Variation of Beach Morphology along the Saco Bay Littoral Cell

An Analysis of Recent Trends and Management Alternatives

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Stephen M. Dickson

Maine Geological Survey
DEPARTMENT OF CONSERVATION
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Contents

ABSTRACT 1

INTRODUCTION 1

HISTORICAL BACKGROUND 2
- Jetty Construction 2
- Dredging and Beach Nourishment 2
- Previous Studies 4
- Regional Planning 5

METHODS 5
- Coastline Orientation 5
- Sea Level Rise 5
- Estimated Net Erosion and Accretion 5
- Shoreline Type, Dry Beach Width, and Total Landward Width to Structures 6
- LIDAR Analysis 6

RESULTS 7
- Coastline Orientation 7
- Sea Level Rise (1962-1995) 7
- Estimated Net Erosion and Accretion (1962-1995) 7
- Shoreline Type, Dry Beach Width, and Total Landward Width to Structures 10
- Alongshore Variation of Beach Profile Shapes 12
- Mean Profile Shapes 12
- Variation of Maximum Profile Elevations (MPE) in Reference to Base Flood Elevations (BFE) 18
- Variation of Overall Beach Profile Slopes 20
- Estimated Net Volume Changes (1962-1995) 21

DISCUSSION 22
- Region 1 (Hills Beach) 23
- Region 2 (Camp Ellis, Ferry Beach, Bay View, and Kinney Shores) 24
- Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point) 25
- Region 4 (Western Beach) 27
- General Discussion 28
- Identification of Regions of Potential Concern 28
- Data and Method Limitations 29
- Correlations 35

RECOMMENDATIONS 37
- Regional Sediment Management 37
- Elevating Above Base Flood Elevations 38
- Widening Dry Beach Widths 38
- Increasing Total Landward Widths 38
- Plan for 100-yr Erosion 39
- Plan for 100-yr Accretion 45
- Consider Shoreline Structure Maintenance or Removal 45
- Proximity to Tidal Inlets 45
- Section 111 Plan Alternatives: Coastal Engineering and Mitigation at Camp Ellis 45

CONCLUSIONS 46

RECOMMENDATIONS FOR ADDITIONAL STUDY 46

CONTINUED RESEARCH 47

REFERENCES 47

APPENDIX A - LIDAR Images 49

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Variation of Beach Morphology along the Saco Bay Littoral Cell: An Analysis of Recent Trends and Management Alternatives

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ABSTRACT

Sandy pocket-beaches comprise only about 2 percent of the Maine coastline; however, they provide numerous economic, environmental, and recreational benefits. These beaches are typically confined into 'littoral cells' by tidal inlets and rocky headlands. Saco Bay, which includes approximately 8 miles of arcuate sandy shoreline, is bound by Fletcher Neck and the Saco River in the south and the Scarborough River and Prouts Neck in the north. This shoreline comprises the largest sand beach and salt marsh system in Maine. The primary source of sediment to the beaches in the bay is the Saco River (Kelley and others, 1995). The bay exhibits a dominant northerly-directed longshore transport direction (Barber, 1995; Kelley and others, 1989).

In 1869, the United States Army Corps of Engineers (Corps) initiated construction of shore-perpendicular jetties in an attempt to stabilize the inlet to prevent channel shoaling, and provide safe navigation for shipping. The structures have impeded the natural flow of sediment into the bay system, diverted sediment farther offshore and into deeper water, disrupted the existing ebb-tidal delta, and made the onshore movement of sediment much more difficult. It appears that the federal jetties have caused accelerated erosion rates on the order of 2-3 feet per year at Camp Ellis, a small beachfront community situated adjacent to the northern jetty (Duffy and Dickson, 1995). Substantial environmental, economic, and social impacts have resulted from erosion that has claimed over 30 homes in the last 100 years at Camp Ellis. The problem continues today, amplified each winter season by northeast storms that batter the southern Saco Bay shoreline with swells and storm surge.

Existing morphologic trends, topographic features, and shoreline types along the Saco Bay shoreline were identified using Light Detection and Ranging (LIDAR) data, aerial photographs, and field inspections. Shorelines from aerial photographs were digitized and recorded in the field using a global positioning system (GPS), and shoreline changes determined. By combining shoreline changes with beach profile data, volumetric estimates of changes in the subaerial-to-intertidal beach were made. Future positions of shorelines and areas possibly susceptible to flooding were projected using this data set. Coastal hazards were identified and preliminary beach management guidance provided.

The Corps, in association with local stakeholders, federal, and state agency personnel, are currently developing mitigation plans for Camp Ellis Beach under Section 111 of the Rivers and Harbors Act. Finally, alternative scenarios proposed by the Corps to alleviate erosion at Camp Ellis Beach are presented and discussed.

INTRODUCTION

The sandy pocket-beaches that comprise only 2 percent of the 3,500 mile Maine coastline provide numerous economic, environmental, and recreational benefits. These beaches are typically confined into 'littoral cells' by tidal inlets and rocky headlands. Saco Bay, which includes approximately 8 miles of arcuate shoreline (a littoral cell), is bound by Fletcher Neck and the

Saco River in the south and the Scarborough River and Prouts Neck in the north. The bay comprises the largest sand beach and salt marsh system in Maine (Figure 1). The primary source of sediment to the beaches in the bay is the Saco River, which provides an estimated 10,000 to 16,000 m^3 of sand per year (Kelley and others, 1995). The bay exhibits a dominant northerly directed alongshore transport direction (Barber, 1995; Kelley and others, 1989). Historically, riverine sediment entered the bay through the Saco River, was stored in an ebb-tidal delta, and wave-action periodically caused shoals to migrate landward and weld onto downdrift beaches.

