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AN “EXPANDED” GEOSPATIAL DATABASE OF BEACH AND BLUFF MORPHOLOGY DETERMINED FROM LIDAR DATA COLLECTED ON THE NORTHERN OREGON COAST: TILLAMOOK AND CLATSOP COUNTIES

TECHNICAL REPORT TO THE
OREGON DEPARTMENT OF LAND CONSERVATION AND DEVELOPMENT



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Cover photograph: Oblique aerial photo of the Clatsop Plains taken adjacent to the south Columbia River jetty and looking south toward Tillamook Head in the distance. Photo by E. L. Harris, DOGAMI.

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TABLE OF CONTENTS

ABSTRACT	1
1.0 INTRODUCTION	2
2.0 BACKGROUND	3
2.1 Management needs and study objectives	3
3.0 APPROACH	4
3.1 Assessment of lidar gridding methods	4
3.1.1 Dune-backed examples	7
3.1.2 Bluff-backed examples	7
3.1.3 Lidar flown in 1997 versus 2002	7
3.1.4 Lidar processing summary	8
3.2 Dune/bluff parameter extraction protocols	8
4.0 RESULTS	11
4.1 Morphological parameters — slope and beach/dune juncture elevations	11
4.2 Coastal change	14
4.2.1 Clatsop County	14
4.2.2 Tillamook County	17
4.3 Geospatial mapping	20
5.0 CONCLUSION	22
6.0 ACKNOWLEDGMENTS	22
7.0 REFERENCES	23

LIST OF FIGURES

Figure 1. Representative beach profile sites near Ecola Creek, Cannon Beach 5

Figure 2. Dune profile #2 and bluff profile 52 interpolation methods 7

Figure 3. Characteristic morphological parameters identified on a dune 8

Figure 4. Histograms showing summary beach slope results for selected subregions along the Tillamook and Clatsop County coast 12

Figure 5. Histograms showing summary beach/dune juncture elevation results for selected sub regions along the Tillamook and Clatsop County coast 13

Figure 6. Net shoreline excursions along the Clatsop Plains and Seaside for the period 1997-2009. 15

Figure 7. Net shoreline excursions along the Clatsop Plains and Seaside for the period 1997-2009. 16

Figure 8. Net shoreline response for the period 1997-1998 and 1997-2002 18

Figure 9. Net shoreline response for the period 1997-2002 and 1997-2009 19

Figure 10. Map showing various geospatial layers that have been developed from the beach transect database 21

LIST OF TABLES

Table 1. Four approaches used in the development of representative digital elevation models from which transects have been extracted 5

Table 2. Root mean squared error (RMSE) values for comparison of extracted profiles and raw 1997 and 2002 lidar data 6

Table 3. Beach/dune/bluff parameters extracted or interpreted from lidar 9

ABSTRACT

The objective of this study has been to develop a coastal geomorphic database that describes the morphological parameters of beaches, dunes, and bluffs present along the central to northern Oregon coast, specifically in Clatsop and Tillamook Counties. The completed product includes a variety of geospatial data layers including transect locations; site-specific information on the slope of the beach, dune, or bluff crest; coastal change information for selected years; and visual products that synthesize several of the identified parameters to enable easy access to information on beach, dunes, and bluffs. This study extends a previous investigation by Allan and Hart (2007) by undertaking more detailed morphological analyses of the beaches and dunes, employing a higher sampling frequency (minimum profile spacing of ~ 25 m as opposed to 100 m [i.e., 4 times the number of transects]), and expanding the effort to include the coastal bluffs and headlands that, respectively, back and

bound pocket beach littoral cells along the Oregon coast. The final outcome of this study is a detailed geospatial database of the beaches and bluffs on the northern Oregon coast, which includes a variety of morphological information, such as beach slope, beach/dune (bluff) juncture elevation and positions, beach/dune (bluff) crest elevation and positions, dune (bluff) face slope, primary frontal dune locations, and the landward limit of the lee or reverse slope of the foredune, where present. Additional information documenting coastal change data was also derived for the 6 m (19.7 ft) contour elevation. These latter data may be used to assess the response of beaches in Clatsop and Tillamook Counties to specific periods when major events occurred (e.g., the 1997-1998 El Niño and the extreme 1998-1999 winters) at individual locations or for entire sections of the coast.

1.0 INTRODUCTION

The purpose of this work is to expand and improve on a previous study undertaken by Allan and Hart (2005), which focused on the development of a GIS database containing information on the morphology of beaches and dunes along the central to northern Oregon coast. These data were originally compiled from an analysis of light detection and ranging (lidar) data flown in 1997, 1998, and 2002. In that study, the authors extracted various beach morphological characteristics from beach profiles established at 100 m spacing along the coast. These data were then used to document changes in beach characteristics (erosion/accretion, beach slopes and beach/dune juncture elevations) spanning the period from 1997 to 2002. The objective of this study is to expand on the earlier work of Allan and Hart (2005) by incorporating additional detailed (higher resolution) lidar data flown by the Oregon Department of Geology and Mineral Industries (DOGAMI) in 2009. Furthermore, this study significantly extends the earlier investigation by undertaking more detailed morphological analyses of the beaches and dunes, employing a higher sampling frequency (minimum profile spacing at ~ 25 m [82 ft] as opposed to 100 m [328 ft], i.e., 4 times the number of transects), and expanding the effort to include the coastal bluffs and headlands that, respectively, back and bound pocket beach littoral cells along the Oregon coast. The final outcome of this study is a detailed geospatial database of beaches and bluffs on the northern Oregon coast, which includes a variety of morphological information, such as ***slope of the beach, beach/dune (bluff) juncture elevation and positions, beach/dune (bluff) crest elevation and positions, dune (bluff) face slope, primary frontal dune locations, and landward limit of the lee or reverse slope of the fore-dune*** if present. Each of these terms and features is fully described in section 3.2, “Dune/Bluff Parameter Extraction

Protocols.” In addition to the above, other data have been extracted that describe the spatial (i.e., alongshore) and temporal changes taking place at specific contour elevations (e.g., erosion/accretion responses at the 3 m [9.8 ft] and 6 m [19.7 ft] contours). Finally, it is important to stress that the “primary frontal dune” and associated “primary frontal dune heel” are terminology used explicitly by the Federal Emergency Management Association (FEMA) to identify aspects of a set of calculations that is used to determine the extent of ocean velocity flooding for the purposes of FEMA Flood Insurance Rate Maps (FIRMs). Accordingly, the location of the primary frontal dune as defined here is not appropriate in defining the broader scope of State-wide Planning Goal 18 beach and dune form areas associated with related local government Goal 18 comprehensive planning program components.

The expansion and enhancement of the database has yielded an unprecedented amount of information concerning the state of beaches and bluffs along the northern Oregon coast (Tillamook and Clatsop Counties). Beach state information of this type may now be used to provide regulatory state agencies, coastal managers, local Government planning authorities, and geotechnical firms with detailed information about the changes taking place on northern Oregon coastal dunes and bluffs since the first lidar flight was flown in 1997. As subsequent lidar flights are flown, the database can be updated to include these new lidar datasets. Furthermore, these data will be available to use in a variety of other projects, including new FEMA coastal flood mapping efforts currently underway on the Oregon coast, and will provide the necessary data required to assist with the development of erosion shoreline hazard mapping.

2.0 BACKGROUND

In 1997, three federal agencies, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center, and the U.S. Geological Survey (USGS) Coastal and Marine Program, initiated an effort to determine the magnitude, spatial patterns, and causative processes of El Niño induced coastal change. The primary approach adopted to map the effects of this particular climate phenomenon involved the use of scanning airborne altimetry or light detection and ranging (lidar) to map the ground surface. Along the Oregon coast, lidar flights of the shoreline have now been undertaken on several occasions:

- October 1997 (pre-El Niño winter)
 - data are available from Coos Bay north;
- April 1998 (post- El Niño winter)
 - data are available from Port Orford north; and,
- September 2002
 - data are available for the entire Oregon coast.

More recently, the Oregon Department of Geology and Mineral Industries contracted with Watershed Sciences, Inc., to collect lidar along the entire coast. These latter data provide the highest resolution data presently available due to their high sampling density (8 points/m²), and, because they consisted of multiple returns, bare-earth digital elevation models of the terrain were able to be extracted. These latter data were flown on two occasions:

- spring/summer 2008—data are available for the southern Oregon coast (south of ~Heceta Head)
- spring/summer 2009—data are available for the northern Oregon coast (north of ~Heceta Head)

Most recently the United States Army Corps of Engineers (USACE) flew bathymetric lidar along approximately three quarters of the coast; data were unable to be collected south of about Cape Blanco. Unfortunately, inclusion of these data was not possible as the data were unavailable at the time of data processing.

2.1 Management needs and study objectives

Management of beaches and dunes in Oregon falls under the jurisdiction of the Oregon Parks and Recreation Department (OPRD), the Coastal Management Program of the Oregon Department of Land Conservation and Development (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) 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 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 scales 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.

Sufficiently detailed beach and bluff morphological information measured on a repeat basis at appropriate time intervals (e.g., seasonal and interannual surveys derived by GPS, or decadal lidar surveys of the coast) and space scales (tens to thousands of meters) will ultimately help coastal managers resolve short and long term specific planning issues by providing an improved understanding of the changes taking place on the Oregon coast. To assist with this process and to improve on our existing knowledgebase

of coastal change, the following tasks were proposed for completion as part of this work:

1. Use existing lidar data measured by the USGS/ NASA/NOAA in 1997, 1998, 2002 and, if available, obtain bathymetric/topographic lidar data flown on the Oregon coast by the USACE in summer 2010. In addition, use the higher-resolution lidar data flown by DOGAMI in 2010 for the northern Oregon coast. This latter dataset provides the most detailed measurement of the topography, as it consists of multi-return lidar data, enabling the generation of bare-earth digital elevation models (DEMs).
2. Develop a virtual Esri ArcGIS® beach database for each littoral cell (including the headlands) on the central to northern Oregon coast. The database would include beach profiles located at a minimum of 50 m (164 ft) apart along the respective littoral cells.
3. Query the data in order to compile information about the characteristics of beaches, dunes, and bluffs and consolidate these data into a geospatial database. Such information would include the beach slope, beach/dune juncture elevation, bluff toe elevation, beach/dune/bluff top elevation, primary frontal dune location, location of the landward limit of the lee or reverse slope of the foredune, bluff face slope, and selected contours documenting change.
4. Compile the morphology data into an ArcGIS geospatial database. Extract appropriate information from the geospatial database documenting the above parameter characteristics along each littoral cell. This could include plots showing alongshore variability in slopes, position of erosion scarps or other morphological features, crest elevation of beaches, and the spatial and temporal variability in specific contour elevations.
5. Produce a technical report.
6. Disseminate beach state/change data and products to DLCD.

