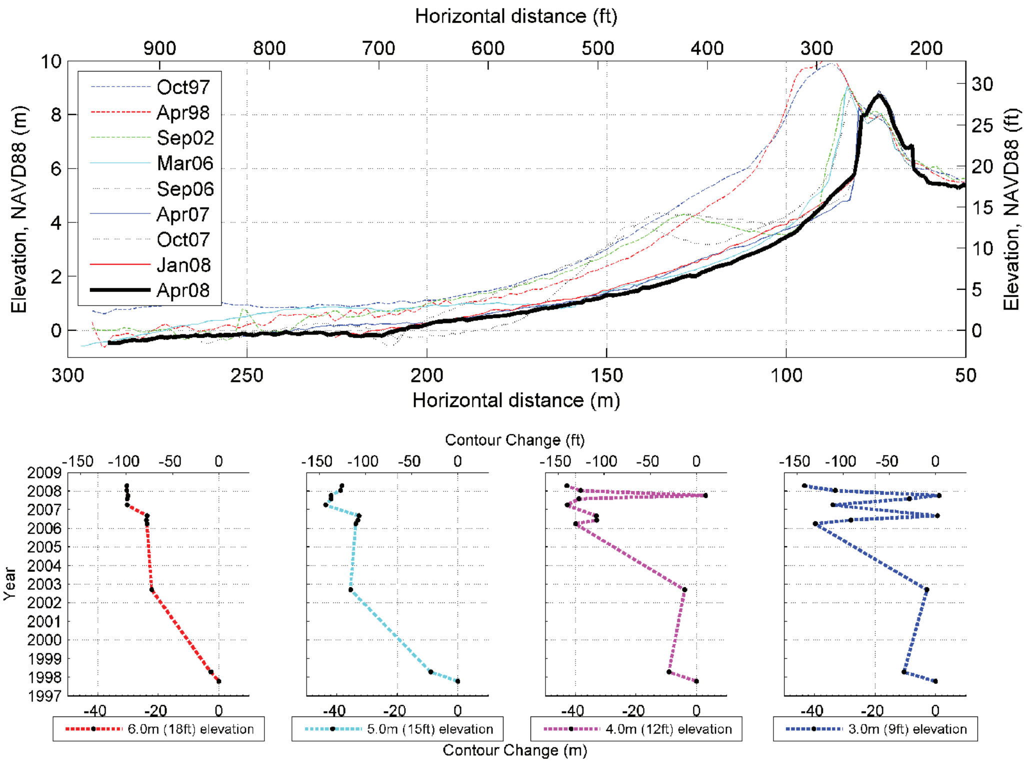
Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Contour Change (ft)
Year
Contour Change (m)
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation

Nesk4:



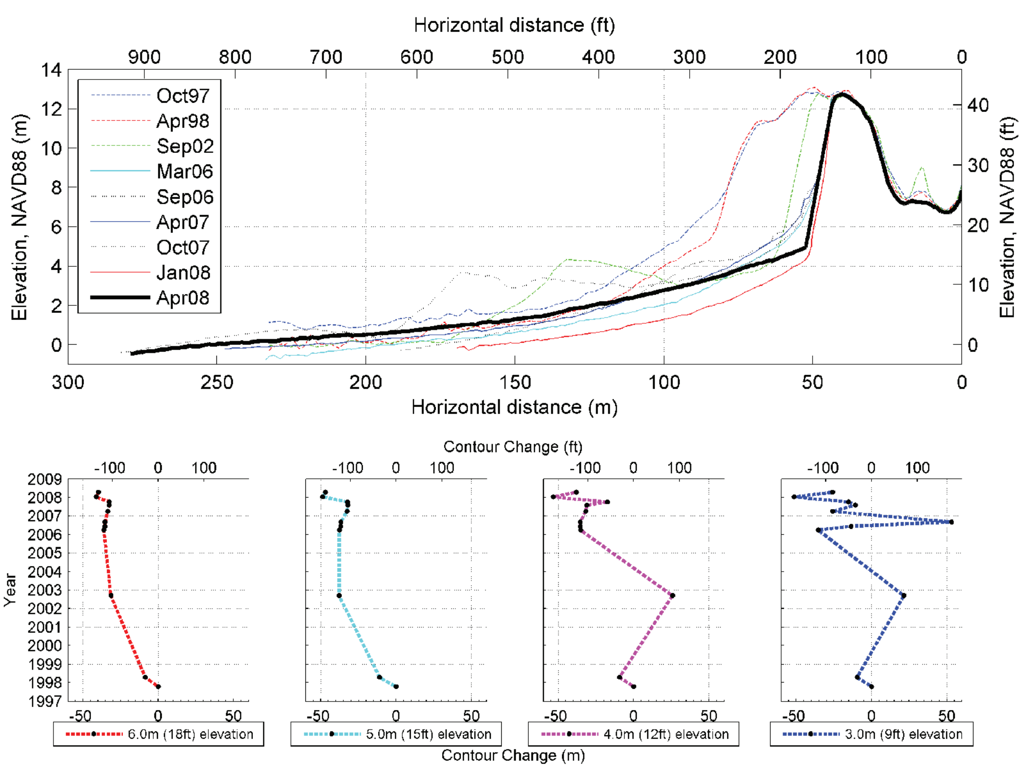
Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Contour Change (ft)
Year
Contour Change (m)
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation

Nesk5:



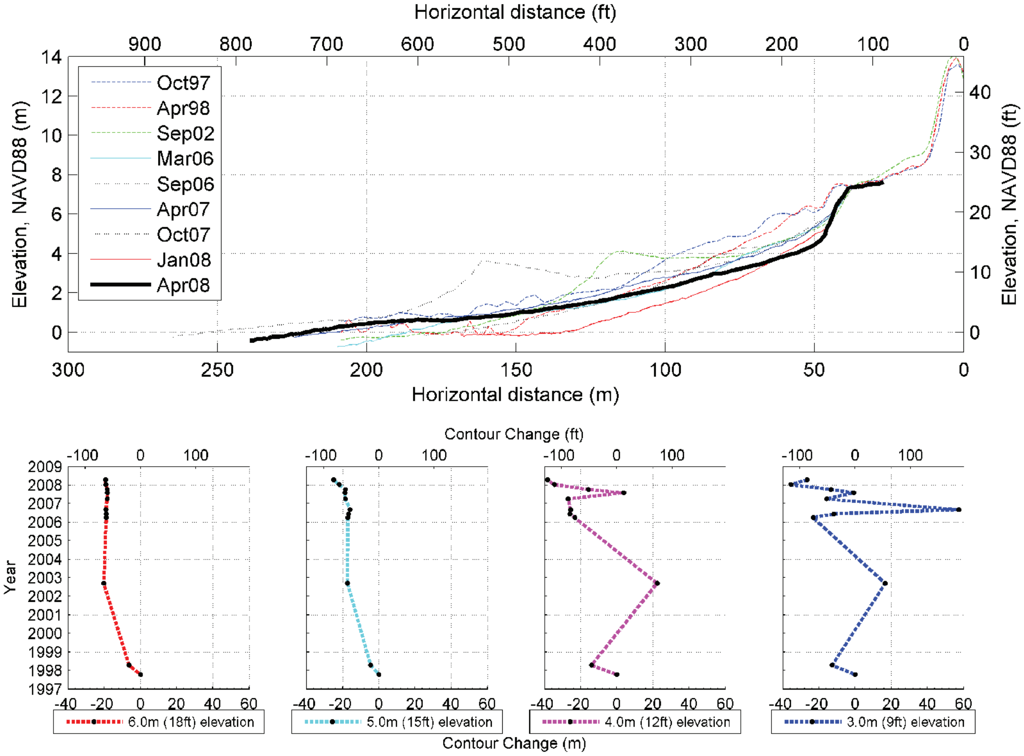
Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Nesk6:

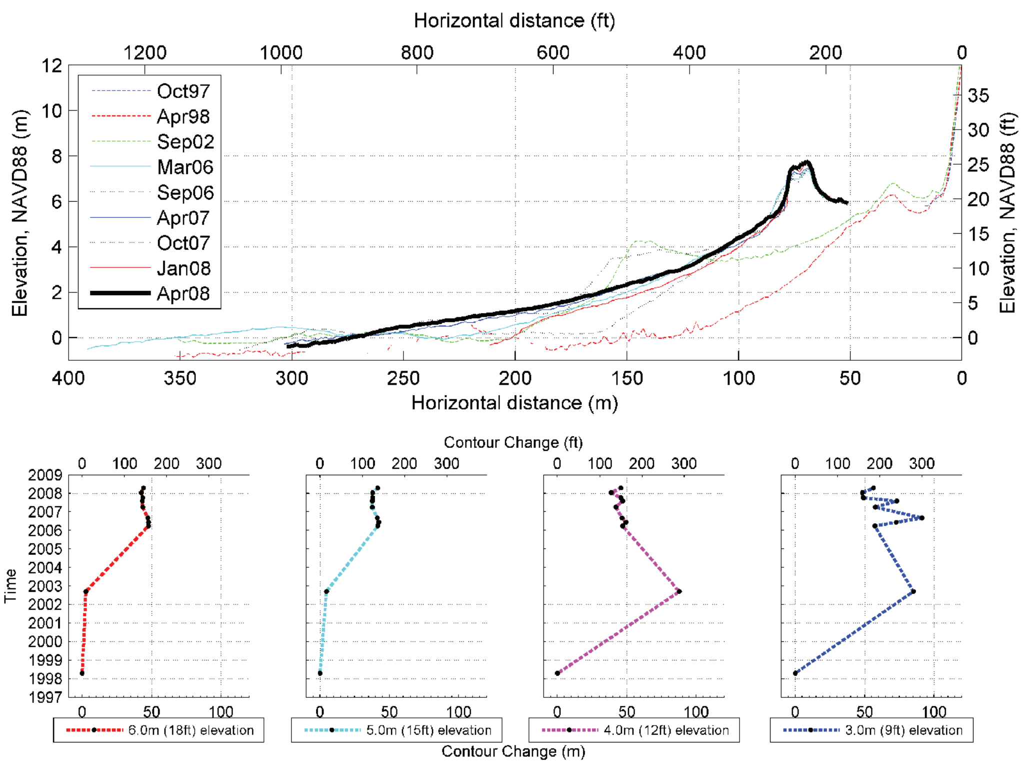


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

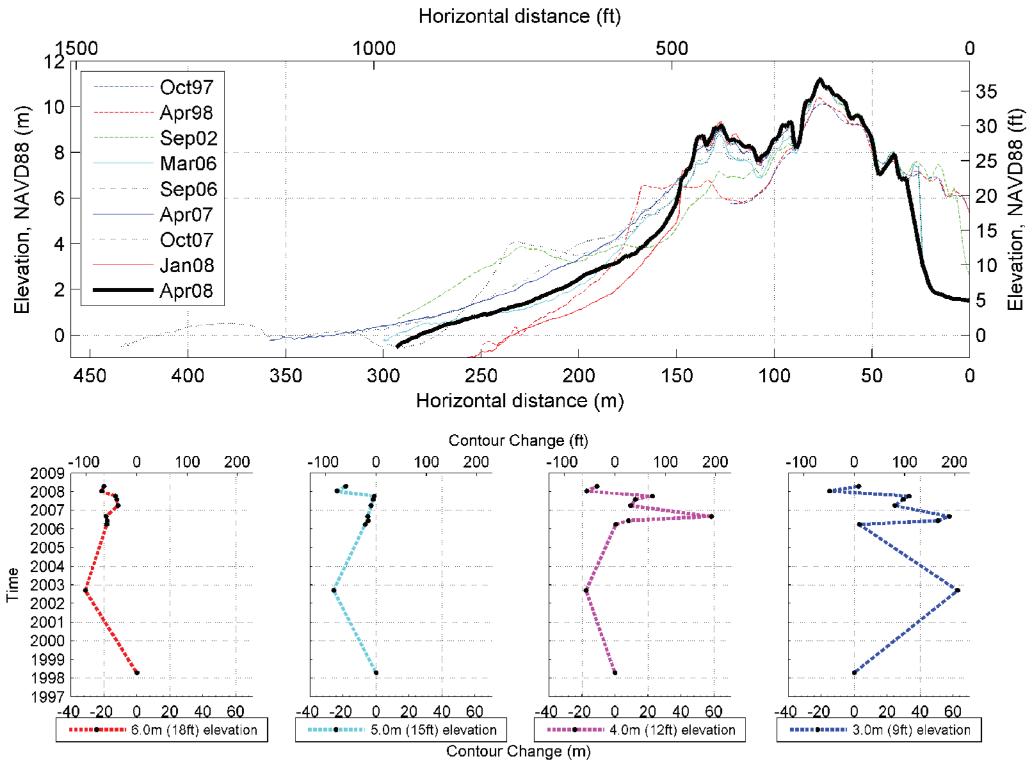
Nesk7:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