In 1869, the United States Army Corps of Engineers (Corps) initiated construction of shore-perpendicular jetties in an attempt to stabilize the inlet to prevent channel shoaling, thereby providing safe navigation for shipping. The jetties have precluded the natural flow of sediment into the bay system by diverting sediment farther offshore and into deeper water, making the onshore movement of sediment a much more difficult process. Since construction, the federal jetties have caused accelerated erosion rates on the order of 2-3 ft per year at Camp Ellis, a small beachfront community situated adjacent to the northern jetty (Duffy and Dickson, 1995). Erosion has claimed over 30 homes in the last 100 years at Camp Ellis, and the problem continues today, amplified each winter season by northeast storms that batter the southern Saco Bay shoreline. A 1995 aerial photograph of the Saco River jetties, river channel and adjacent beaches is shown in Figure 2.

The objectives of this report are to: 1) discuss existing morphologic trends and features along the Saco Bay shoreline; 2) present recommendations for the management of Saco Bay's sandy beaches; and 3) discuss the status of federal involvement in mitigating shoreline erosion along Saco Bay.

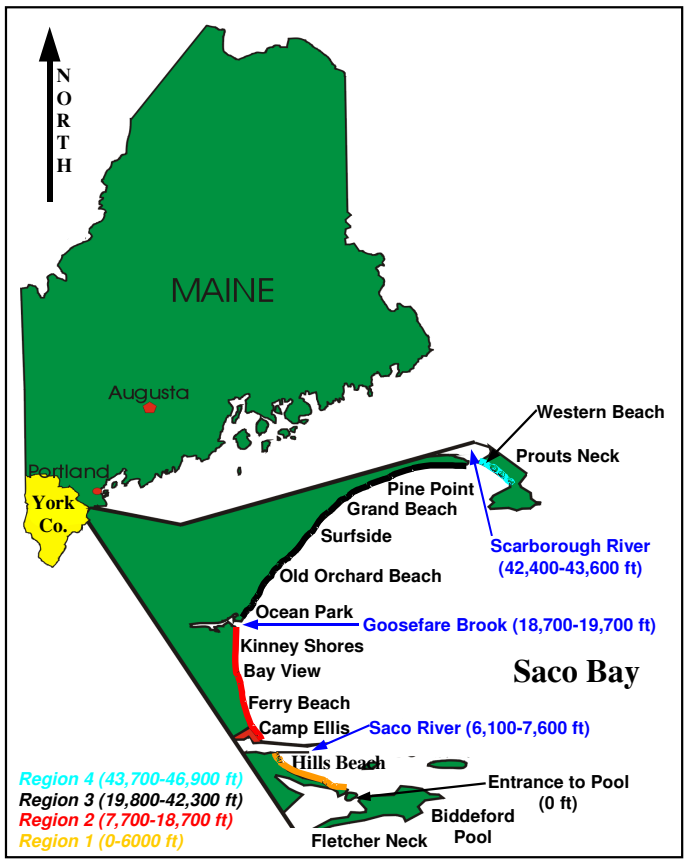

Figure 1. Site location map, including a close-up of the Saco Bay littoral, located within York and Cumberland Counties. Saco Bay is bound by Fletcher Neck to the south and Prouts Neck to the northeast. Alongshore distance begins approximately at the entrance to The Pool (0 ft) and ends at the southeastern end of Western Beach, at Prouts Neck (46,900 ft). Region 1 extends southeast-northwest along Hills Beach (light green, 0-6,000 ft). Region 2 extends roughly northwards from the north jetty of the Saco River to the south side of Goosefare Brook (7,700-18,700 ft). Region 3 extends from Goosefare Brook northeast to the Scarborough River. Region 4 extends northwest-southeast along Western Beach (43,700-46,900) to its terminus at the cliffs along Prouts Neck. Refer to *Results* section for further explanation.

HISTORICAL BACKGROUND

Jetty Construction

In the 1800s, the Saco River served as an integral harbor and port-of-entry for the textile mills of Saco and Biddeford. Due to navigational hazards caused by shoaling at the mouth of the river, the Corps initially placed wooden bulkheads and several buoys to mark shoaled channel areas in 1827. In 1865, Congress authorized the construction of a rock jetty at the northern end of the Saco River. Since initial construction in 1869, a southern jetty was added in 1890, and numerous improvements and repairs have been made to keep the jetties structurally sound and attempt to control river shoaling (Table 1).

Dredging and Beach Nourishment

Maintaining a safe, navigable channel at the Saco River has been a focus of the Corps since beginning the navigation project in 1827. Periodic dredging of the channel has been necessary to keep the navigation channel open. Although the actual volumes vary from report to report, Table 2 summarizes some of the dredging activity at the Saco River from 1827-1992. Most of the dredged sediment was used for beach nourishment at Camp Ellis. On average (from 1928-1992), the Corps dredged approximately 11,100 yd^3/yr from the navigation channel at the Saco River. From 1969-1996, the Corps has placed an average of 16,920 yd^3 of sand at Camp Ellis Beach as some form of beach nourishment. The Corps has also dredged extensively to maintain a navigable inlet at the Scarborough River at the northern end of Saco Bay (Table 3), however the majority of dredged material was discarded through offshore disposal. 1996 dredging of the Scarborough River resulted in the placement of approximately 90,000 yd^3 of sediment in a nearshore berm off of Camp Ellis Beach (Irish and Lillicrop, 1999). On average, the Corps dredged approximately 16,140 yd^3/yr for the Scarborough River navigation project.