3.0 APPROACH

3.1 Assessment of lidar gridding methods

In order to perform dune/bluff parameter extraction from lidar, it is first necessary to examine the various methods available for interpolating and gridding the raw data. The objective here is to assess the performance of two specific interpolation techniques (nearest neighbor [NN] versus triangulated irregular network [TIN]) available in ArcGIS¹, and vary the grid cell size (e.g., 0.5 [1.6 ft], 1 [3.3 ft], and 3 m [9.8 ft] cells). Figure 1 identifies the locations of several beach profile sites where various grid tests were performed, while Table 1 summarizes the approaches we examined. These tests were performed at two representative profile sites located on a dune-backed beach just north of Ecola Creek, at Cannon Beach, Oregon (Figure 1), and three additional sites located along a bluff-backed beach in the community of Falcon Cove. In each case, the raw lidar data from the entire region bounding these two focus areas were gridded. *The extracted cross-section information derived from*

each of the DEMs was then compared with the raw point data extracted within ± 0.5 m (± 1.6 ft) from each of the transect lines in order to assess the overall performance of the interpolation techniques. For our purposes, performance was determined by fitting a least-squares linear regression through the points and by assessing the residual errors. Figure 2 presents a sample of the results shown for both a dune- and bluff-backed beach.

Initially, a 3 m (9.8 ft) grid cell DEM was developed from the raw lidar point data using a TIN approach (Table 1). This was done primarily because the 1997, 1998, and 2002 lidar data had a point spacing of 0.5-2 m (1.6–6.6 ft) along the open coast. However, this initial effort yielded very poor (“jagged”) results. Because the objective of this study reflects a balance between maximizing our ability to capture and interpolate the dune/bluff morphology while balancing the precision of the various lidar datasets, no further assessments were made using a 3 m (9.8 ft) cell.

¹ <http://www.esri.com/software/arcgis>

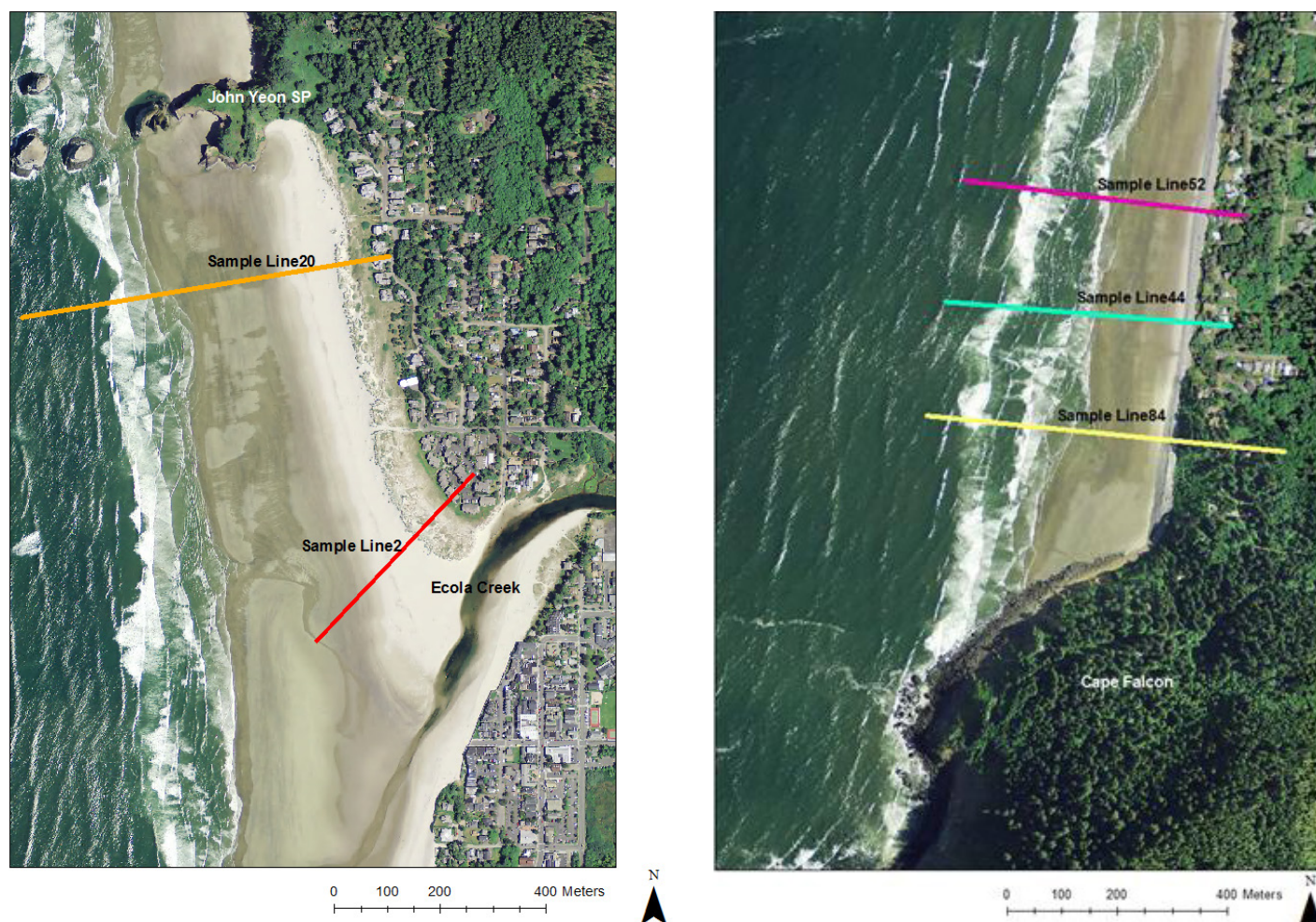


Figure 1. Representative beach profile sites that cross (left) dune-backed and (right) bluff-backed beach near Ecola Creek, Cannon Beach, Oregon.

Table 1. Four approaches used in the development of representative digital elevation models (DEMs) from which transects have been extracted.

Approach	Gridding Resolution	Interpolation Method
1	3 m (9.8 ft)	TIN
2	1 m (3.3 ft)	TIN
3	0.5 m (1.6 ft)	NN
4	1 m (3.3 ft)	NN

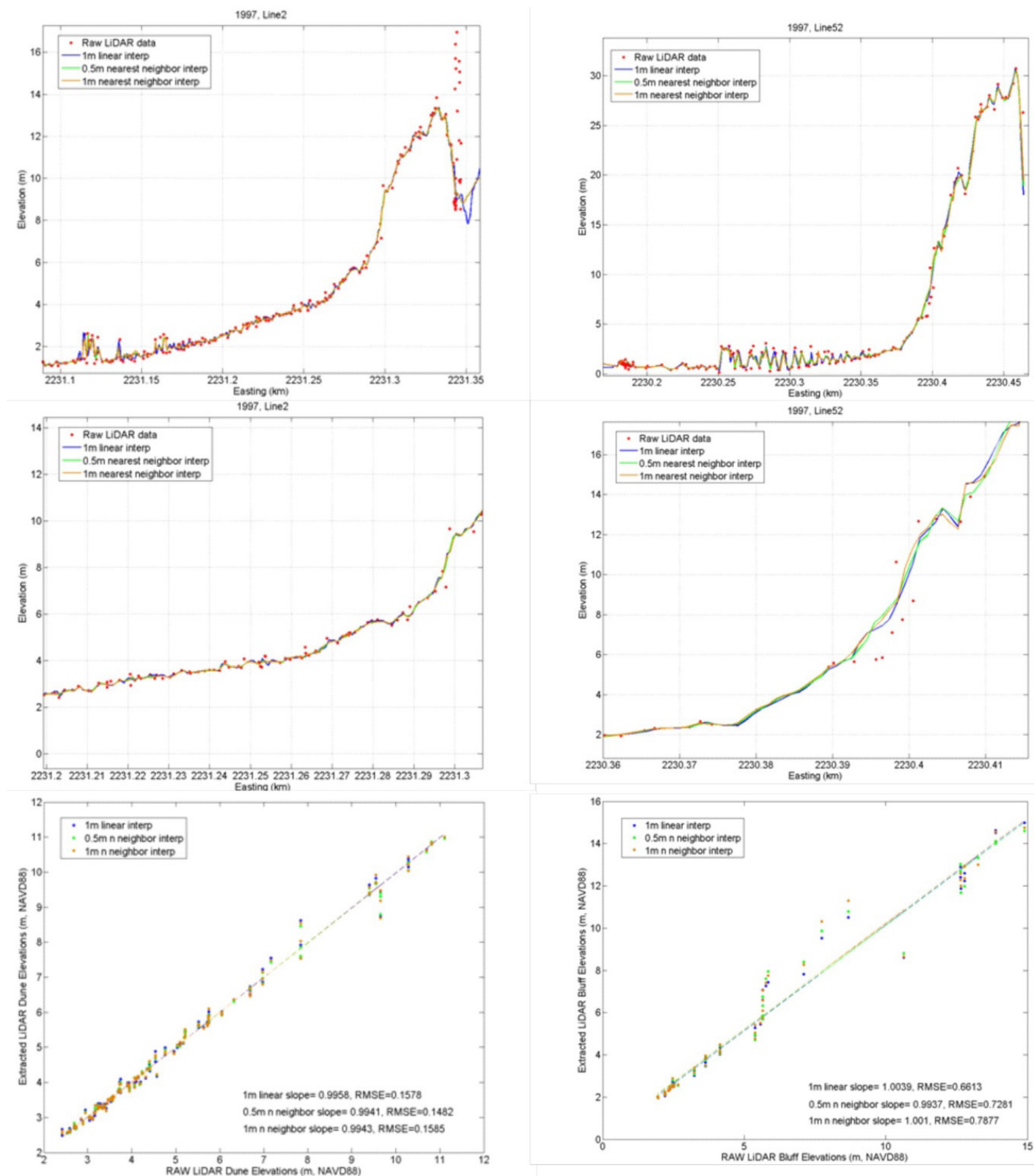


Figure 2. (top) Dune profile 2 (Line 2) and bluff profile 52 (Line 52) extracted from 1997 raw lidar data (red dots) using 1 m (3.3 ft) triangulated irregular network (blue), 0.5 m (1.6 ft) nearest-neighbor (green), and 1-m (3.3 ft) nearest-neighbor (brown) interpolation methods. (middle) Zoomed extent of unvegetated area being used for comparison of interpolation methods. (bottom) Results of correlation and root mean squared error (RMSE) analysis when interpolation techniques are compared with raw lidar data.