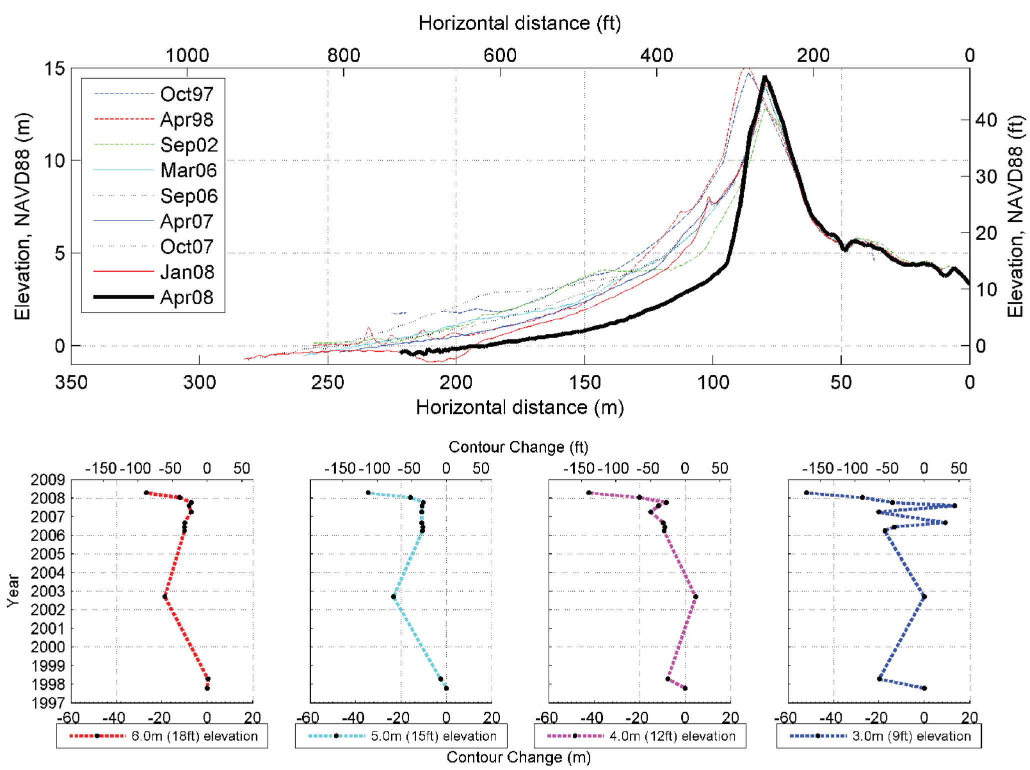
Nesk8:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
Horizontal distance (m)
Contour Change (ft)
Time
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

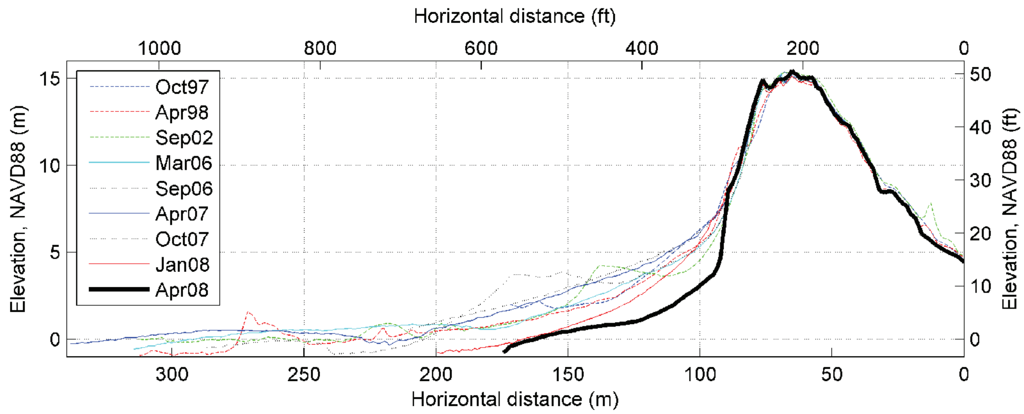
Nesk9:

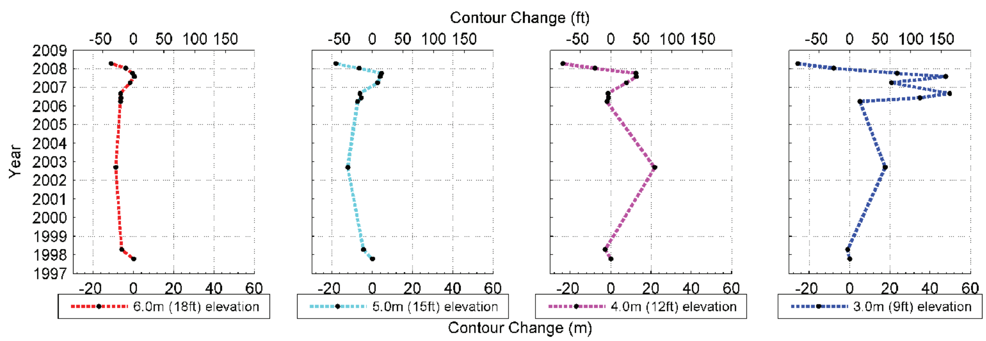


Nesk10:

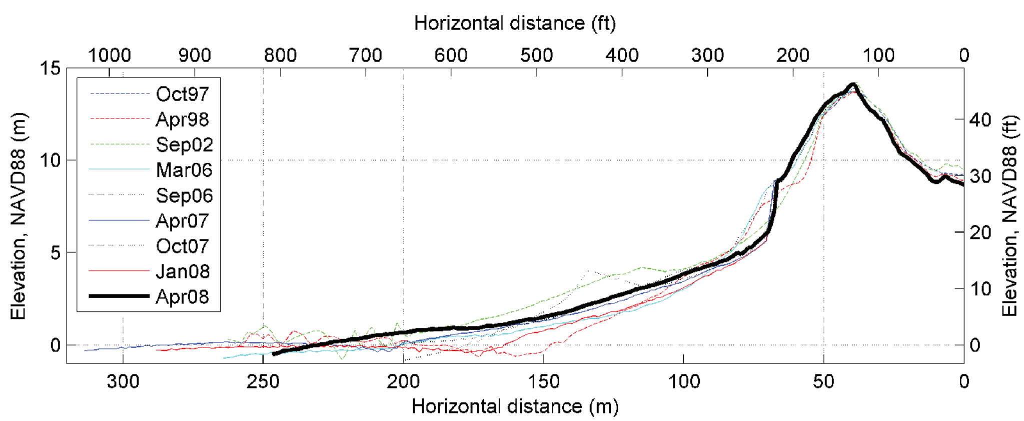


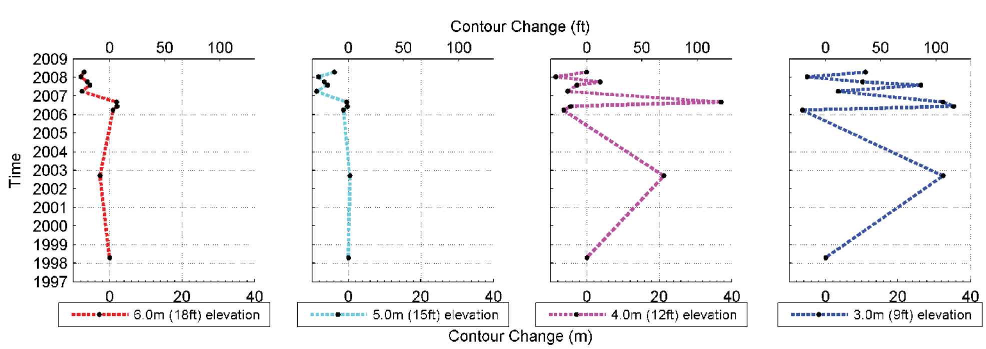
Nesk11:



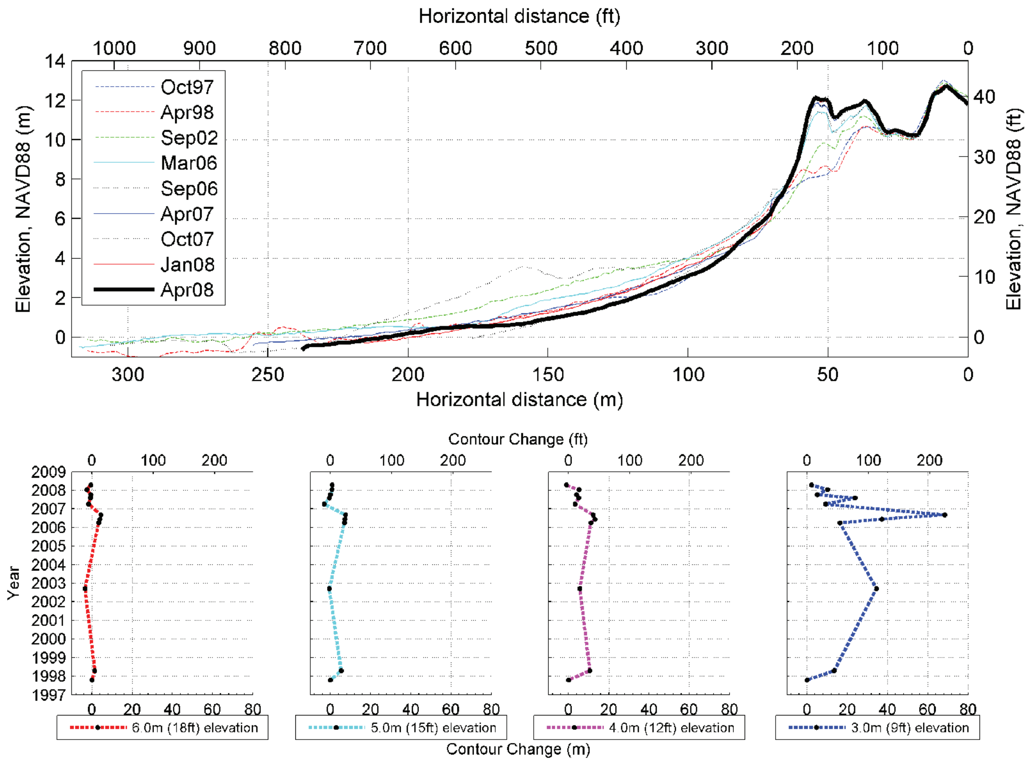


Nesk12:

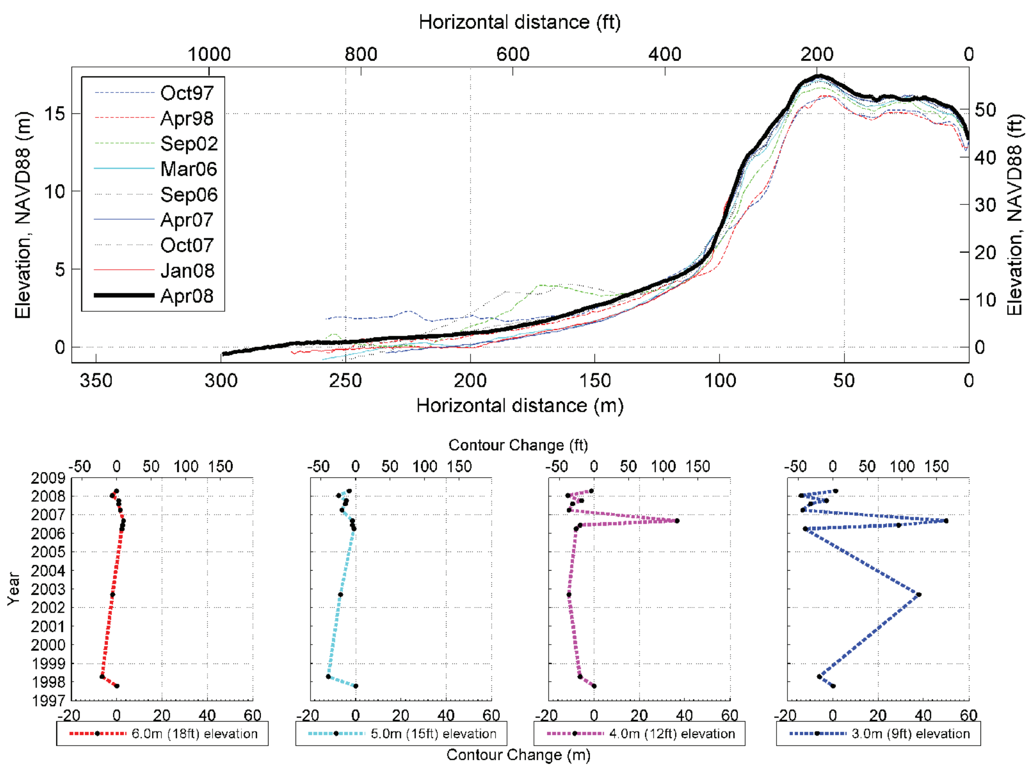




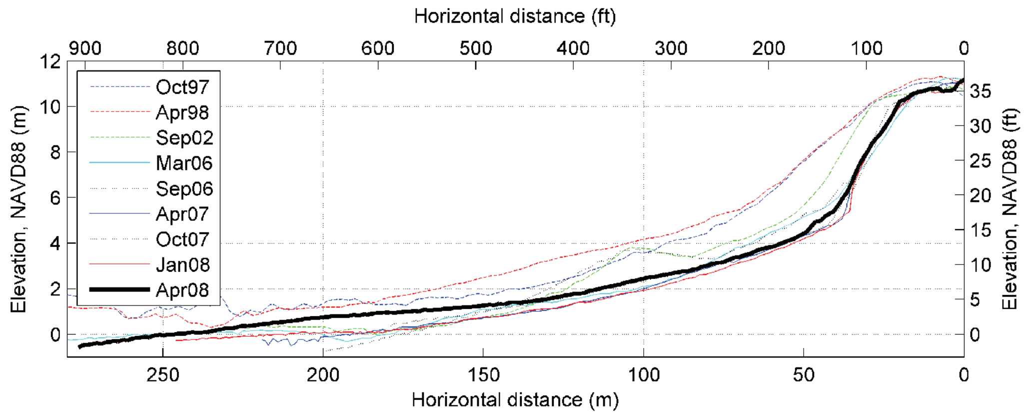
Nesk13:

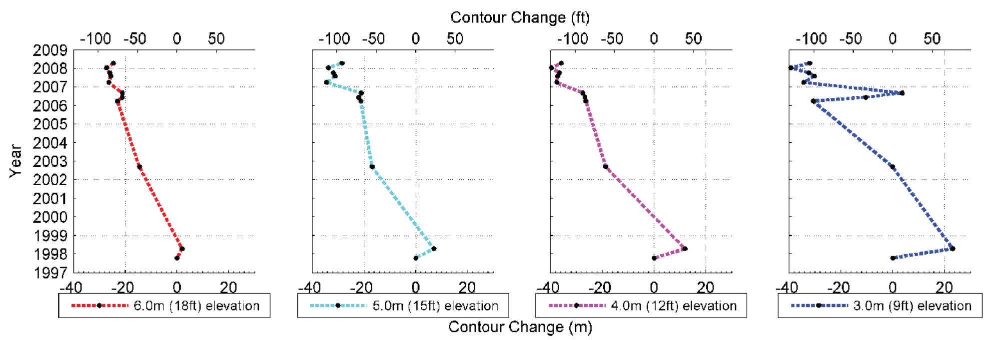


Nesk14:



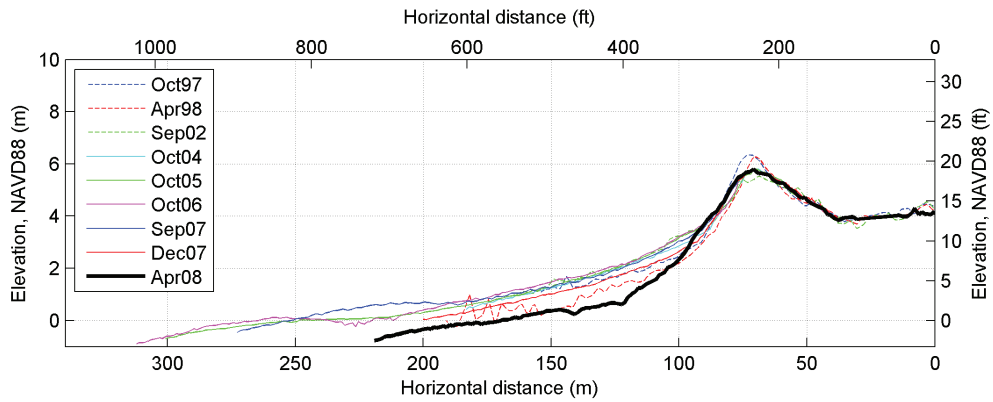
Nesk15:

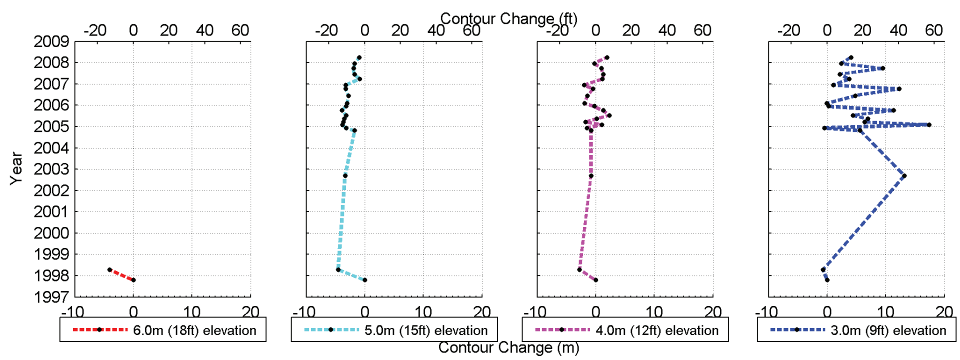

Horizontal distance (ft)
900 800 700 600 500 400 300 200 100 0
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Mar06
Sep06
Apr07
Oct07
Jan08
Apr08
250 200 150 100 50 0
Horizontal distance (m)


Contour Change (ft)
-100 -50 0 50
Year
2009 2008 2007 2006 2005 2004 2003 2002 2001 2000 1999 1998 1997
-40 -20 0 20
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

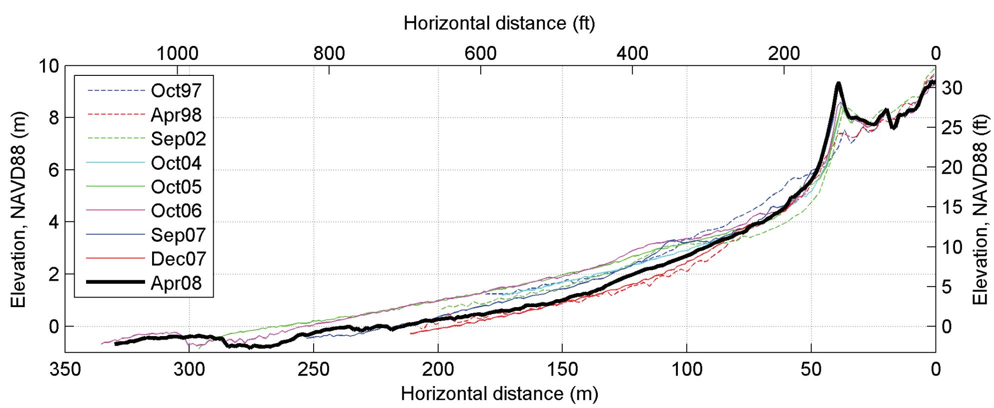
Bayocean Spit sites

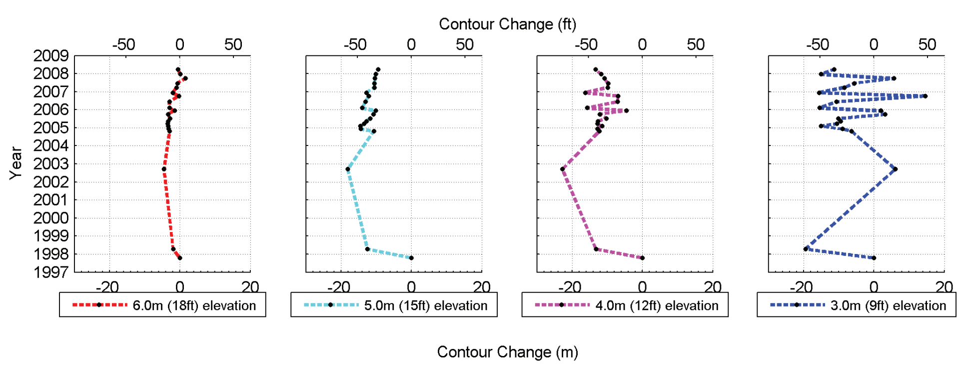
Bay1:



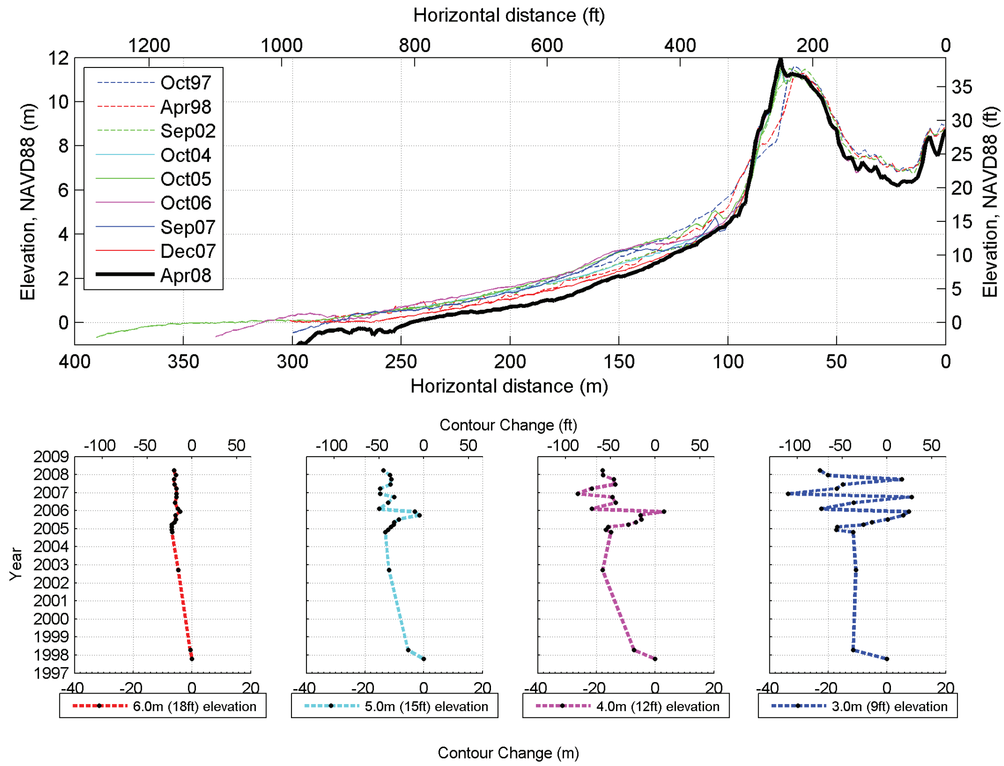


Bay2:

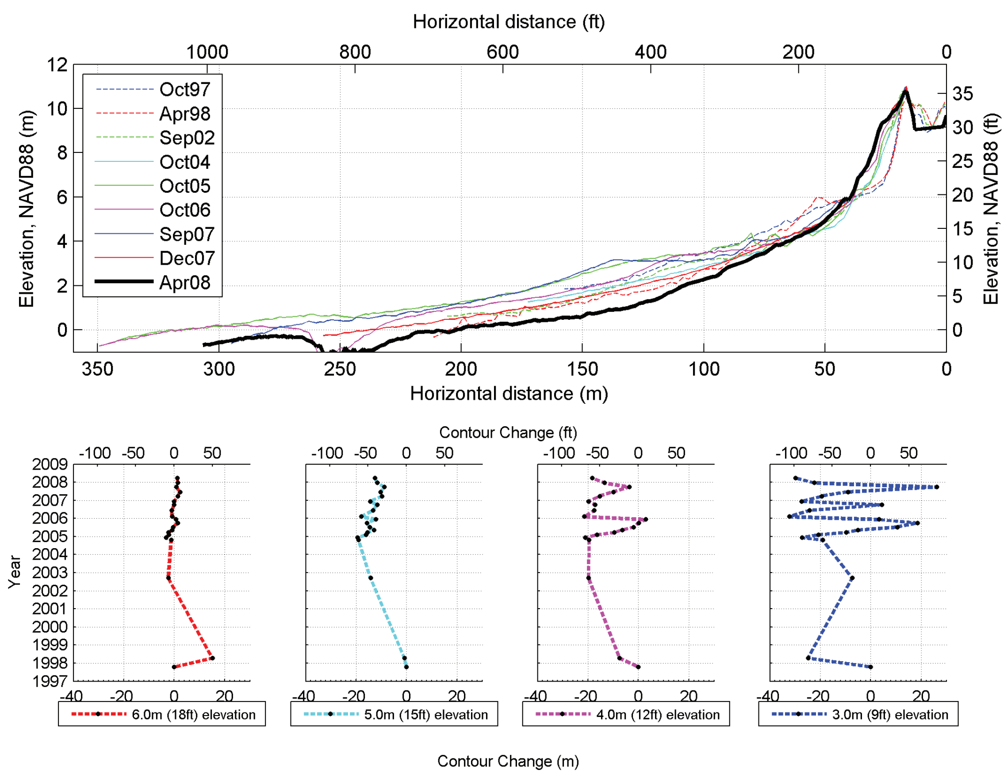




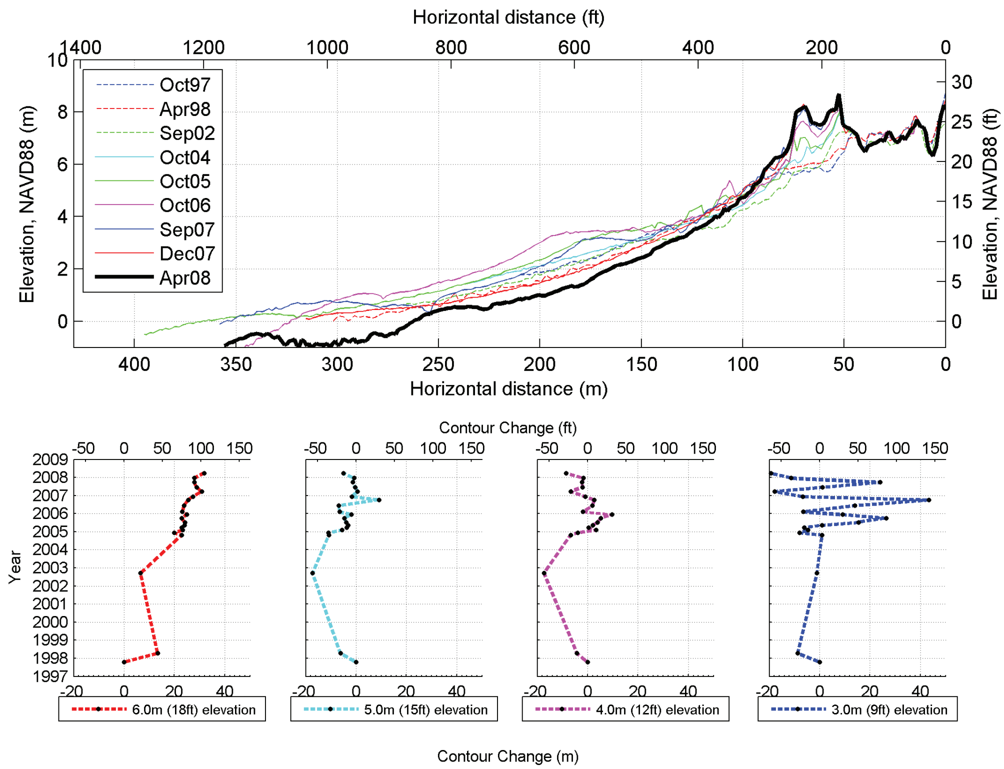
Bay3:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

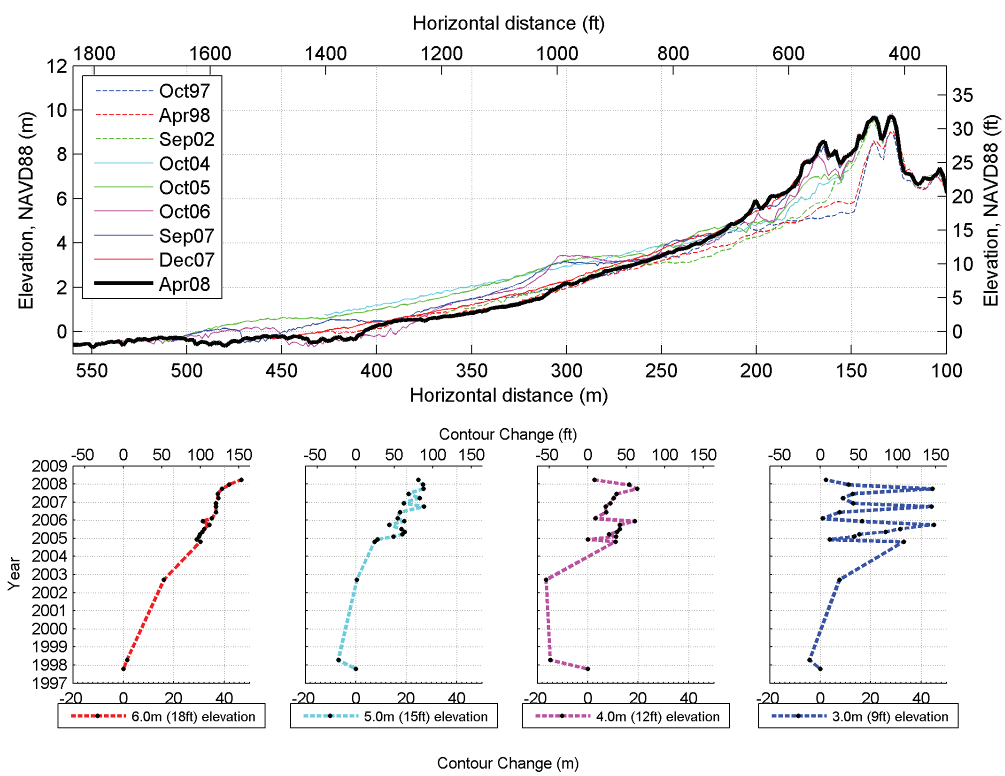
Bay4:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

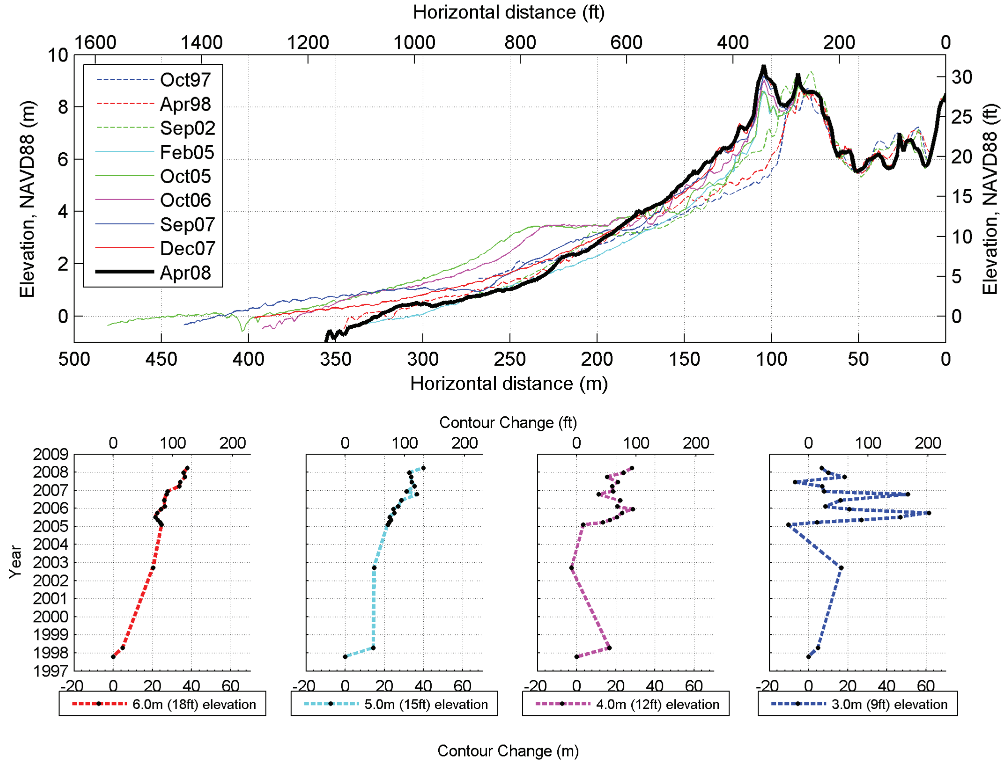
Bay5:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Bay6