Figure 2. Aerial view (1995) of the Saco River jetties, with portions of Hills Beach, Camp Ellis Beach, and Ferry Beach (not to scale).

TABLE 1. History of Saco River stabilization.

1827 Constructed two wooden piers, placed navigation buoys, removed obstructions.
1866 Northern jetty authorized by Congress.
1869 Northern jetty construction initiated.
1872 Northern jetty completed (4,200ft long, 20ft at base, 10ft wide at crest, to +10ft MLW).
1873 Jetty raised and strengthened at exposed places.
1883 Suggestion to raise jetty to +15ft MLW, extend to Sharp's Ledge, and construct a southern jetty to mitigate shoaling.
1888 Construction on north jetty in progress.
1890 South jetty construction authorized and initiated; north jetty raised to +15ft MLW for 2,100ft from seaward end.
1896 Completed repair and raising of north jetty to +15ft MLW to 3,840ft from seaward end. South jetty completed in 1897. Remaining 700ft of north jetty raised by 1898.
1900 Additional survey restates suggestion to extend northern jetty to Sharp's Ledge.
1912 Repair of jetties and extension of southern jetty completed. Construction of spur jetty, 400ft parallel to shore, 150ft seaward of shoreline.
1927 Construction to extend northern jetty additional 1,600ft seaward commenced; south jetty repaired.
1930 Repair on south jetty continued, including re-topping; northern jetty only extended 880ft seaward.
1935 Additional 860ft extension commenced; inner end of north jetty repaired.
1937 Northern jetty extended 830ft.
1940 Repairs recommended on spur dike and portions of northern and southern jetties.
1958 Maintenance and repair to increase height of inner end of northern jetty. Jetty extended shoreward to maintain connection to land.
1969 Raising (to +17ft MLW) and tightening of northern jetty completed.
1973 Maintenance of south jetty completed.

TABLE 2. Saco River dredging and Camp Ellis beach nourishment.

Year	Vol. (yd^3)	Disposal	Nourish. (yd^3)
1827	unknown	unknown	N/A
by 1872	109,959	unknown	N/A
1912	85,378	unknown	N/A
1919	"large quantity"	beach	Unknown
1928	82,969	unknown	N/A
1939	79,552	unknown	N/A
1940	62,977	unknown	N/A
1965	37,000	upland	N/A
1969	87,354	beach	87,354
1969	73,130	beach	73,130
1973	37,000	nearshore	N/A
1978	80,000	beach	80,000
1978	50,000	beach	50,000
1982	7,300	beach	7,300
1992	13,079	beach	Unknown
1992	85,935	beach	85,935
1992	24,990	channel	N/A
1996	N/A	nearshore	90,000**
TOTAL	**916,625**		**473,719**
AVG./yr (1928-1992)	**11,100**	**AVG./yr (1969-1996)**	**16,920**

** material from Scarborough River
(sources: Program for the Study of Developed Shorelines, 1996; Kelley and others, 1995; and Normandeau Associates, 1994)

TABLE 3. Scarborough River dredging

Year	Volume (yd^3)	Disposal
1956	128,099	inshore
1962	150,000	offshore
1965	32,577	offshore
1969	47,000	offshore
1973	188,800	offshore
1975	9,090	offshore
1996	90,000	nearshore**
TOTAL	**645,566**	
AVG./yr	**16,140**	

** material from Scarborough River
(sources: Program for the Study of Developed Shorelines, 1996; Kelley and others, 1995; and Normandeau Associates, 1994)

Previous Studies

Several studies, theses, dissertations, and reports have focused on coastal processes and sediment movement patterns within Saco Bay. In addition, the Corps conducted many studies, dating back to 1882, in conjunction with the federal project at the Saco River (Table 4).

Farrell (1972) noted a distinct fining in sediment size from south to north, in addition to accretion occurring at Pine Point, at the northern end of Saco Bay, and postulated a northerly dominant direction of sediment transport. Work by Wommack (1979) in support of a report prepared for the City of Saco also suggested a northerly-directed net transport direction. In addition, Nelson (1979) found significant evidence of a net northern transport based on analysis of historic shoreline changes. Recent work by Kelley and others (1995) and Barber (1995) created a sand budget for Saco Bay based on previous work by others, and coupled the use of side-scan sonar imaging, bottom sampling, and historical maps and aerial photographs to further conclude that not only is the dominant net transport in a northern direction, but that the Saco River has been and still is the major sediment source for Saco Bay.

The most complete Corps' study, completed in 1955, indicated that Camp Ellis underwent accretion immediately following construction of the northern jetty, from about 1872-1909. This accretion probably occurred due to the onshore migration of abandoned ebb-tidal delta shoals by wave action, consistent with similar phenomena seen at inlets following stabilization (Hansen and Knowles, 1988). However, since about 1909, Camp Ellis has undergone severe erosion. From 1859 to 1955, the Camp Ellis shoreline lost 61,933 m^3/yr of sand (USACE, 1955). This erosive trend has continued to the present on the order of 2-3 ft per year, resulting in the loss of 33 homes since 1968 (Saco Bay Planning Committee, 2000). For comparison, the majority of sandy beaches along Maine's coastline have an average annual erosion rate of generally 1 foot or less (Nelson, 1979). The high erosion rate at Camp Ellis may be attributed to several factors: 1) interruption of natural sediment supply to the downdrift beach and scouring adjacent to the jetty due to the northerly-directed alongshore current; 2) diversion of riverine sediment farther offshore into a deep-water ebb-tidal delta; and 3) wave focusing along Camp Ellis beaches due to reflection of waves by the jetty.