3.1.1 Dune-backed examples

The first plot (Figure 2 top, left panel) shows a cross-section of gridding methods 2 through 4 at Line2. Raw 1997 lidar points are also included as red dots to demonstrate how well the approaches fit the data. Points extracted west of ~2,231.2 km start to become scattered, indicating that the lidar beam is probably encountering wave swash, which the beam is unable to penetrate. Similarly, scatter is apparent east of 2,231.3 km and is probably caused by vegetation (e.g., trees, shrubs, and dune grass), which will produce anomalous elevation results in the derived profile elevations.

In order to best compare the different grid techniques against the actual lidar data, a subset of the profile data was extracted and confined to the nonvegetated portion of the dune/beach (and bluff/beach) shown in Figure 2 (middle panel), and a least-squares linear regression was fit to the data. In general, our analyses indicate that the remaining three contrasting grid DEMs perform well in describing the overall shape of the dune profile. Figure 2 (bottom panel) also demonstrates that the derived lidar DEMs correlate well with actual ground point data. Therefore, performance of the interpolation routines will be based on the root mean squared error (RMSE) when compared with the raw lidar data. Although results vary for each profile, all three approaches produce similar RMSE errors (within several centimeters). Similar results were also identified at the Line 20 profile site, with the 0.5 m (1.6 ft) NN algorithm producing slightly better agreement with the lidar data than did the other two approaches.

3.1.2 Bluff-backed examples

Because lidar performance varies depending on the terrain (e.g., slope), similar analyses were carried out on a stretch of coast located just north of Cape Falcon (Figure 2, right panel) that is backed by bluffs of varying heights. The steep nature of bluffs potentially can introduce anomalies due to the varying slopes, height, complex topography, and presence of vegetation when compared with results from dune-backed beaches. As a result of these influences, there is potential for the RMS errors to be significantly higher on bluff-backed versus dune-backed shores. Results from our analyses are demonstrated in Figure 2 (right panel), with the results confirming this observation, with the RMSE values for all three interpolation methods being significantly (~2 to 3 times) higher when compared with results from the dune-backed stretch of beach (Figure 2, left panel).

Also evident is a lack of agreement for which interpolation approach is most appropriate based on RMSE values. In fact, no two of the three representative profiles are shown to be best described by a common interpolation method.

3.1.3 Lidar flown in 1997 versus 2002

Additional comparisons were undertaken to compare the data flown in 1997 versus those collected in 2002 (in both years the data were flown through a cooperative agreement between USGS, NASA, and NOAA). In general, we expected the extracted morphology from the 1997 lidar would yield less accurate results when compared to the raw data (i.e., be characterized by higher RMS errors), in part due to that dataset's coarser sampling. As a result, we performed similar analyses for a dune-backed and bluff-backed subset of profiles using the same three interpolation methods applied to the lidar collected in 2002. Contrary to the hypothesis that the 2002 lidar dataset would produce more accurate results, it appears that the 1997 and 2002 datasets yield very similar results. In fact, the 1997 dataset has, on average, marginally lower RMSE values when compared to the 2002 dataset (Table 2).

For robustness, this approach was also applied to 31 profiles of a dune-backed beach and 34 profiles of a bluff-backed beach; batch RMSE statistics are summarized in Table 2. RMSE values still indicate that, on average, the 0.5 m (1.6 ft) NN approach is the best method for interpolation of the lidar dataset for both the dune-backed and bluff-backed terrain, but the variability among the three methods

Table 2. Root mean squared error (RMSE) values for comparison of extracted profiles and raw 1997 and 2002 lidar data. Results are shown for both a dune- and a bluff-backed section of beach.

Interpolation Method	Mean RMSE	Mean RMSE
	<i>1997 dune backed</i>	<i>2002 dune backed</i>
1 m TIN	0.13 m (0.43 ft)	0.13 m (0.43 ft)
0.5 m NN	0.12 m (0.39 ft)	0.12 m (0.39 ft)
1 m NN	0.12 m (0.39 ft)	0.13 m (0.43 ft)
3 m TIN	0.15 m (0.49 ft)	0.17 m (0.56 ft)
	<i>1997 bluff backed</i>	<i>2002 bluff backed</i>
1 m TIN	0.65 m (2.13 ft)	0.64 m (2.1 ft)
0.5 m NN	0.61 m (2.0 ft)	0.63 m (2.1 ft)
1 m NN	0.63 m (2.1 ft)	0.66 m (2.17 ft)
3 m TIN	0.91 m (3.0 ft)	0.92 m (3.02 ft)

is comparable. For comparison, RMSE values were also calculated for the original 3 m (9.8 ft) grid using linear interpolation and, as expected, slightly higher values were experienced by both the dune- and bluff-backed beaches.

3.1.4 Lidar processing summary

To summarize, all three gridding methods (i.e., triangulated irregular network and nearest neighbor) using 1 m (3.3 ft) grid cells or less were found to replicate the overall beach and bluff morphology in a consistent manner, when compared to the raw lidar point data. Of the four approaches examined, the TIN method using a 3 m (9.8 ft) grid cell performed the worst, yielding very jagged results that were essentially unusable for defining various morphological beach and bluff parameters. Although the 0.5 m (1.6 ft) NN approach produced marginally better (lower) RMSE values on average (particularly for the dune-backed coast), gridding at 0.5 m (1.6 ft) almost certainly is stretching the limits

of the pre-2008/2009 lidar datasets that have a resolution of ~ 1 point/m². As a result, for the purposes of this study we have used the triangulated irregular network (TIN) algorithm with a 1 m (3.3 ft) cell size for gridding lidar data measured in 1997, 1998, and 2002. Data from the 2008/2009 lidar dataset, which has a much higher resolution of 8 points/m², were also gridded using a TIN approach, though the grid cell used was 0.5 m (1.6 ft), which better reflects the point spacing of the these latter data.

3.2 Dune/bluff parameter extraction protocols

In order to effectively extract dune and bluff parameters (e.g., dune/bluff toe, crest, slope etc.), it is necessary to establish various selection criteria to avoid user subjectivity. The first step in this process is to define the parameters of interest pertinent to both the bluffs and dunes. Figure 3 displays these features on a sample dune-backed beach profile measured adjacent to the Sand Lake estuary. Beach

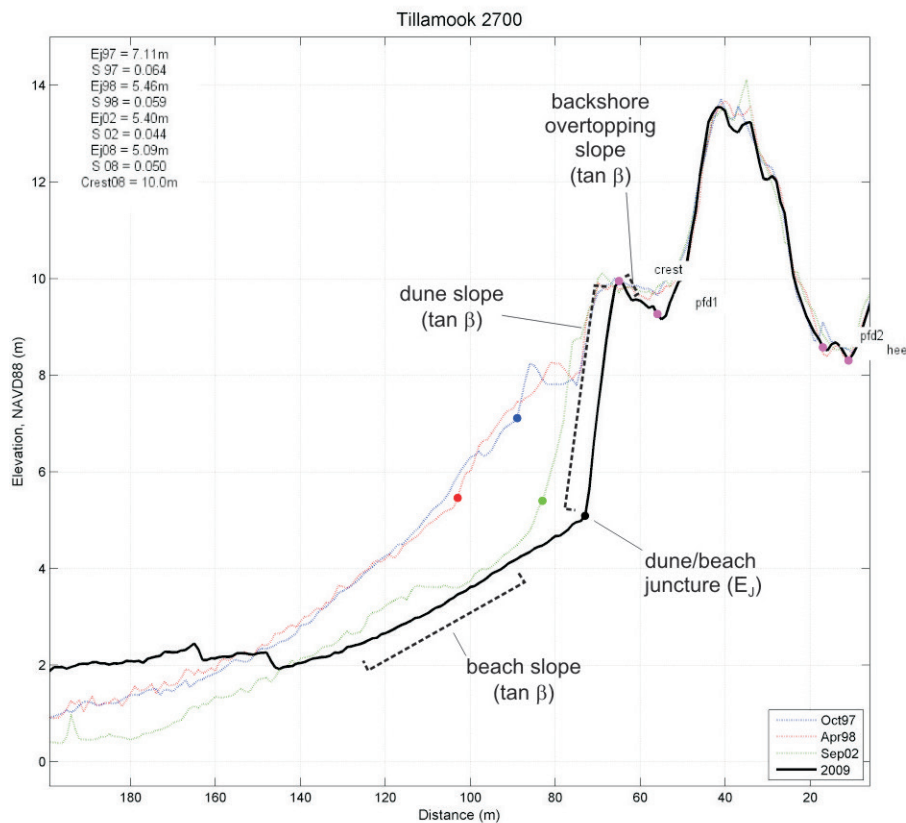


Figure 3. Characteristic morphological parameters identified on a dune. Note: seaward is to the left and landward is to the right of the dune. Identified beach slopes and beach/dune juncture elevations for different years are included in the upper left corner of the figure.

and bluff parameters identified in this study are included in Table 3. A description of each of these follows:

1. *Beach slope ($\tan \beta$)* – The degree of inclination to the horizontal. Usually expressed as a ratio (e.g., 1:25, indicating one unit rise in 25 units of horizontal distance), or in a decimal fraction (0.04). Calculation of the beach slope was defined by linear regression and encompassed the region of the beach that spans the 2- to 4-m contours (i.e., the storm swash runoff zone).
2. *Beach/dune juncture elevation (E_j)* – The point of break in slope between a dune and beach face. The beach/dune juncture was defined using a combination of visual cues of the slope inflection point between the dune and beach interface, and from local knowledge of the beach. With respect to the latter, there were situations where a clear break in slope was not always discernible. For those situations, information from adjacent transects along with aerial photographs were used to help guide the final choice.