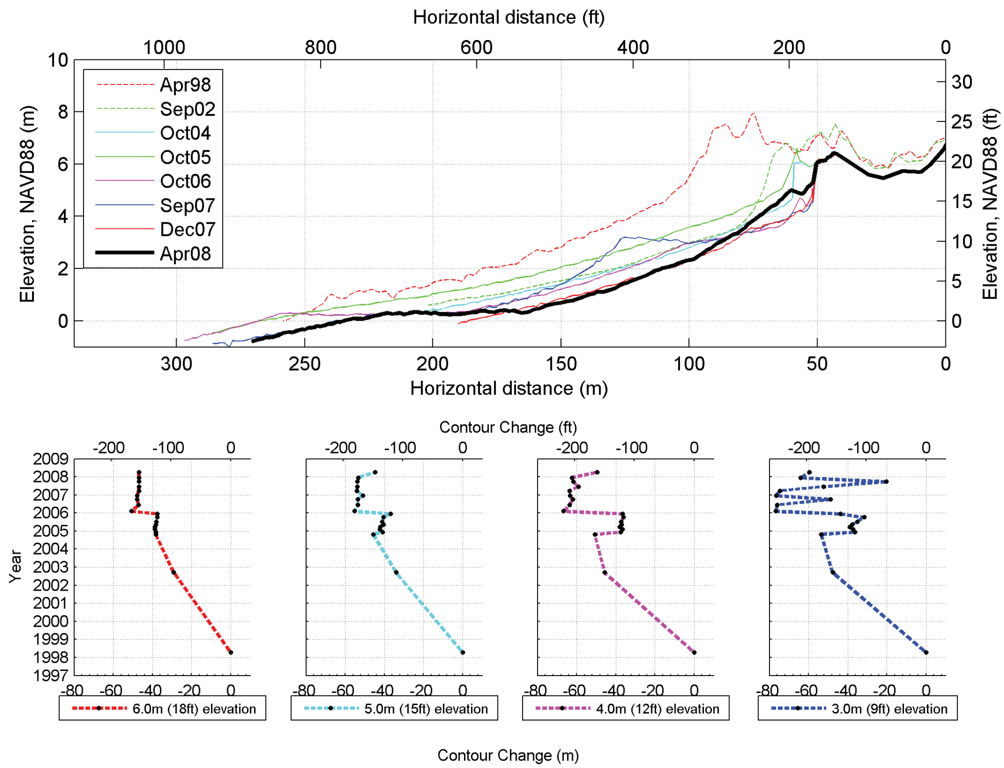

Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Bay7

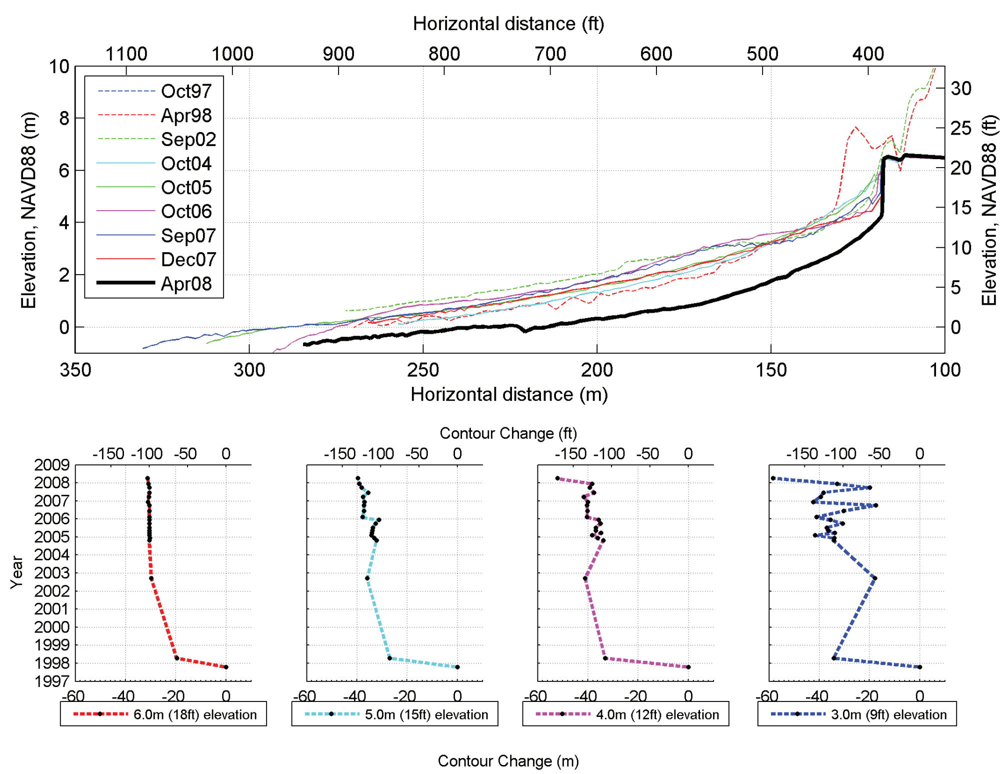

Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Feb05
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Rockaway sites

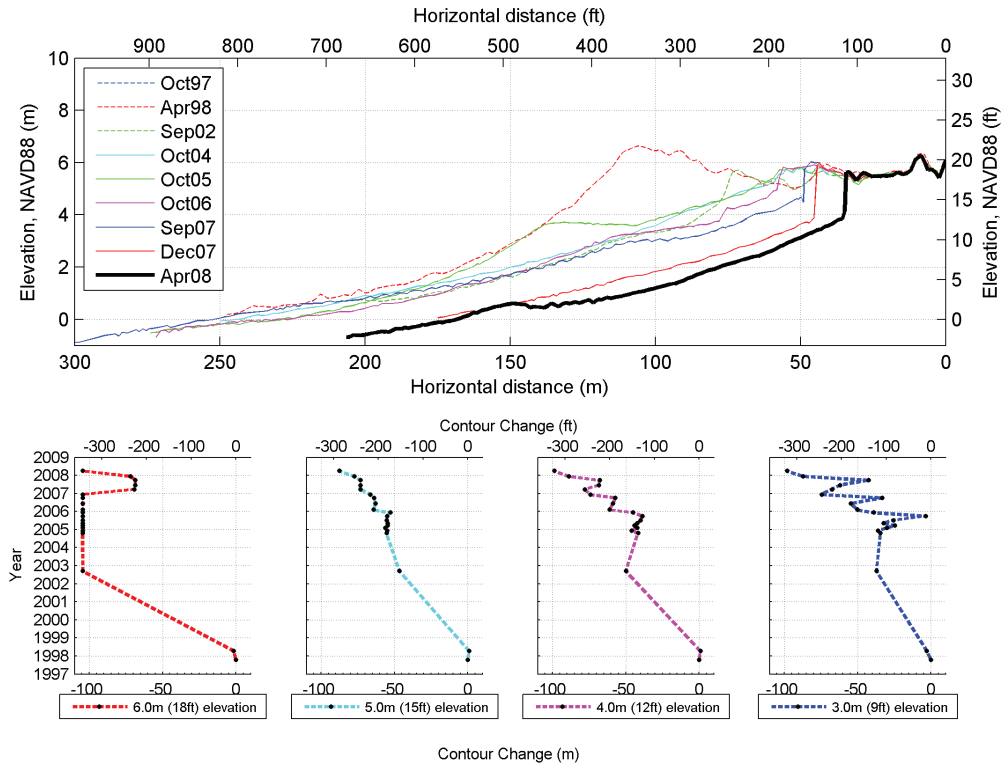
Rck1:



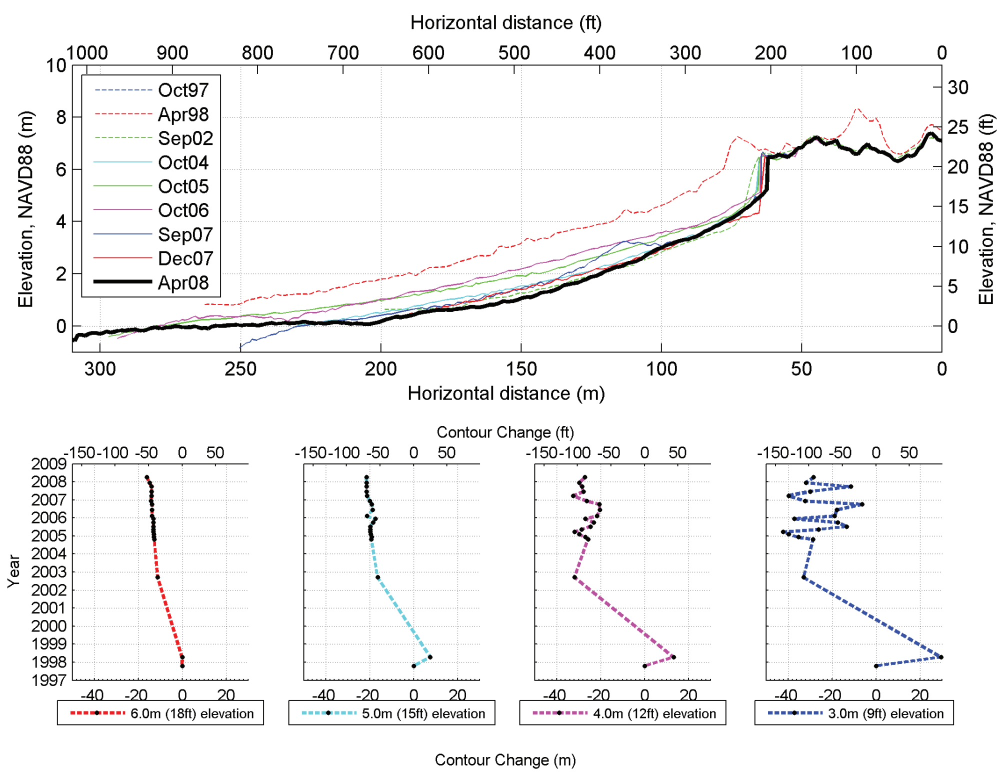
Rck2:



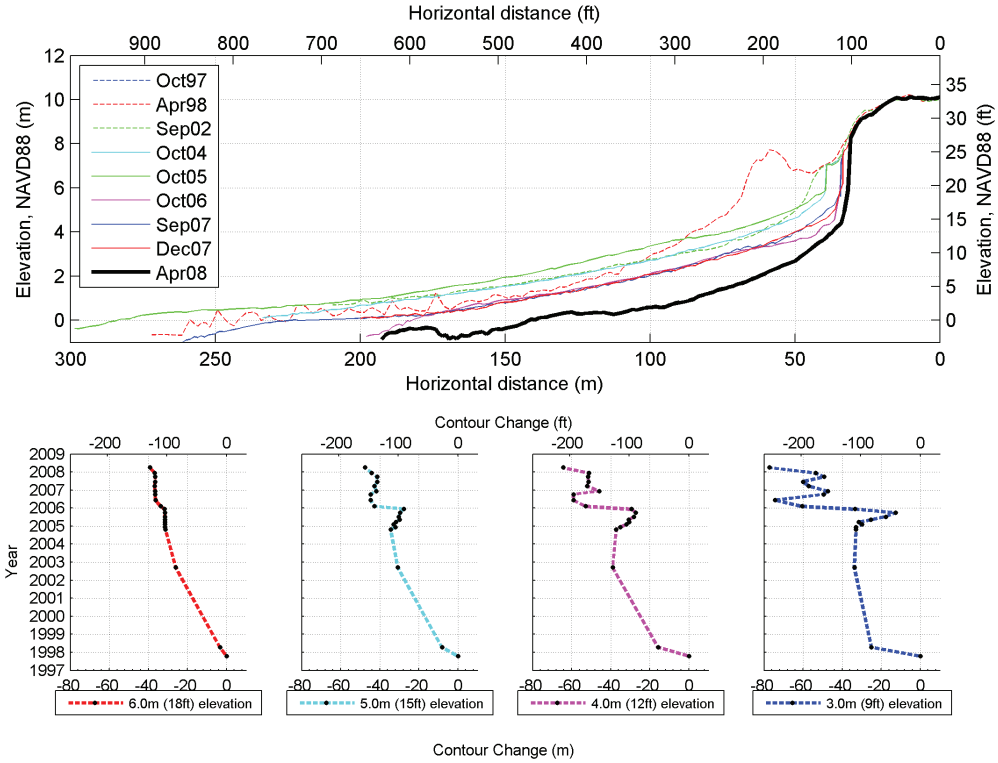
Rck3:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

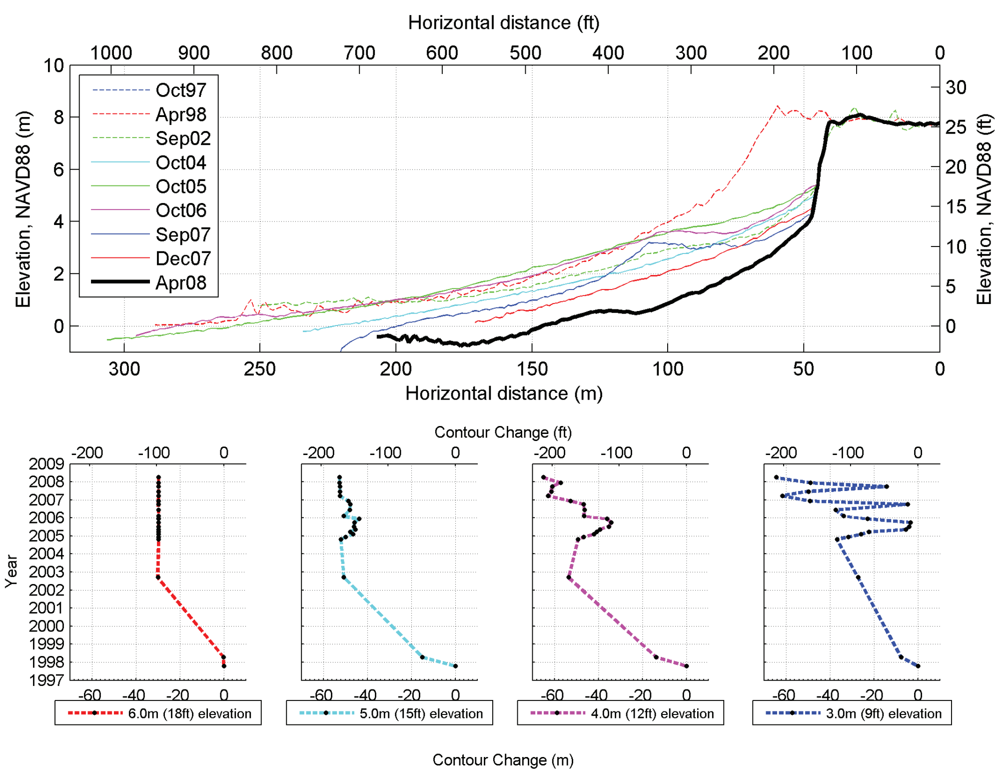
Rck4:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

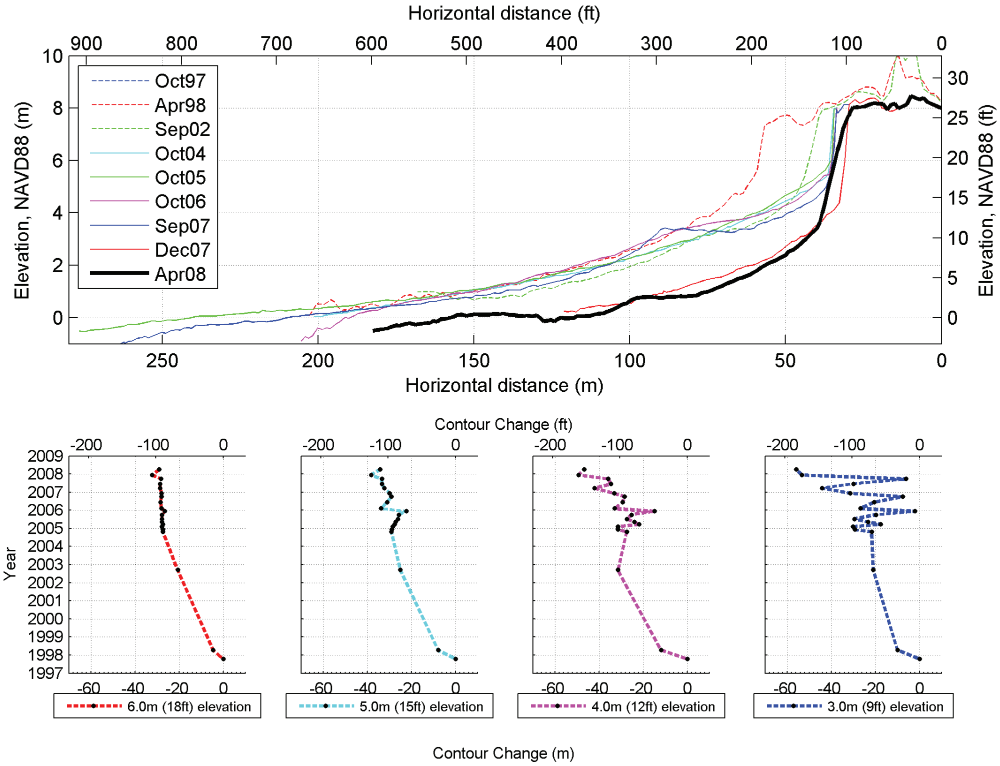
Rck5:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

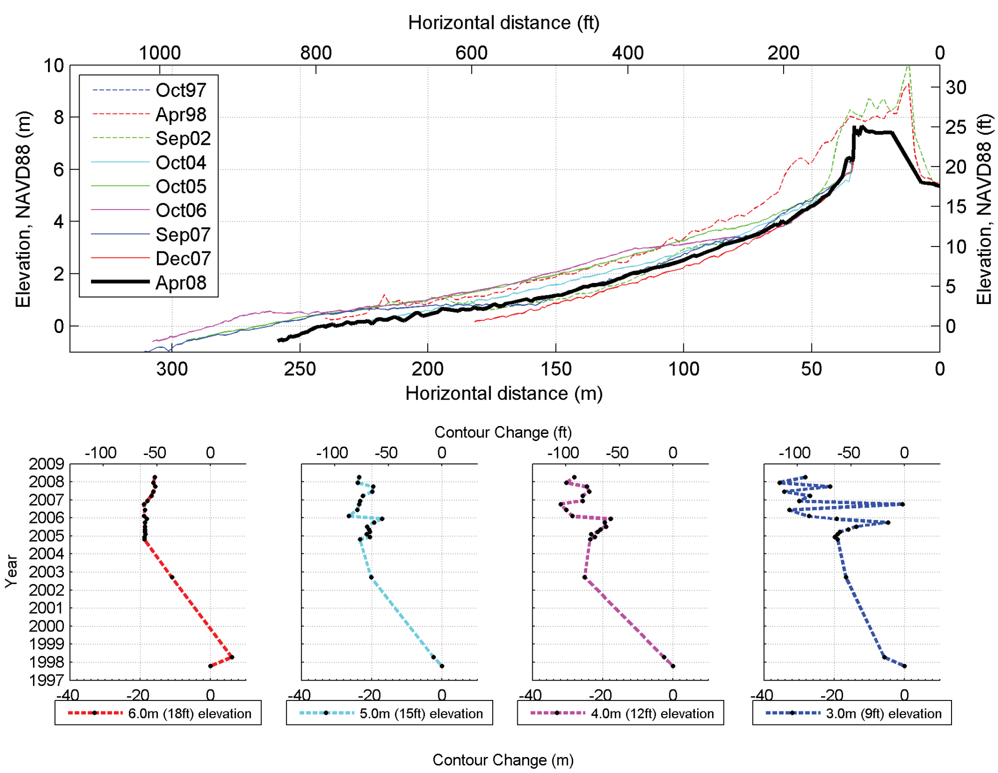
Rck6:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

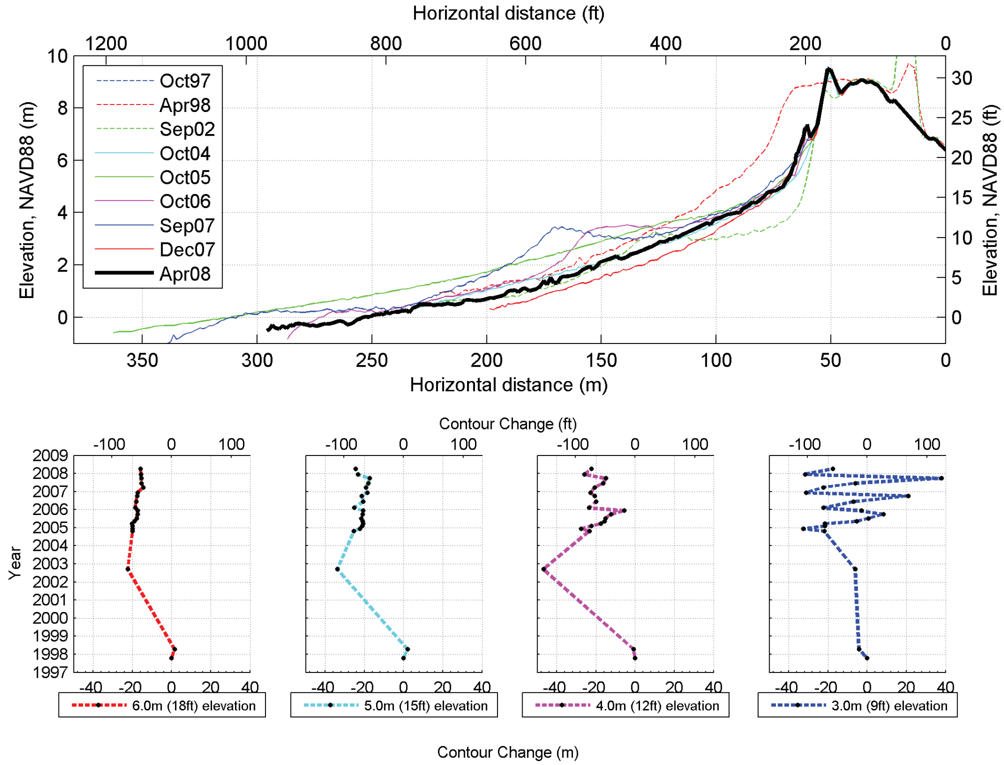
Rck7:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