Throughout the history of the navigation project, the Corps maintained that 1) sediment transport was in a southern direction; 2) the main sediment source was reworked offshore material; and 3) there was no evidence that the federal project was responsible for erosion problems seen at Camp Ellis (USACE, 1955, 1976, 1991). In 1991, the Maine Department of Environmental Protection and City of Saco requested a study by the Corps under Section 111 of the River and Harbor Act of 1968 (PL 90-483), suggesting that the northern jetty of the Saco River navigation project was responsible for erosion problems in the area. The Corps conducted a Section 111 Study in 1992 in order to determine if shoreline damages in the vicinity of Camp Ellis were attributable to the federal navigation project. An alternatives analysis including five different potential solutions to the erosion problem was considered. Conclusions found that the existing structure appeared to be causing reflective forces that may be contributing to some extent to the erosion occurring in the area. However, it was also noted "significant erosion would likely occur even in the absence of the navigation project" (USACE, 1992). Because the potential benefits of several alternative solutions did not offset estimated costs of those solutions, no further federal involvement was deemed necessary at the time.

It was not until after a 1995 model study (Table 4) by the Corps' Waterways Experiment Station (WES) that the Corps ac-

TABLE 4. U.S. Army Corps of Engineers studies on beach erosion and jetty improvements in the Saco River area.

1882	Preliminary Examination *
1883	Survey Report *
1884	Preliminary Examination *
1885	Survey Report *
1910	Reports on Examination and Survey of Saco River *
1924	Reports on Preliminary Examination and Survey of Saco Harbor and River *
1930	Report on Saco River *
1934	Reports on Saco River *
1939	Report on Ferry Beach
1939	Preliminary Examination (Review of Reports) of Saco River
1955	Beach Erosion Control Report on Cooperative Study, Saco
1961	Beach Erosion Control Report on Cooperative Study, Hills Beach
1967	Detailed Project Report, Small Navigation Project, Saco River
1976	Erosion Reconnaissance Report, Camp Ellis Beach
1987	Definite Project Report, Section 14 Investigation, Emergency Shoreline Protection
1991	Assessment of Coastal Processes in Saco Bay
1992	Section 111 Reconnaissance Report, Beach Erosion Study
1995	Model Study of Beach Erosion
2001	Draft Section 111 Shoreline Damage Mitigation Study

** submitted to Congress for review and approval*

knowledged that the dominant sediment transport direction is from south to north, and that the jetty structure caused an increase in wave sizes due to the reflectivity of the jetty, which subsequently caused increased erosion along Camp Ellis (USACE, 1995a). This study was based on the construction of a 1:100 scale physical model at the Corps' WES laboratory in Vicksburg, Mississippi. The model study included the modeling of several mitigation alternatives, including structural improvements and beach-fill.

Regional Planning

While Camp Ellis and parts of Ferry Beach and Hills Beach are experiencing accelerated erosion, Old Orchard Beach and Pine Point at the northern end of the bay are experiencing accretion (e.g., Pine Point grew 137 m seaward from 1877 to 1923 (Farrell, 1972)). Therefore, beach management issues along Saco Bay need to be dealt with on a regional basis.

The Southern Maine Beach Stakeholder Group, in connection with the Maine State Planning Office, published a document titled *Improving Maine's Beaches* in April 1998 (MSPO, 1998). The Group, comprised of local property owners, municipal officials, business, environmental, and state organizations from within Saco Bay and beyond, outlined issues of concern and made recommendations on how to address them.

In 1999, the Saco Bay Planning Committee was formed as a result of the *Improving Maine's Beaches* document. This Committee released the Saco Bay Regional Beach Management Plan (SBPC, 2000), which focused on identifying and addressing beach management issues in Saco Bay at local, state, and federal levels. Emphasis was placed on the federal jetty at Camp Ellis as having a "…profound effect on the sand flow for *all* of Saco Bay, depriving the southern end….of sand and creating an abundance at the northern end." Such regional planning is vital for the long-term solution of the localized erosion problem at Camp Ellis.

The Saco Bay Implementation Team, comprised of property owners, municipal officials, and state and federal organizations (including the Corps), has been meeting for several years now in hopes of developing a solution to the erosion problems at Camp Ellis Beach. In 2001, Congress appropriated $350,000 to the Corps for a design/feasibility study, followed by $1.2 M funding in 2002 for jetty alterations.

METHODS

In preparing a 'regional' analysis of beach erosion, several different sources of data were available. Surprisingly little beach profile data was available from the Corps considering the number of reports (Table 4) and the length of Corps involvement with the Saco River navigation project. Therefore, historic shoreline change was documented in this report using aerial photographs from the Maine Geological Survey (MGS). Beach profile data were created using topographic data from a Light Detection and Ranging (LIDAR) flight completed along the Maine shoreline by the National Oceanic and Atmospheric Administration (NOAA) in 2000. Each of the particular methods employed are discussed below.

Coastline Orientation

The analysis of large-scale morphologic variation begins with the determination of general orientations of the shoreline (Gorman and others, 1998; Wijnberg, 1995). Orientation provides an initial indication of the hydrodynamic forces acting on the beach, for example, the shoreline's exposure to incoming wave energy from the Gulf of Maine.

The frequency and alongshore variation of orientations were determined for coastline segments at 100-foot intervals along the Saco Bay shoreline. Orientations were measured at the wet-dry beach intersection using 1995 aerial photograph mosaics (see *Estimated Net Erosion and Accretion*). All orientations reference the meteorological convention (compass bearing, degrees clockwise from True North).

Sea Level Rise

Sea level data was taken from the NOAA Portland, Maine tide gauge (#8418150). The average annual rates of sea level rise were determined for the overall time period of tide gauge data collection (1912-2001), and for this specific study period (1962-1995). First order linear regression (e.g., "rise over run") was used to determine the average rates of sea level rise for both time periods.