Table 3. Beach/dune/bluff parameters extracted or interpreted from lidar. Format below reflects the direct output from the MATLAB programming code. Note: NaNs (not-a-number) were used to fill portions of the table where no data was available or could not be derived.

Code	Dune Parameters	Code	Bluff Parameters
d1	Primary frontal dune (PFD) crest	d1	NO PFD DUNE CREST (NaN)
d2	Dune crest	d2	Bluff/scarp crest (likely area affected by waves)
d3	Primary frontal dune (PFD) heel #1	d3	NO PFD HEEL #1 (NaN)
d4	Primary frontal dune (PFD) heel #2	d4	NO PFD HEEL #2 (NaN)
d5	Dune heel (landward limit)	d5	NO DUNE HEEL (NaN)
d6	Backshore overtopping slope of dune (-ve = slope drops landward, +ve = slope rises landward)	d6	Backshore overtopping slope of bluff
d7	Dune face slope	d7	Bluff face slope
d8	NO BLUFF TOE (NaN)	d8	Bluff toe (beach/bluff junction, B_j)
d9	NO BEACH SEAWARD OF BLUFF (NaN)	d9	2008/09 beach slope in front of bluff/where applicable, composite beach slope option included here
d10	1997 beach slope	d10	1997 beach slope
d11	1998 beach slope	d11	1998 beach slope
d12	2002 beach slope	d12	2002 beach slope
d13	2008/2009 beach slope/where applicable, composite beach slope option included here	d13	2008/2009 beach slope
d97	1997 beach/dune (or beach/bluff) juncture	d97	1997 beach/dune (or beach/bluff) juncture
d98	1998 beach/dune (or beach/bluff) juncture	d98	1998 beach/dune (or beach/bluff) juncture
d02	2002 beach/dune (or beach/bluff) juncture	d02	2002 beach/dune (or beach/bluff) juncture
d08	2008/2009 beach/dune (or beach/bluff) juncture	d08	2008/2009 beach/dune (or beach/bluff) juncture
d14	NO PROJECTED BLUFF TOE (NaN)	d14	2008/2009 projected bluff toe (based on d9 and d15)
d15	NO BLUFF SLOPE (NaN)	d15	2008/2009 bluff slope (slope specific to the bluff backshore above B_j). This is equivalent to the steepest section of the bluff (e.g., scarp).
d16	Additional dune heel	d16	Additional dune heel
d17	Additional PFD	d17	Additional PFD
d18	Very top of bluff crest	d18	Very top of bluff crest
type	Dune (1), bluff (2), or structure (3)	type	Dune (1), bluff (2), or structure (3)

3. *Bluff toe juncture elevation (B_j)* – The point of break in slope between a bluff and beach face. The beach/bluff juncture was defined using a combination of visual cues of the slope inflection point between the bluff and beach interface, and from local knowledge of the beach.
4. *Dune/bluff crest elevation (D_c)* – The dune crest is the highest elevation of the dune profile. Defined manually from visual inspection of the transect. Depending on the profile, the dune crest may be the same as the PFD crest. In many cases, multiple crests may be present.
5. *Primary frontal dune (PFD)* – A continuous or nearly continuous mound or ridge of sand with relatively steep seaward and landward slopes and subject to erosion and overtopping from high tides and waves during major coastal storms. Typically, the PFD reflects the westernmost dune. In all cases we attempted to distinguish the PFD designation from ephemeral dunal features that periodically form and may be similarly destroyed by storm waves. As noted in section 1.0, "Introduction," it is important to stress that the "primary frontal dune" and associated "primary frontal dune heel" are terminology used explicitly by the Federal Emergency Management Association (FEMA) to identify aspects of a set of calculations that is used to determine the extent of ocean velocity flooding for the purposes of FEMA Flood Insurance Rate Maps (FIRMs). Accordingly, the location of the primary frontal dune as defined here is not appropriate in defining the broader scope of Statewide Planning Goal 18 beach and dune form areas associated with related local government Goal 18 comprehensive planning program components.
6. *Primary frontal dune heel #1 (PFD #1)* – Additional PFD heel identified in cases where there was some uncertainty about the actual location of the PFD heel. Aside from assessment of the morphology, additional information such as changes in dune vegetation identified between subsequent lidar surveys, and/or aerial photos, was used to assess the location of the PFD heel.
7. *Primary frontal dune heel #2 (PFD #2)* – Additional PFD heel identified in cases where there was some uncertainty about the actual location of the heel. Typically, this extra feature class is located landward of PFD #1.
8. *Dune heel* – This is the landward limit of the dune system. The dune heel is most often identified by a point of break in slope behind the dune where the terrain flattens. In the majority of cases, defining the dune heel was extremely challenging due to the presence of multiple dunes.
9. *Dune/bluff face slope* – The degree of inclination of a dune/bluff face to the horizontal. The dune/bluff face slope was defined by linear regression and reflected the region between the dune/bluff toe and the upper extent of the near-linear face of the dune or bluff. In many cases, the upper extent could be defined by the crest of the dune or bluff.
10. *Backshore overtopping slope* – The degree of inclination to the horizontal of the portion of dune subject to wave overtopping during large storm events. The backshore overtopping slope was defined by linear regression and reflected the region between the zone where overtopping would first occur (e.g., a dune crest) and the first major break in slope landward of the first overtopping point).

Although the majority of the above parameters can be defined in a consistent manner, a few of the parameters are open for interpretation and thus are prone to larger errors due to their greater subjectivity. Of these, the location of the dune heel presented the greatest challenge for interpretation. To that end, additional visual cues were used to help define several of the features, including adjacent transect information and information derived from aerial photographs and lidar DEM hillshades and contours². As a result, of all of the identified parameters the dune heel is the least well constrained, especially in areas containing multiple dune forms. Similarly, defining the PFD heel was also found to be challenging, especially in those areas where recent dune development had occurred or where the dune was characterized with multiple breaks in slope.

² Lidar contours were generated separately at 1 m intervals for the 2008/2009 data only.

4.0 RESULTS

In total, 1,951 transects were processed along the Clatsop County coastline and 3,657 transects were queried and interpolated along Tillamook County, for a sum of 5,608 beach profiles. Here we briefly present and discuss some of the results and findings that can be extrapolated from such a database, highlighting the usefulness of such a product for a variety of potential end users. Additional detailed information pertinent to each of the identified parameters listed in Table 3 is documented in two Excel worksheets for all transect sites: *Clatsop_morphology_parameters.xlsx* and *Tillamook_morphology_parameters.xlsx*. Geospatial information (e.g., shorelines, beach/dune juncture lines, transect lines etc.) are contained in two Esri ArcGIS geodatabases, *clatsop_coastal_lidar_analyses_Final.gdb* and *tillamook_coastal_lidar_analyses_Final.gdb*.

4.1 Morphological parameters — slope and beach/dune juncture elevations

Figures 4 and 5 summarize the results for two of the morphological parameters (slope and beach/dune juncture elevations, respectively) determined for four subregions along the Tillamook County and Clatsop County coasts. These subregions include the Clatsop Plains, Cannon Beach, Rockaway Beach, and Neskowin. Results from these types of plots highlight several interesting and contrasting patterns about the geomorphological characteristics present within each of the subregions.

As can be seen from Figure 4, beach slopes tend to be lowest in the Cannon Beach subcell ($\bar{x} = 0.030$, $\sigma = 0.009$) and steepest at Neskowin ($\bar{x} = 0.055$, $\sigma = 0.029$), a response that is entirely due to the contrasting sediment grain-sizes present in both regions. For example, mean grain-sizes have been measured and shown to be significantly coarser at Neskowin when compared with measurements obtained at Cannon Beach (Peterson and others, 1994). Furthermore, our analyses indicate that for the most part beaches are on average steeper along the Tillamook County coast when compared with Clatsop County beaches, a finding that probably reflects differences in the predominant sediment sources identified along both these coasts (Clemens and Komar, 1988; Komar, 1997). Aside from differences in the grain-size statistics, the slope histograms also demonstrate that in general the range of beach slopes tends to be much narrower in Clatsop County ($\sigma = 0.009 - 0.011$) when compared with Tillamook County ($\sigma = 0.019 - 0.029$), the

latter characterized by a wide range of beach slopes that vary from gently sloping to steep (Figure 4). Again, these differences are ultimately a function of the varying grain-sizes that predominate in these areas as well as antecedent conditions (e.g., shore platforms on which the sand is located) that prevail along portions of Clatsop County. Finally, it is worth noting that for the most part the shape of the distributions is somewhat consistent from year to year. Of note, however, is the apparent shift in the beach slopes to finer grain-sizes in 2002 along much of the coast. This response almost certainly reflects the fact that much of the central to northern Oregon coast experienced considerable erosion during the 1997-1998 and 1997-1998 winters. While the 2002 lidar data clearly documented the landward extent of the erosion that was experienced from these two winters, the data also captured the presence of berms that developed on the lower beach face, which reflects the migration of sand from the nearshore back onto the subaerial beach as the beaches began the recovery process. Hence, due to this large shift in sand back onto the beaches, the beaches were more dissipative. By 2009, however, the beaches had essentially returned to a more typical state, with more normal beach slopes.