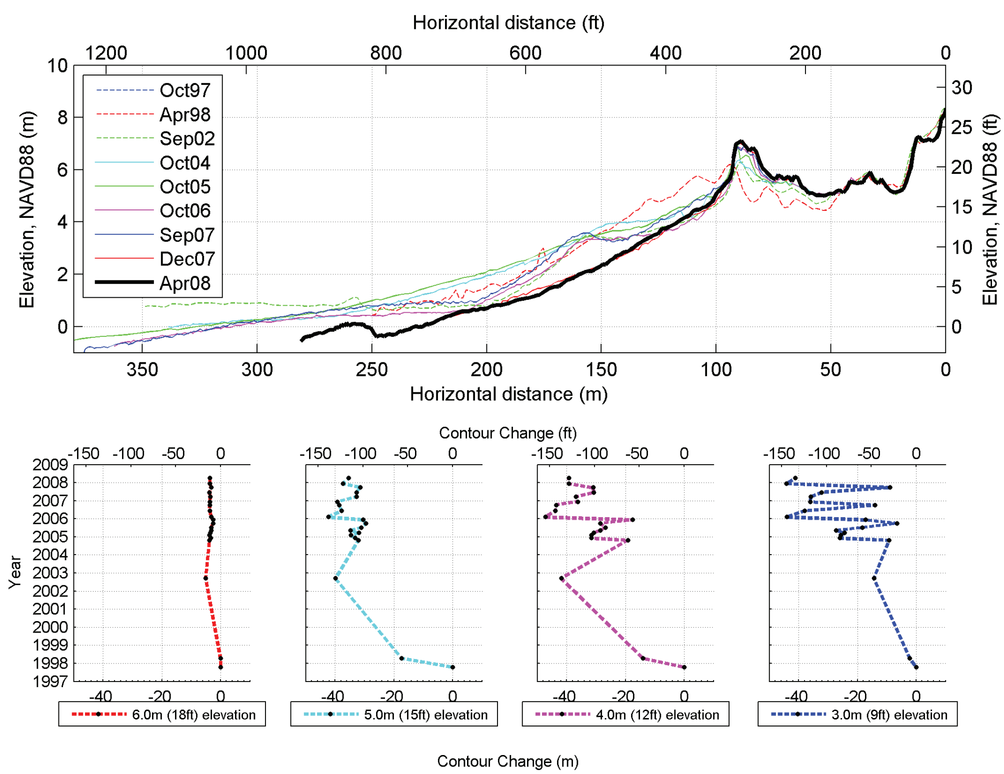
Rck8:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Rck9:

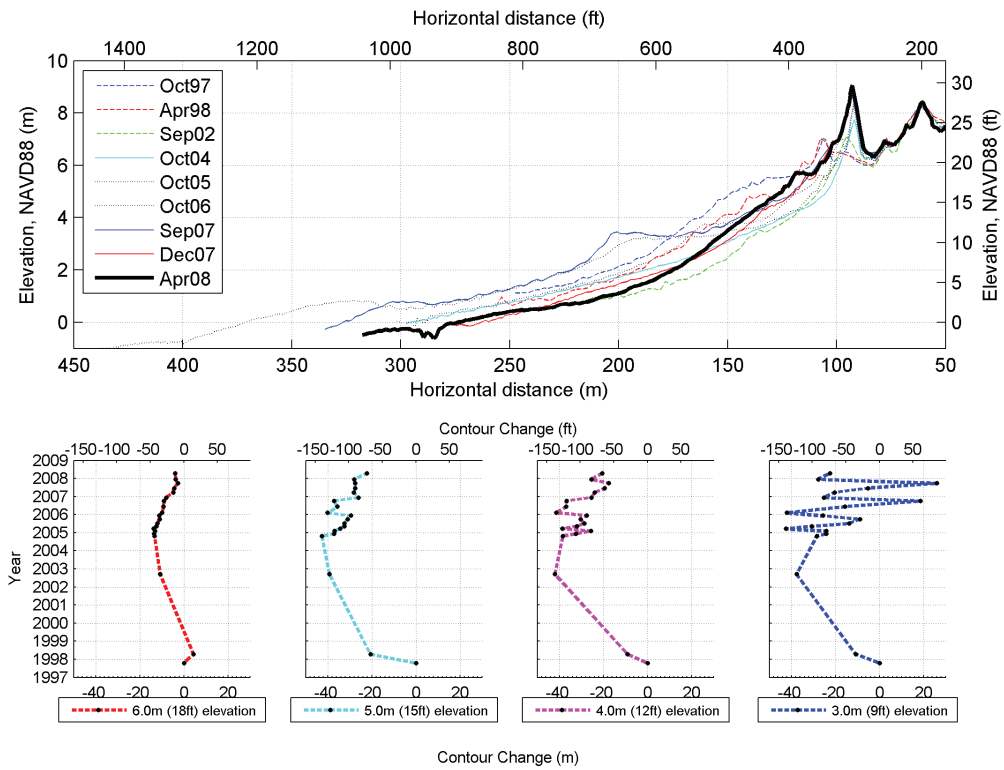

Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Rck10:

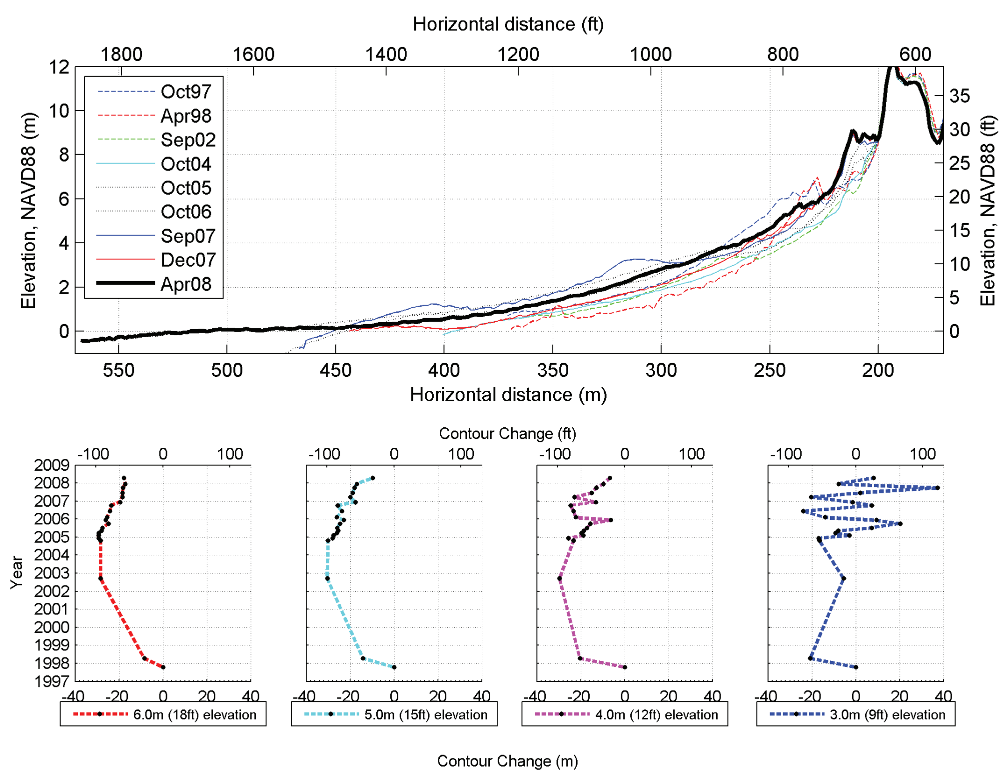

Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Nehalem sites

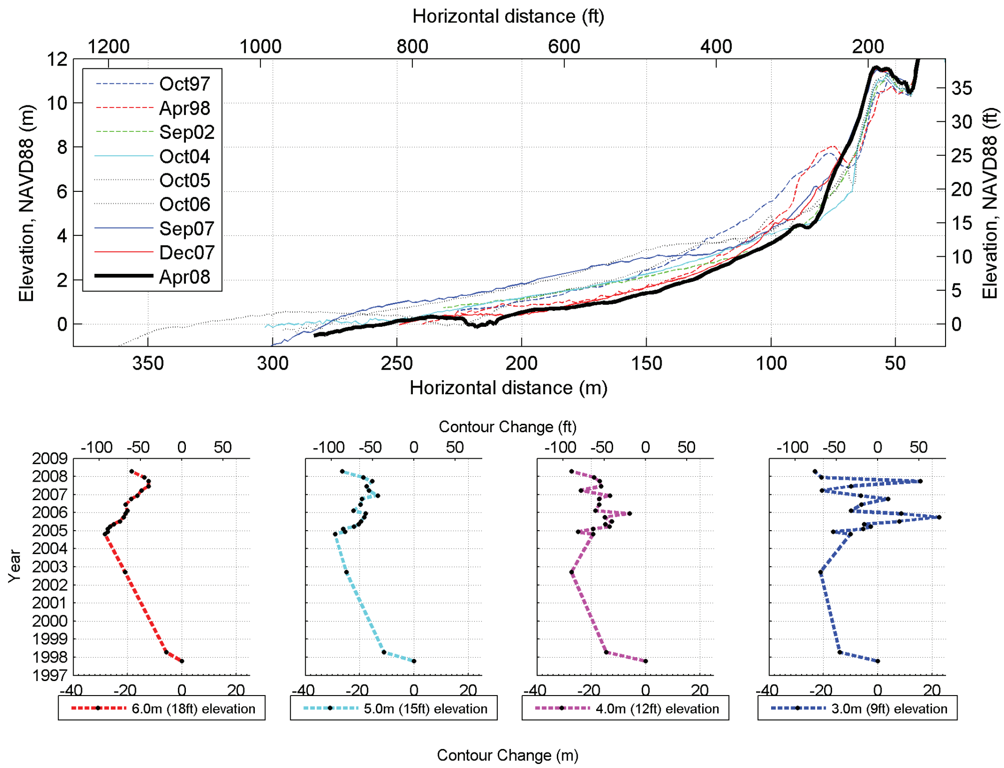
Neh1:



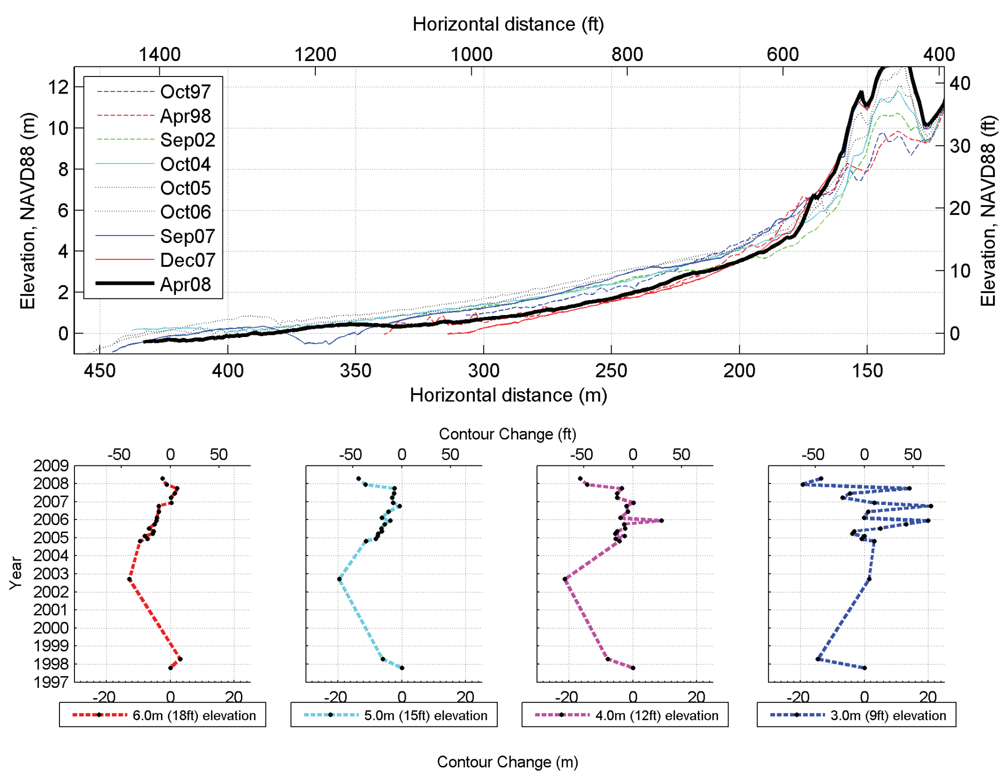
Neh2:



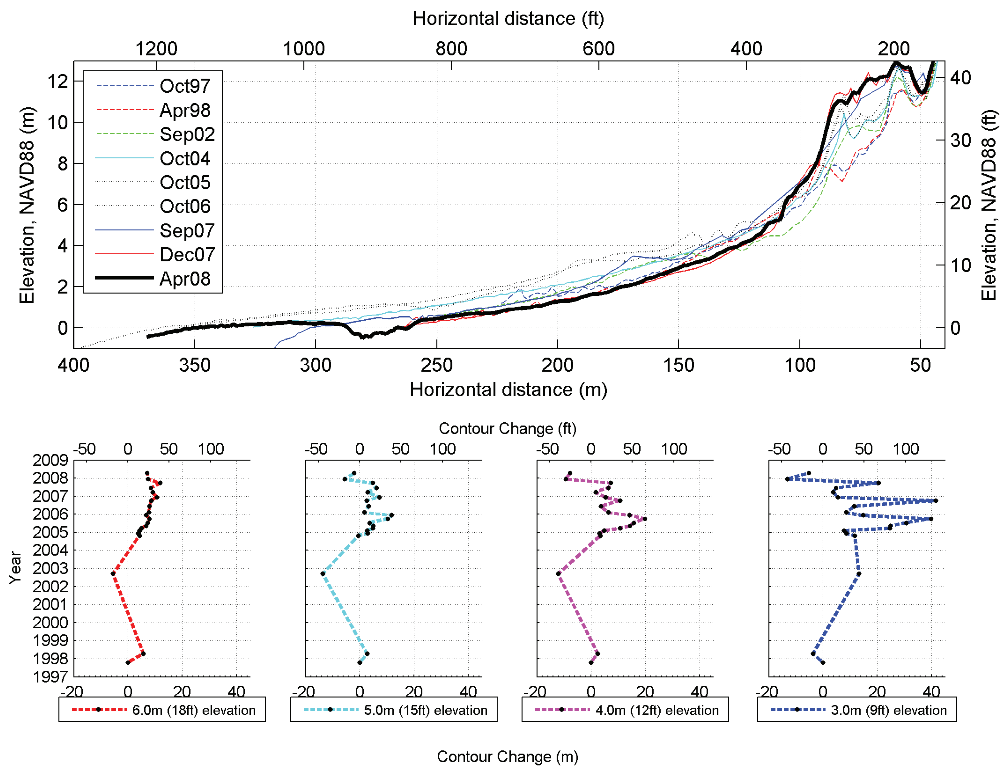
Neh3:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

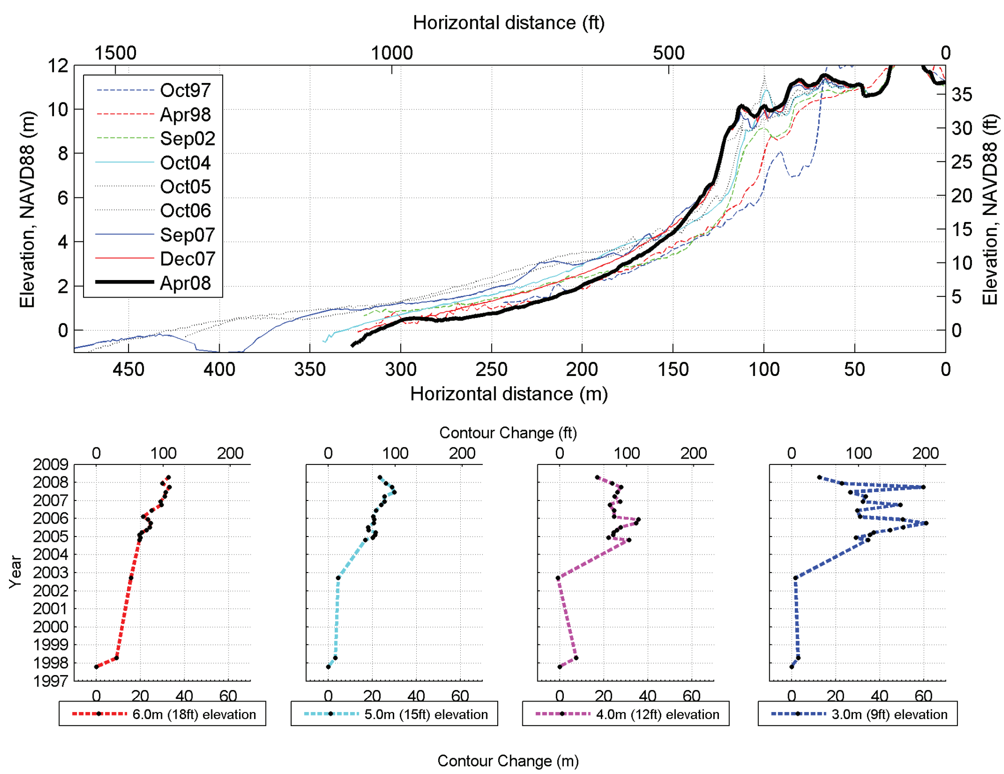
Neh4:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

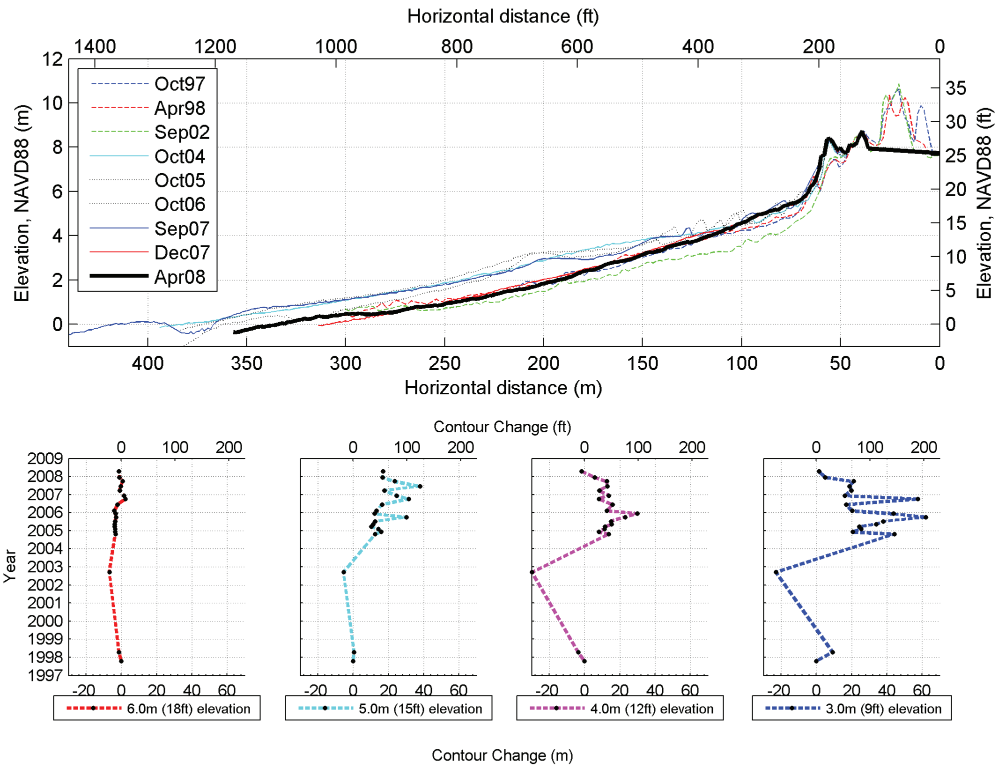
Neh5:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

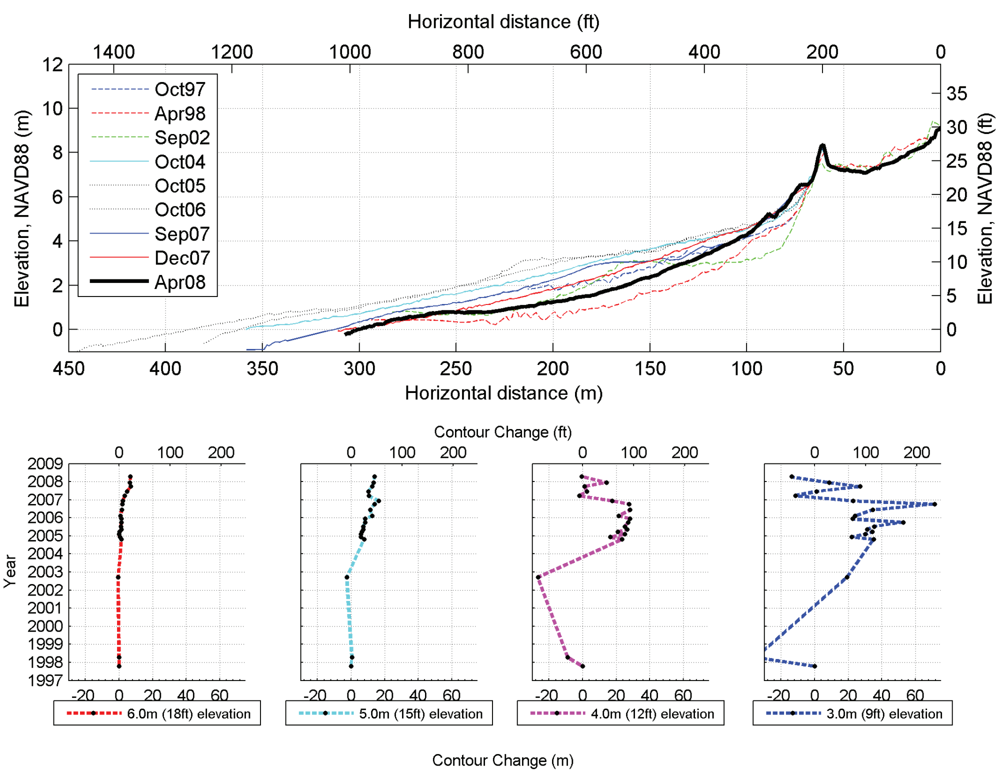
Neh6:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Horizontal distance (m)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Neh7:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)

Neh8:


Horizontal distance (ft)
Elevation, NAVD88 (m)
Elevation, NAVD88 (ft)
Oct97
Apr98
Sep02
Oct04
Oct05
Oct06
Sep07
Dec07
Apr08
Horizontal distance (m)
Contour Change (ft)
Year
6.0m (18ft) elevation
5.0m (15ft) elevation
4.0m (12ft) elevation
3.0m (9ft) elevation
Contour Change (m)