Estimated Net Erosion and Accretion

Aerial photographs were used to estimate net erosion and accretion along the Saco Bay shoreline, from Hills Beach in the south to Pine Point in the north. Photographs from 1962 and 1995 were chosen in order to document shoreline position changes. Photographs were scanned using an Epson Expression™ 1600 scanner at 600 dpi and digitized using Corel Photo-Paint™ and CorelDraw™ Version 8. 1962 photographs were standardized to the 1995 photograph scale (1:12,000). Control points, including homes, roadways, and existing structures (e.g., seawalls), were used on each individual photograph during the scaling process. After each photograph was set to the 1995 scale, 1962 and 1995 overlay-mosaics of the Saco Bay shoreline were created. Control points were then checked again for accuracy.

Two Erosion Reference Features (ERFs) were used for local conditions: 1) the seaward edge of vegetation; and 2) in developed areas with no vegetation, the seaward edge of shoreline structures. These ERFs were digitized along the length of the

bay for the 1962 and 1995 photographs. The disadvantage of using the seaward edge of vegetation or existing structure in determining net erosion is that it fails to identify erosion if the structure or vegetation line is held in place by reconstruction or maintenance over the study time period. This may be interpreted as stability, when in actuality, erosion has occurred on the beach.

The 1962 and 1995 vegetation lines were overlain on the 1995 aerial photograph. Transects were set at 100 foot intervals along the shoreline (from the southern end of Hills Beach northward to the eastern end of Western Beach at Prouts Neck (a total length of approximately 46,900 ft, roughly 9 miles) and the net erosion or accretion (in ft) was determined between each subsequent shoreline position.

Shoreline Type, Dry Beach Width, and Total Landward Width to Structures

Using the mosaic of 1995 aerial photographs, four different shoreline types were found to exist (from a seaward to landward direction): 1) seawall to structure; 2) vegetated dune to structure; 3) vegetated dune and seawall to structure; and 4) seawall and vegetated dune to structure. For this report, portions of the shoreline comprised of rock outcrops are considered stabilized.

Aerial photographs were also used to determine the distance (x) from the seaward edge of an existing structure or vegetated dune to the first habitable dwelling structure (i.e., home, motel, etc.) at each 100-foot interval. Next, dry beach widths (*dbw*) along Saco Bay were mapped during field investigations conducted on August 21 and August 26, 2002. A Garmin® GPS 12 Map handheld was utilized to map the high water line along the beaches, in addition to the seaward edges of vegetated dunes and stabilization structures. The GPS was set to record track points at an interval of every second in the WGS84 datum. Dry beach width data was projected using ArcView® GIS 3.2. *Dry beach width (dbw)* and distance from seaward edge of structure (x) data were combined to create the *Total Landward Width (Z)* criteria

$$\text{Total Landward Width (Z)} = x + dbw$$

An example is provided below for a vegetated dune to structure shoreline type (Figure 3).

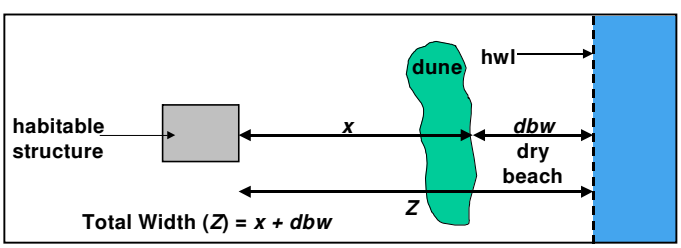

Figure 3. Calculation of Total Landward Width for a vegetated dune to structure shoreline type.

LIDAR Analysis

Beach Profiles. Topographic data from a 2000 LIDAR flight (September 28-29, 2000) was available from NOAA for Saco Bay (NOAA, 2000). Data was projected in ArcView® GIS 3.2 using the LIDAR Data Handler and Spatial Analyst extensions. Beach profile vertical and horizontal data are referenced to the North American Vertical Datum of 1988 (NAVD88) and the North American Datum of 1983 (NAD83), respectively. Beach profiles were created at each 100-foot alongshore transect used for historical shoreline changes. Profiles generally started near the 13 ft (~4 m) contour (landward of the dune crest, where applicable) and extended seaward to near -3ft (–1 m) NAVD. Beach profile data were exported into Microsoft® Excel and MATLAB® for further analysis. Exported images of LIDAR data utilized for this study are in Appendix A.

Maximum Profile Elevations and Base Flood Elevations. The maximum elevations (e.g., dune crest or top of seawall) at each 100-foot interval along the Saco Bay shoreline were determined from beach profiles created using the LIDAR topographic data. These elevations were compared with the Base Flood Elevations (BFE) taken from Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM) to determine possible flood-prone sections of the Saco Bay shoreline.

Beach Slopes. For each beach profile created, beach slope values were calculated using a first order polynomial (linear) expression for profiles from their maximum to minimum elevations

$$h=Sx+c$$

where S is profile slope, x and h are associated horizontal and vertical values, and c is the y-intercept (Figure 4).