Figure 5 documents the distribution of the beach/dune juncture (E_j) elevations for the same regional beach sites described above. As defined previously, the beach/dune juncture reflects the point of break in slope between a dune and the active beach. The histograms depicted in Figure 5 again highlight the regional variability in beach/dune juncture elevations present along this coast. Highest elevations are observed along the Clatsop Plains, a region of coast that is actively building and aggrading as new sand is redistributed from the nearshore onto the beach face. However, with progress south, the juncture elevations decrease, with beaches at Cannon Beach and at Neskowin (and to a lesser extent Rockaway) showing generally lower elevations and a much greater range of beach/dune juncture elevations. Also of interest is that the identified patterns highlight the impact of the extreme 1997-1998 and 1998-1999 winter storms, which resulted in considerable erosion along the north coast. For example, all the plots indicate a general lowering (i.e., the histogram is shifted to the left) of the beach/dune junctures as a result of the 1997-1998 El Niño winter; the beach/dune junctures were lowered even farther in the 1998-1999 winter as depicted in the 2002 distribution. However, since then, the beaches have been slowly

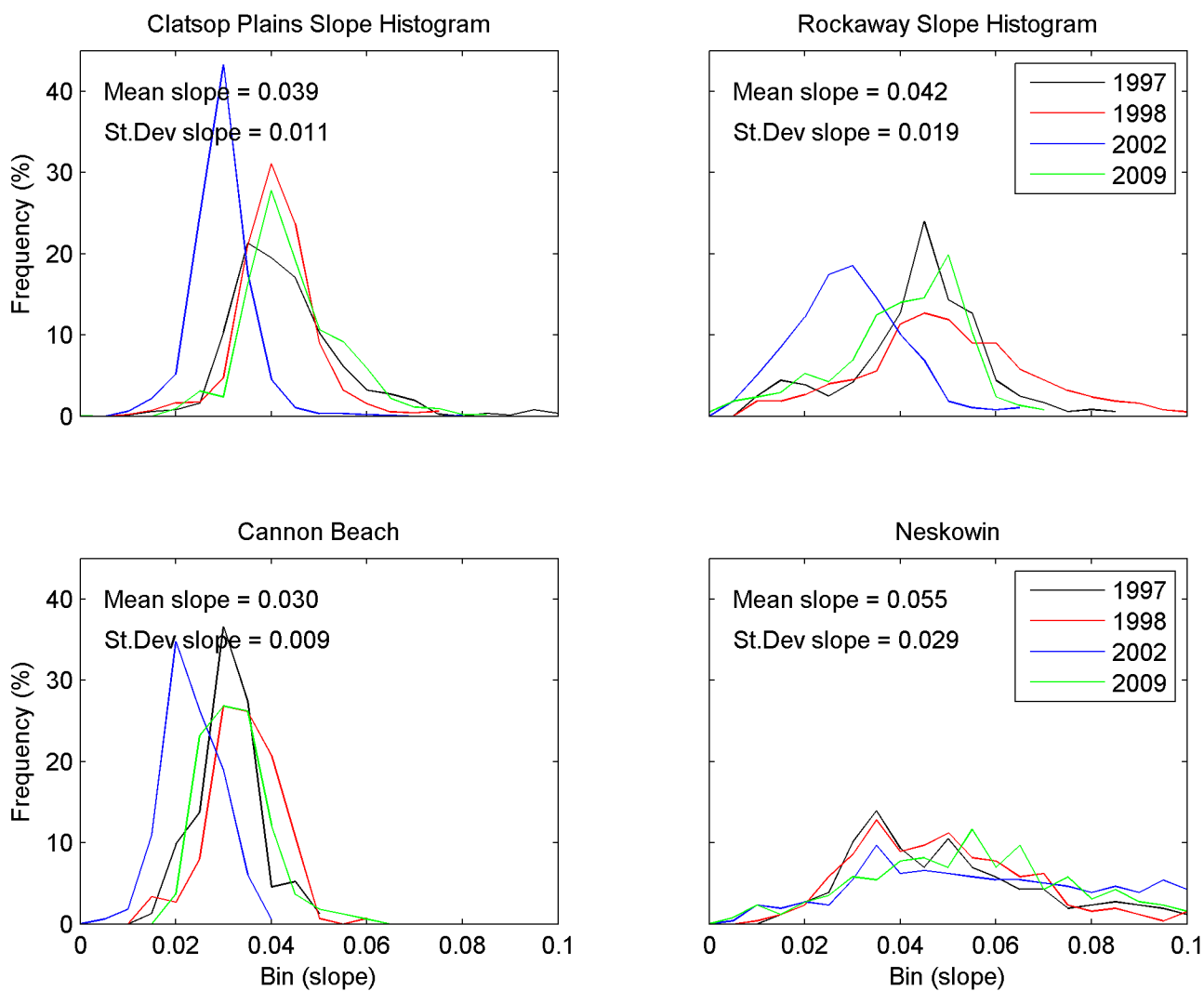


Figure 4. Histograms showing summary beach slope results for selected subregions along the Tillamook County and Clatsop County coasts.

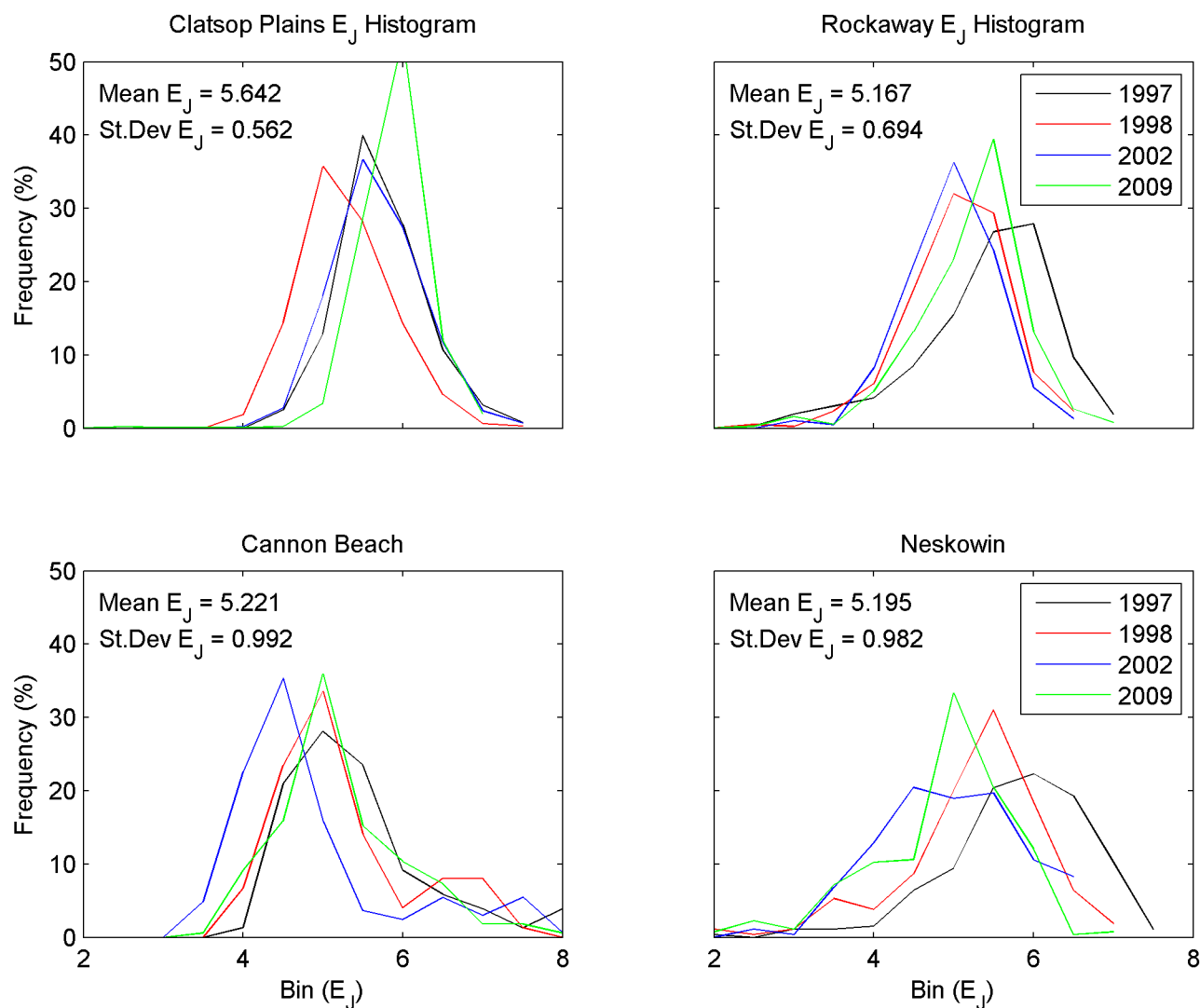


Figure 5. Histograms showing summary beach/dune juncture elevation results for selected sub regions along the Tillamook County and Clatsop County coasts.

aggrading and rebuilding, which is causing the beach/dune juncture elevations to be raised. This last response is encouraging and suggests that the beaches are gradually returning to pre-storm condition.

4.2 Coastal change

Beach profiles provide important information concerning the temporal (time) and spatial (cross-shore) variability of the shape of a section of beach. The information derived from these "repeated" lidar surveys provides important clues about the morphology of the beach (described in sections 3.2 and 4.1), as well as a measure of the response of the beach to variations in the offshore 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 also contain important information on how the beach responds to major storms, such as the extreme 1997-1998 and 1998-1999 winters, in the form of 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. One approach for defining the degree to which beaches may erode or build and advance seaward is to examine the response of the beach at different contour elevations across the beach with time. Specific contour elevations of interest include the 6.0 m (19.7 ft) and 5.0 m (16 ft) contour due to their proximity to the dune toe (Allan and Hart, 2005, 2008). After the data have been extracted, they may be made relative to a common baseline (e.g., 1997, when the first lidar flight was flown) and plotted for every transect along a particular coast, enabling a more detail understanding of the alongshore response of a region to storms and other processes.

For the purposes of this study, we examined the response of the beach at the 6 m (19.7 ft) contour, as it has been found to be the best measure for documenting the effect of major storms and for gauging any predominant patterns of coastal change (Allan and others, 2003; Allan and Hart, 2008). After the transect data were processed, the same data were re-analyzed using a customized script in MATLAB®, which interpolates the along-transect position of the 6 m (19.7 ft) contour at all transect sites. These data were then plotted for various regions in Clatsop County and Tillamook

County. Specific information documenting measured changes at each transect site is fully documented in the two Excel worksheets included with this publication: *Clatsop_change_analyses.xlsx* and *Tillamook_change_analyses.xlsx*, as well as in the accompanying ArcGIS geodatabases.

4.2.1 Clatsop County

The Clatsop County coastline extends north from Falcon Cove to the Columbia River jetty. A substantial portion of the coast is composed of the Clatsop Plains, which reflects a progradational shoreline that has formed over the past 4,500 years and, more recently, has been extensively modified due to jetty construction at the mouth of the Columbia River. The shoreline consists of a series of dunes fronted by wide sandy beaches. South of Tillamook Head, the remainder of the Clatsop coast is characterized by dissipative fine sand beaches that are backed predominantly by bluffs of varying height.

Figure 6 shows the net shoreline response (1997–2009) as measured at the 6 m (19.7 ft) contour elevation derived for the region spanning the Clatsop Plains to Seaside. In general, these results indicate several interesting patterns:

- Erosion dominates the very northern tip of the Clatsop Plains, immediately adjacent to the south Columbia jetty.
- With progress south, there is a small region characterized by little significant change (i.e., undergoing both periodic erosion and accretion). This section extends south to about Northing 284000 m.
- South of Northing 284000 m, there is a region of active accretion which *increases* toward the south, then decreases south of about Northing 273000 m toward the Necanicum estuary (blue band).
- Around the mouth of the Necanicum estuary, there is an area characterized by large shoreline excursions encompassing both erosion and accretion responses.
- Along the Seaside coastline, the lidar data indicate that this section is also accreting, though it is characterized by very large fluctuations along the shore as ephemeral dunes form, aggrade, and are subsequently reworked by aeolian processes.

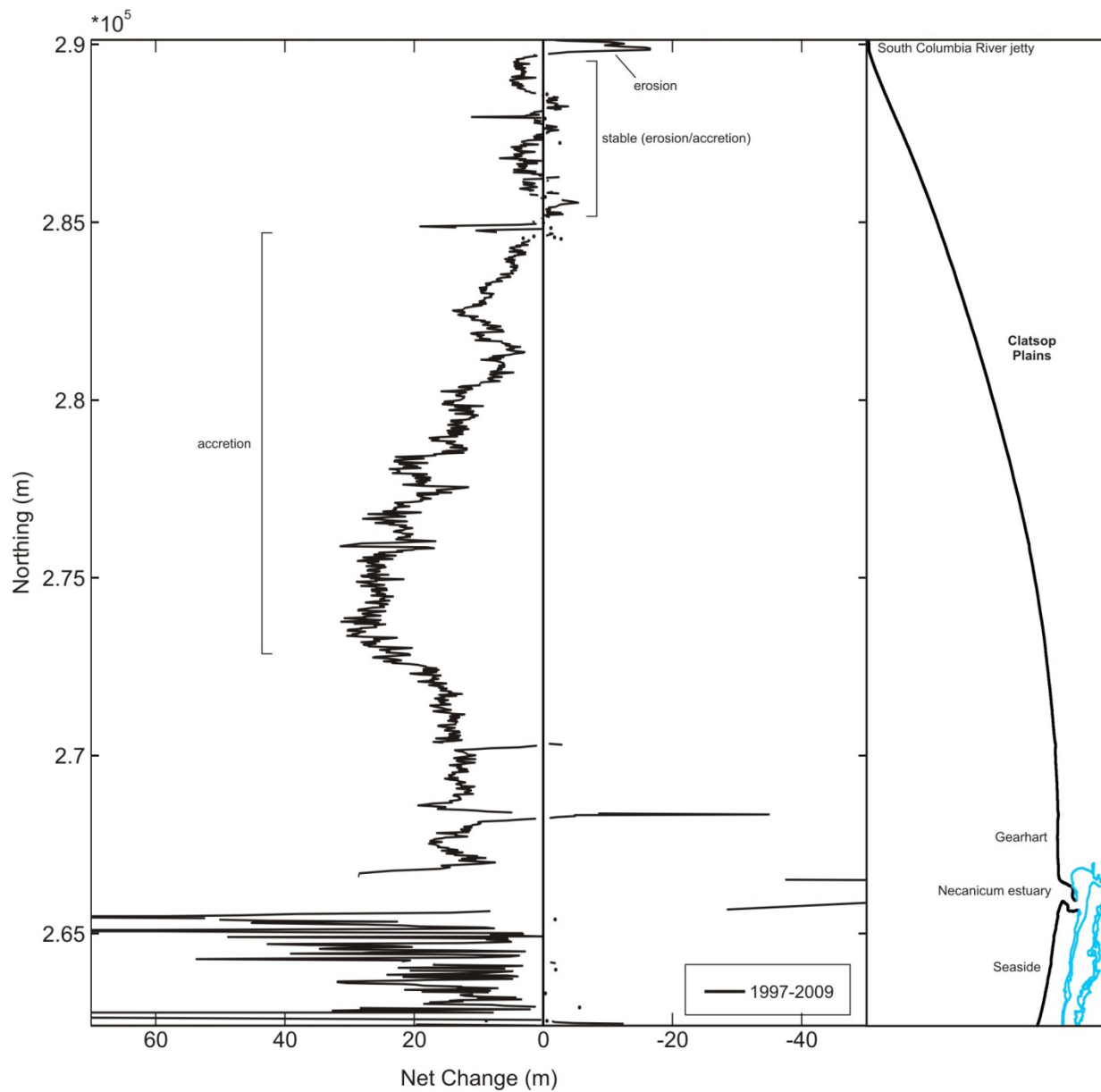


Figure 6. Net shoreline excursions along the Clatsop Plains and Seaside as measured at the 6 m (19.7 ft) contour for the period 1997-2009. The blue band is Necanicum estuary.

Similar analyses of coastal change have been derived for the remainder of the Clatsop County shoreline. Figure 7 presents those results for the coast from Cannon Beach south to Falcon Cove. Overall, shoreline changes in this region are much lower when compared with beaches in the north and probably reflect the fact that this shore has limited sediment inputs that are largely derived from erosion into coastal bluffs. As can be seen in Figure 7, the change results indicate that significant accretion has occurred on the north side of Ecola Creek in Cannon Beach. Accre-

tion also characterizes the section of shore to the north of Haystack Rock, while to the south much of the shore between Haystack Rock and Hug Point has experienced a small amount of erosion, ranging from negligible to several meters over the past 12 years. This pattern also characterizes much of the shore between Arcadia Beach and Arch Cape. Again, the degree of erosion over the past decade is relatively small. In contrast, beaches with the Arch Cape littoral cell are mostly stable, having accreted several meters as a gravel berm present there gained more sediment and