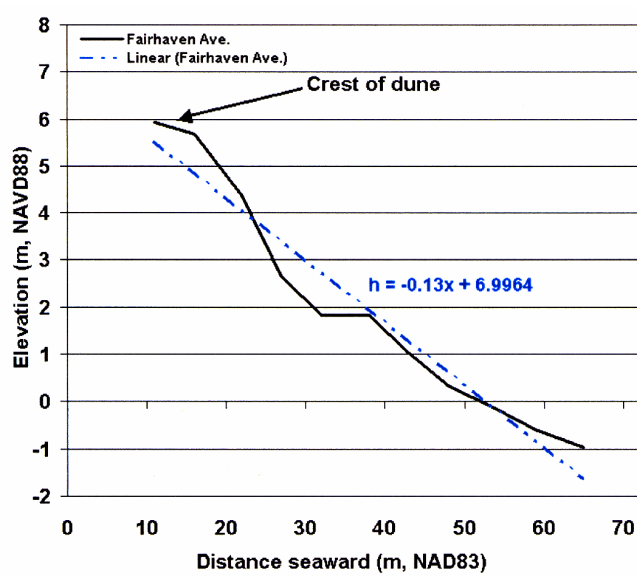

Figure 4. Graph of a beach profile near Fairhaven Avenue along Camp Ellis Beach.

Estimated Net Volume Changes. Net volumetric changes were estimated using LIDAR profile data in conjunction with net erosion and accretion rates determined from aerial photographs. Due to a lack of profile data from 1995 and 1962, it was assumed that each 2000 LIDAR profile was representative of existing beach conditions during both of those time periods. Therefore, by using net erosion or accretion values, profiles were offset either landward (erosion) or seaward (accretion), and the resulting area of change (*A*) was determined using the expression:

$$A = L \, x \, H$$

where *L* is the length of the rectangle created and *H* is the height. Assuming that each profile was representative of the beach 50 ft (15 m) in either alongshore direction of its location (for a total of 100 ft), the net volumetric change for each profile transect was determined using the simplified calculation:

$$V = L \, x \, W \, x \, H$$

where the *W* is width of shoreline represented by the beach profile (100 ft, 30.5 m). Because the LIDAR beach profiles only extend to a vertical elevation of approximately –3 ft (-1 m) NAVD, volumes calculated only *include the dune, berm, and a portion of the intertidal segment* of the beach, and in no way represent volume changes undergone by the entire beach profile. Figure 5 is a schematic of this calculation. Volumes were summed for different regions in order to determine overall volume changes for each region from 1962 to 1995 (see regional delineations below under *Results*).

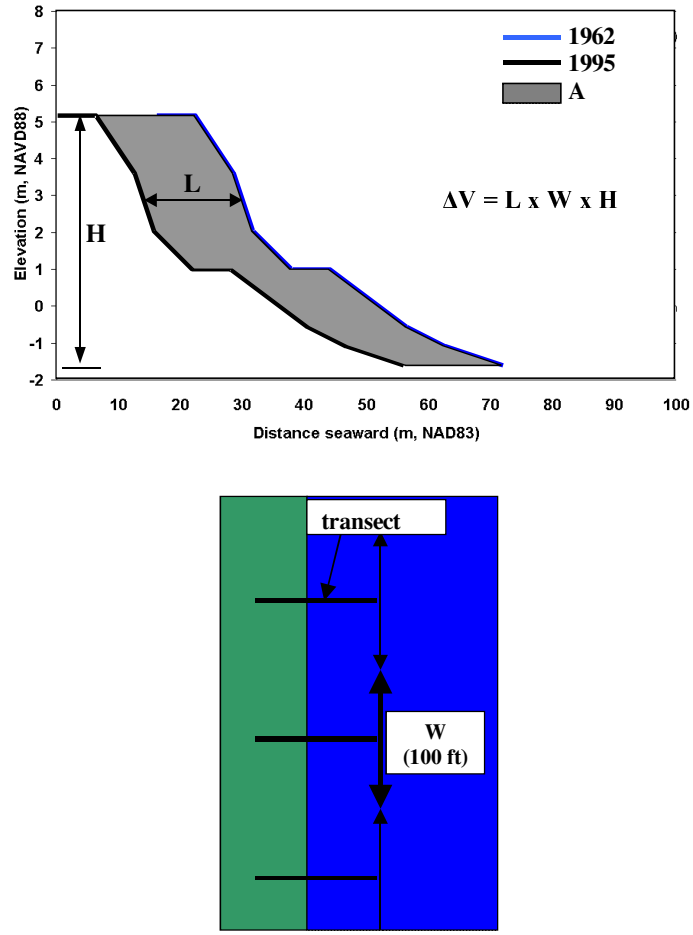

Figure 5. Schematic representation of volumetric change calculation.

RESULTS

Alongshore variations (from south to north) of different shoreline characteristics (e.g., coastline orientation, net erosion or accretion, etc.) along the Saco Bay shoreline are presented in Figures 9-23. The Saco Bay shoreline was divided into four different regions based on morphologic and littoral characteristics, as shown in Table 5A and illustrated on Figure 1. Regions were further subdivided into compartments, and labeled alphabetically (Table 5B). *All distances are referenced to zero (0) being the southern end of Hills Beach, near the entrance to The Pool.* Results are generally presented in relation to the different regions (and their compartments) described.

Coastline Orientation

Mean orientations for each region and compartment are presented in Table 5. Coastline orientation varies from 100-175° from true north (TN) within region 1, from 135-190° in region 2, from 115-270° in region 3, and from 115-200° in region 4 (Figure 6). A graph illustrating the percent occurrence of coastline orientations (every 10 degrees) shows that approximately 23% of the entire bay shoreline is oriented between 211-220° (corresponding with region 3), with a secondary peak of 12% at 171-180° (Figure 7).

Sea Level Rise (1962-1995)

The average annual rate of sea-level rise for the Portland tide gauge's overall record (1912-2001) was 1.9 mm/yr (Figure 8A). The average annual rate of sea-level rise during the study period (1962-1995) was slightly lower at 1.1 mm/yr (Figure 8B).