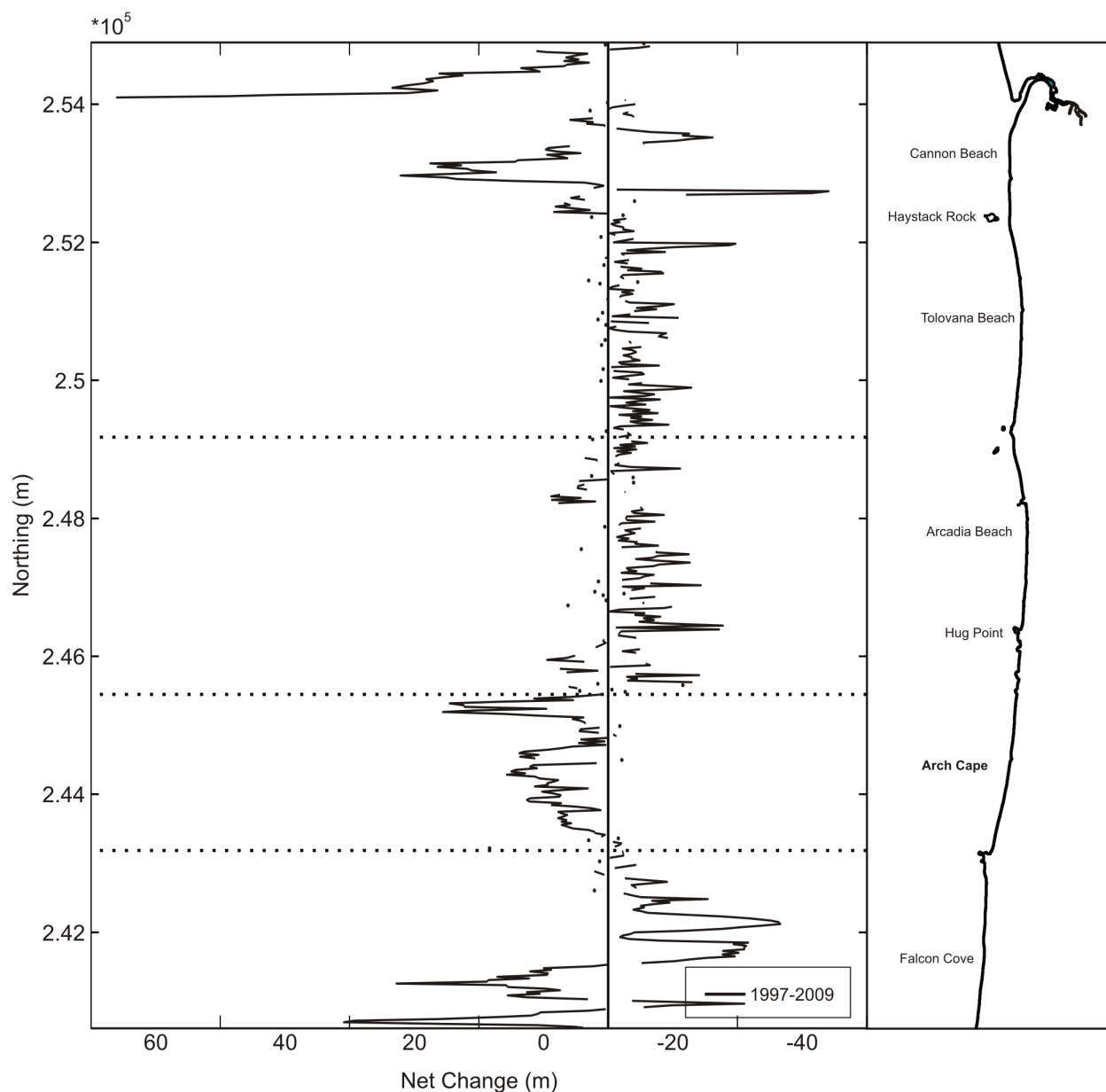


Figure 7. Net shoreline excursions along the Clatsop Plains and Seaside as measured at the 6 m (19.7 ft) contour for the period 1997–2009. Dashed line indicates the position of headlands.

built higher. Finally, shoreline changes in Falcon Cove indicate significant erosion (up to 15 m [49 ft] of retreat) in the central to northern half of the cell, while the south end is relatively stable, having gained additional cobble. However, these latter responses probably reflect mostly fluctuations in the position and volume of the cobble berm that fronts the bluffs that make up the bulk of this shore. For example, analyses of the actual transects in this area indicate that the bluffs themselves have eroded by no more than several meters during the past 15 years.

4.2.2 Tillamook County

The Tillamook County coastline consists largely of fine to medium sand beaches that are backed by dunes of various heights. The beaches are typically bounded at their distal ends by resistant headlands formed of basalt, which provide effective barriers to the transportation of sediment around the headlands.

Similar change analyses have been performed for the Tillamook County coastline, which extends from Cascade Head in the south to the Tillamook-Clatsop county line at Neahkahnie Mountain in the north. Erosion has been especially acute along significant portions of this coast, including the community of Neskowin (Allan and Hart, 2007), along much of Netarts Spit (Allan and Komar, 2004; Allan and others, 2003), and along Rockaway beach (Allan and Hart, 2008; Allan and others, 2009), located just north of Tillamook Bay.

Figure 8 documents the response of the dune-backed portion of this coast for the period 1997-1998 and for 1997-2002, the latter encompassing the extreme 1998-1999 winter season. As can be seen from Figure 8, although the 1997-1998 El Nino caused some erosion along the Tillamook County coast, the most significant impacts did not occur until the following 1998-1999 winter season, when the coast was impacted by several major storms. Thus, the combined winters effectively produced a "one-two punch" along the coast, characterized by successive storm erosion events with little time in between for the beaches to recover. As can be seen from Figure 8, the most acute erosion occurred along much of the Rockaway littoral cell, Netarts Spit, Tierra Del Mar, and at Neskowin.

Figure 9 extends the same analyses to include the most recent lidar survey flown in 2009 and thus represents the first insight as to how the Tillamook County coast has continued to respond since the 2002 lidar flight. From these new results, several changes are apparent and worth highlighting:

- Erosion has continued along much of the shore to the north of the community of Neskowin.
- Along Nestucca Spit, beaches and dunes appear to have recovered a little although for the most part remain in a degraded state.
- Beach recovery is also nonexistent in the vicinity of Tierra Del Mar and along the dunes to the immediate north. However, significant accretion has occurred on the south side of the Sand Lake Estuary and farther north up to the south side of Cape Lookout.
- Erosion continues unabated on Netarts Spit, with little to no change having occurred near Oceanside. Considerable accretion has occurred on the south side of Netarts Bay on the spit tip.
- Beach recovery is prevalent along Bayocean Spit and particularly along the northern half of the spit where the dune face has clearly advanced (prograded) seaward by many tens of meters when compared to its original position in 1997 (i.e., the zero line).
- Erosion continues unabated along the bulk of the Rockaway subcell and in many locations is considered to be acute. This contrasts with significant aggradation along Nedonna Beach at the north end of the subcell and adjacent to the Nehalem jetties.
- Beach recovery is also occurring along the bulk of Nehalem Spit, with the area near Manzanita having also prograded seaward.

These findings are entirely consistent with findings from ongoing beach monitoring work occurring along the Tillamook County coastline (e.g., Allan and Hart, 2007, 2008). Given these changes, one can conclude that the bulk of the Tillamook coast remains in a degraded or poor state, such that were the area to experience storms of a comparable nature to those experienced in 1998-1999, it would be expected that massive erosion would again occur, potentially endangering many homes built adjacent to this coast.

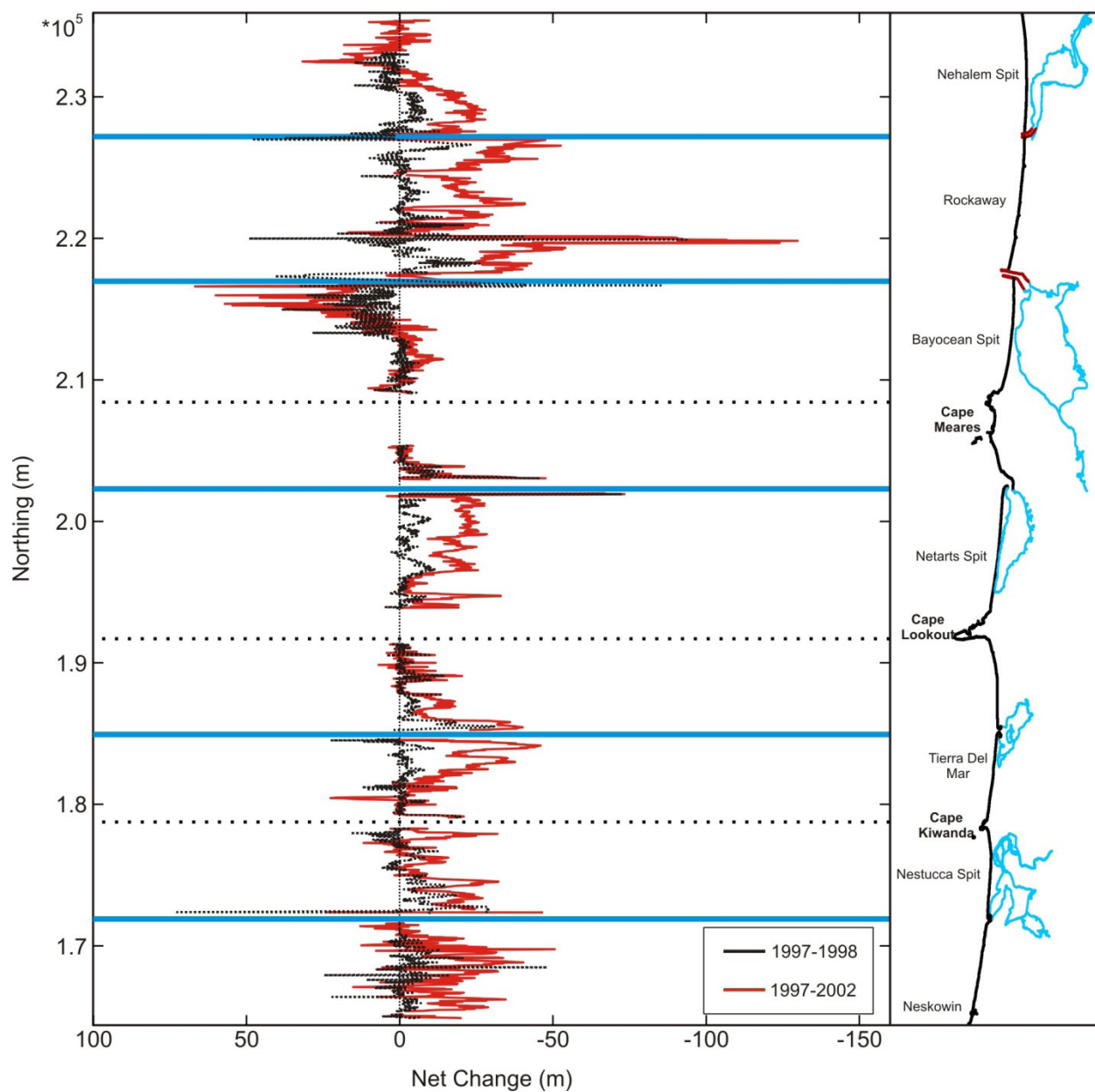


Figure 8. Net shoreline response as measured at the 6 m (19.7 ft) contour elevation for the periods 1997-1998 and 1997-2002. Cyan band denotes the location of estuary mouths; dashed line indicates the position of headlands.