Estimated Net Erosion and Accretion (1962-1995)

Figure 9 illustrates the patterns of net erosion and accretion along Saco Bay from 1962-1995. The Saco Bay shoreline in general is relatively stable to accretive, however several pockets of distinct erosion exist in the Camp Ellis area (7,800-12,800 ft). The areas of largest net accretion are located in region 1 (1,000-2,000 ft, and 4,000-6,000 ft), and region 3

TABLE 5. A) Four regions of Saco Bay based on littoral boundaries;

Region	Distance (ft)	Mean Orientation (° from N)	South Boundary	North Boundary	Towns/Beaches
1	0-6,000	134	N side of Pool	S jetty Saco River	Hills Beach
2	7,700-18,700	174	N jetty Saco River	S side Goosefare Brk	Camp Ellis, Ferry Beach, Bay View, Kinney Shores
3	19,500-42,600	225	N side Goosefare Brk	W jetty Scarborough River	Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point
4	43,700-46,900	140	Ferry Rocks, Scarborough River	Bluffs Prouts Neck	Western Beach

B) Compartments designated within each region based on morphologic characteristics.

Region	Compartment	Distance (ft)	Mean Orientation (° from T N)	South Boundary (approx)	North Boundary (approx)	Towns/Beaches
1	A	0-2,000	117	N side of Pool	Surf St	Hills Beach
	B	2,100-4,000	124	Surf St	N end seawall	Hills Beach
	C	4,100-6,000	160	N end seawall	S jetty Saco River	Hills Beach
2	A	7,700-12,700	168	N jetty Saco River	Pond Ave, Long Pond	Camp Ellis, Ferry Beach
	B	12,800-18,700	178	Pond Ave, Long Pond	S side Goosefare Brk	Bay View, Kinney Shores
3	A	19,700-25,400	205	N side Goosefare Brk	Fernald Ave	Ocean Park, OOB
	B	25,500-35,800	217	Fernald Ave	Little River Rd	OOB, Surfside, Grand Beach
	C	35,900-42,300	254	Little River Rd	W jetty Scarborough River	Grand Beach, Pine Point
4	A	43,700-44,800	125	E side Scarborough River	Hole #2	Western Beach
	B	44,900-46,900	149	Hole #2	Bluffs Prouts Neck	Western Beach

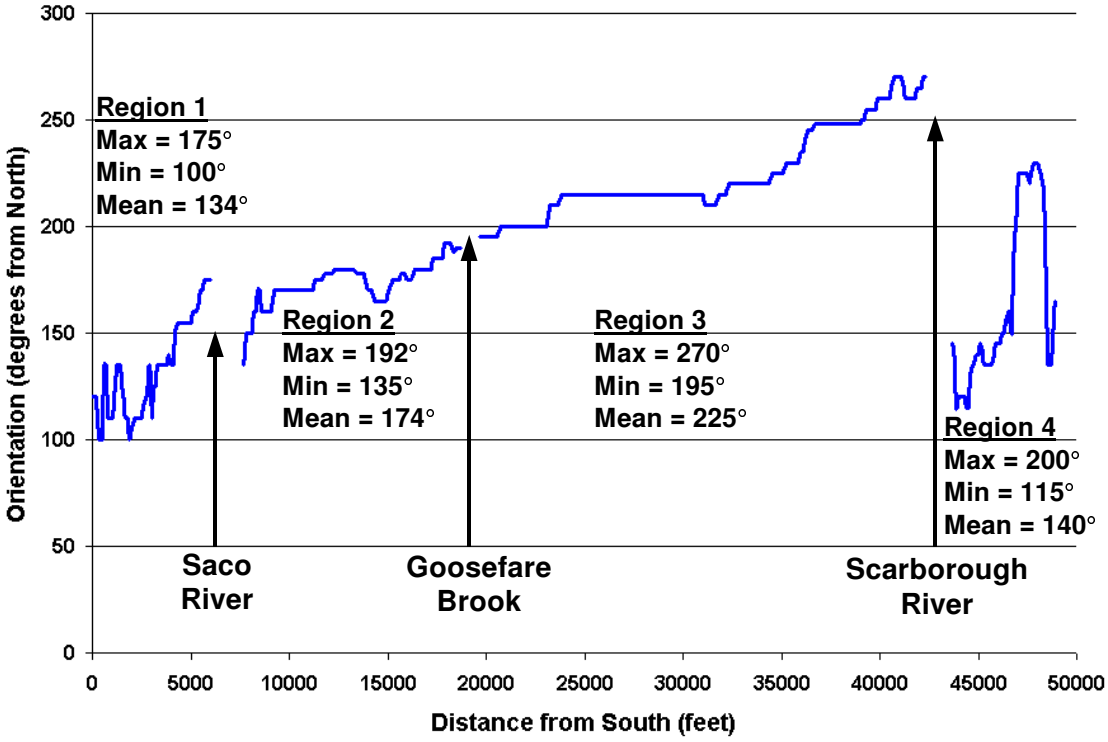

Figure 6. Longshore variation of coastline orientation (meteorological convention, degrees from North). Note the dramatic increase in orientation within region 1 (0-6,000 ft), and the gradual increase in orientation through regions 2 and 3.