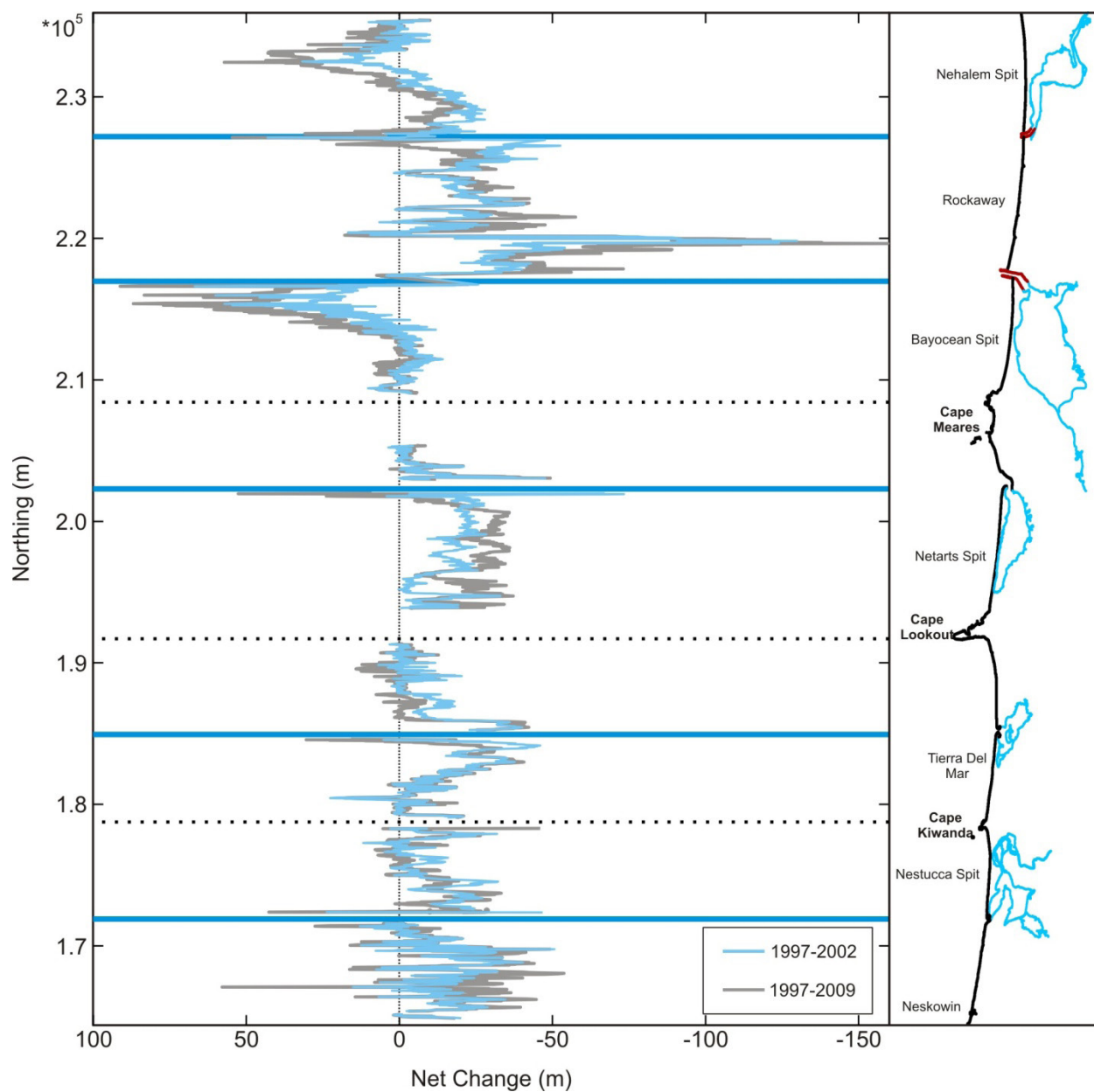


Figure 9. Net shoreline response as measured at the 6 m (19.7 ft) contour elevation for the periods 1977-2002 and 1977-2009. Cyan band denotes the location of estuary mouths; dashed line indicates the position of headlands.

4.3 Geospatial mapping

Figure 10 presents an example of the types of geospatial products that have been developed for both counties using the transect data. These include geospatial products depicting the location of the primary frontal dune (PFD), various dune heels (the product of more than one dune system if present), where applicable the most landward dune heel, the dune/bluff top, the position of the beach/dune juncture for multiple years, and point data containing information documenting the net change at individual transect loca-

tions. In the example shown in Figure 10, located just south of Twin Rocks in Tillamook County, it can be seen that the PFD tracks very close to a number of homes located in the central-upper portion of the figure. A number of dune heels have been identified at this location from an analysis of the lidar transect data and from the bare-earth digital elevation lidar models. Of particular significance, Figure 10 highlights the significant change to the position of the beach/dune juncture elevation (E_j) from 1998 to 2009, as well as the locations of the points where the 6 m (19.7 ft) change analysis (TM_6mchange_locations) was performed.

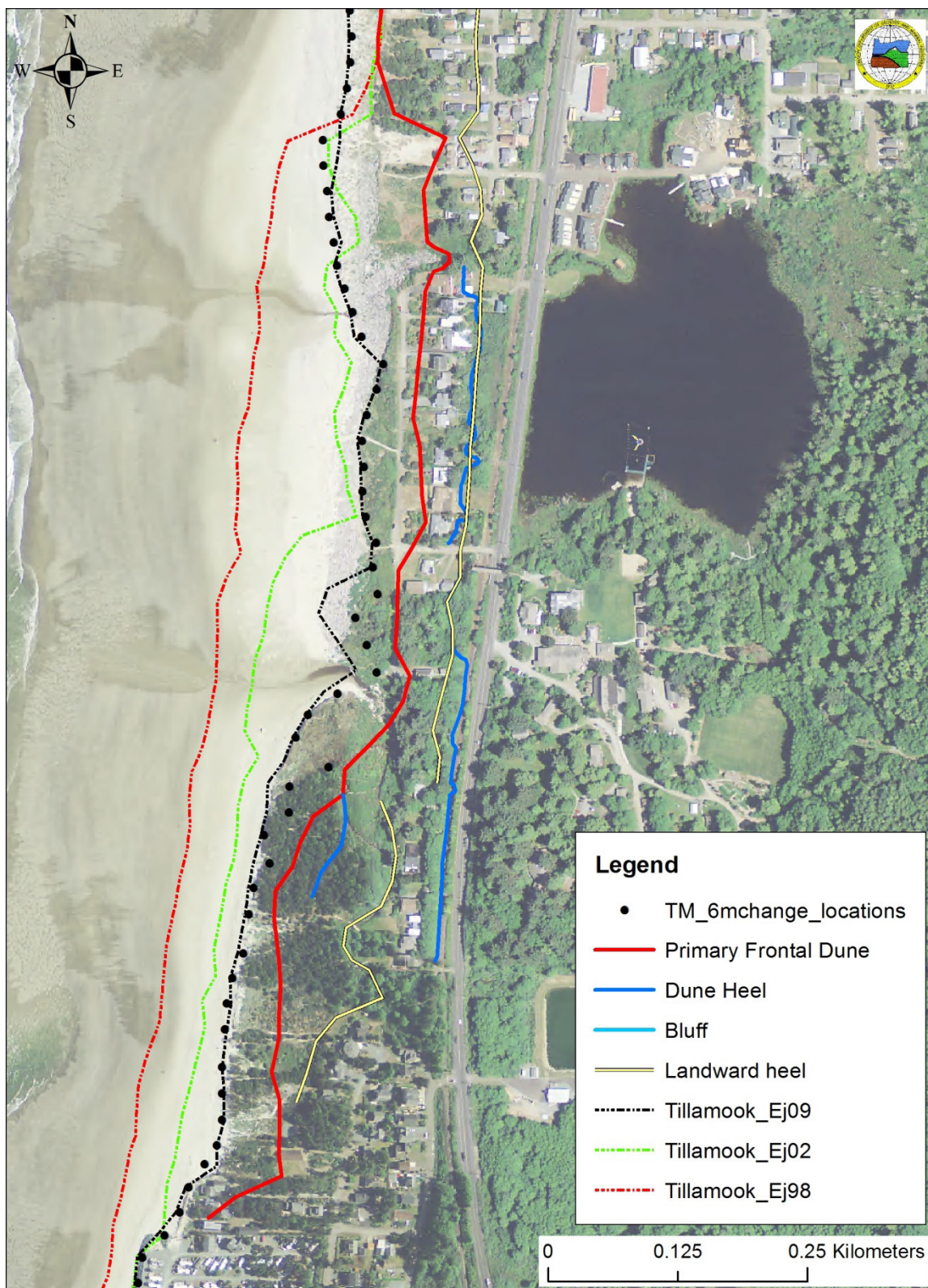


Figure 10. Map showing various geospatial layers that have been developed from the beach transect database. Example shown reflects a portion of the coast located just south of the community of Twin Rocks in Tillamook County.

5.0 CONCLUSION

The objective of this study has been to develop an entirely new coastal geomorphic database that describes the various morphological parameters of beaches, dunes, and bluffs along the central to northern Oregon coast, specifically in Clatsop and Tillamook Counties. The completed product includes a variety of geospatial data layers including transect locations; site-specific information on the *slope of the beach, dune, or bluff crest*; *coastal change information for selected years*; and *visual products* that synthesize several of the identified parameters, enabling easy access to information on beach, dunes, and bluffs. This study reflects a significant improvement of a previous effort undertaken by Allan and Hart (2005). The present study extends the earlier investigation by undertaking more detailed morphological analyses of the beaches and dunes, employing a higher sampling frequency (minimum profile spacing at ~ 25 m [82 ft] as opposed to 100 m [328 ft], i.e., 4 times the number of transects), and expanding the effort to include the coastal bluffs and headlands that, respectively, back and bound the pocket beach littoral cells along the Oregon coast. The final

outcome of this study is a detailed geospatial database of the beaches and bluffs on the northern Oregon coast that includes a variety of morphological information, such as slope of the beach, beach/dune (bluff) juncture elevation and positions, beach/dune (bluff) crest elevation and positions, dune (bluff) face slope, primary frontal dune locations, and landward limit of the lee or reverse slope of the foredune if present. In addition to site-specific information on the morphology of the coast, additional change data have been derived that describe the spatial (i.e., alongshore) and temporal changes taking place along the 6 m (19.7 ft) contour elevation, providing a measure of the beach following the major storms of the late 1990s. Hence, these latter data may be used to assess the response of beaches on a transect-by-transect basis in Clatsop and Tillamook Counties to specific time periods, when events occurred (e.g., the 1997-1998 El Niño winter) and lidar was collected, as well as enabling the entire suite of change data to be plotted for reaches of coast.

6.0 ACKNOWLEDGMENTS

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