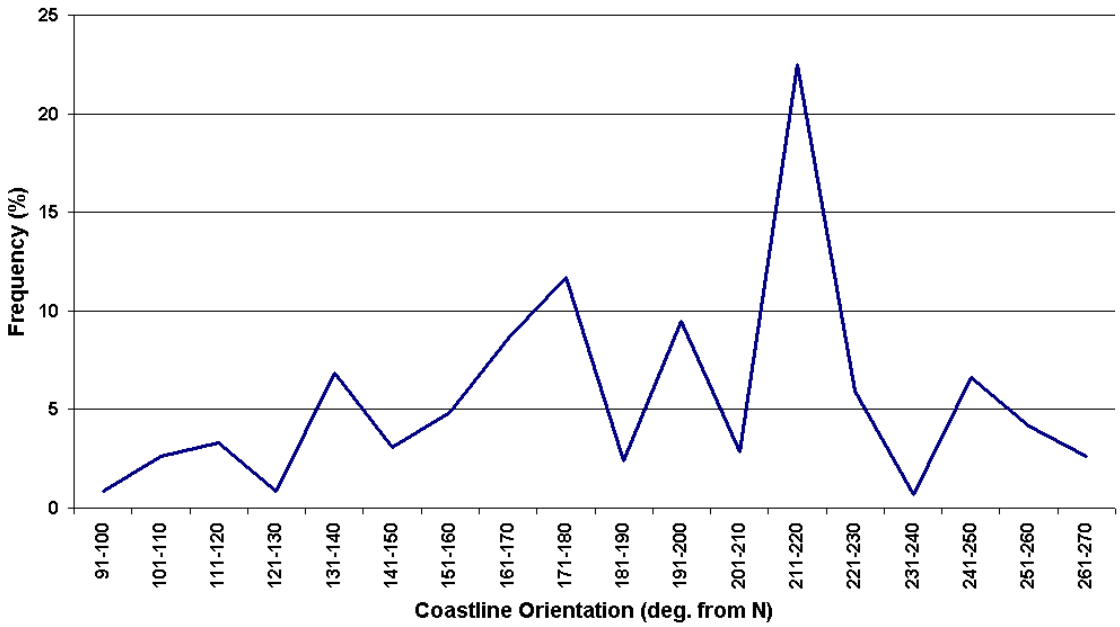

Figure 7. Percent occurrence (frequency) of coastline orientations along Saco Bay. Primary peak (211-220°) relates to region 3, while secondary peak (171-180°) relates to stretches of shoreline within region 2.

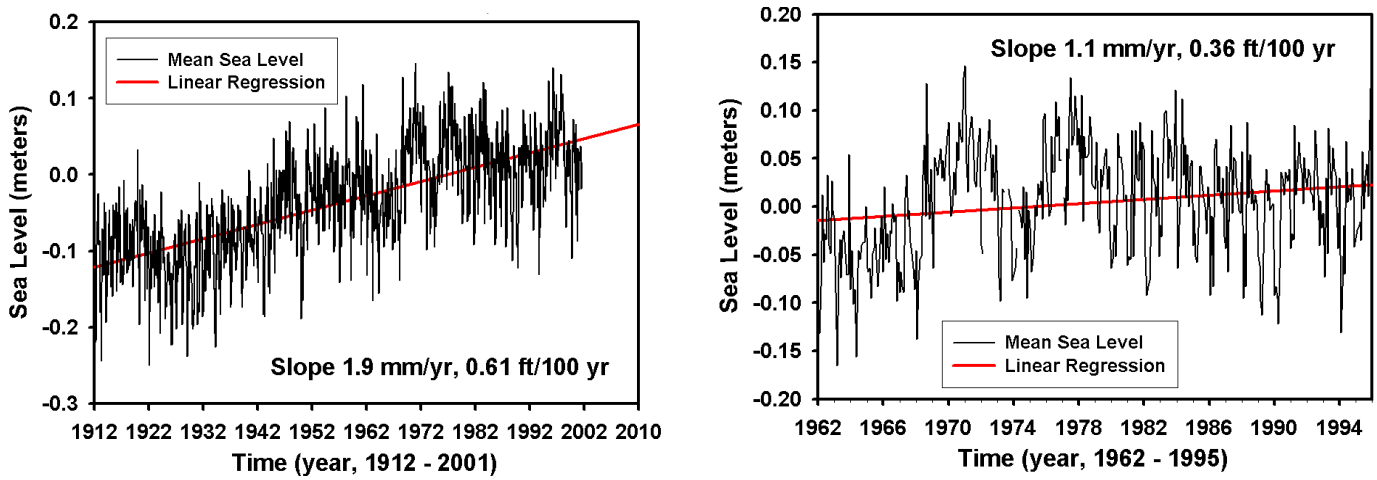

Figure 8. A) Average annual mean sea level for the time period 1912-2001, taken from the Portland, ME tide gauge (NOAA #8418150). The average annual rate of rise is 1.9 mm/yr. B) The average annual sea level rise for the study period (1962-1995) is slightly lower at 1.1 mm/yr.

(23,500-25,600 ft and 37,000-42,600 ft). The highest net accretion was over 300 ft (~5,800-6,000 ft), nearest the southern jetty of the Saco River.

Region 1 (Hills Beach): Accretion and segments of little shoreline change dominate the shoreline south of the Saco River (Figure 9). This region was divided into three distinct compartments. Compartment 1A stretches from The Pool (0 ft) northwestwards approximately 2,000 ft to Surf Avenue. The southernmost portion of compartment 1A (0-800 ft, north to near Sky Harbor Drive) is rocky headland. The beach from here northward to near Surf Avenue (2,000 ft) exhibits high net accretion. Compartment 1B encompasses the central portion of Hills Beach (2,000-4,000 ft, the narrowest part of the island near 4,000 ft), and is generally stable, with a small pocket of slight net erosion (~ -50 ft) near Surf Avenue (2,000 ft). Pockets of high net accretion (>100 ft) are located within compartment 1C (4,100-6,000 ft) with the largest net accretion (~300 ft) occurring adjacent to the southern Saco River jetty.

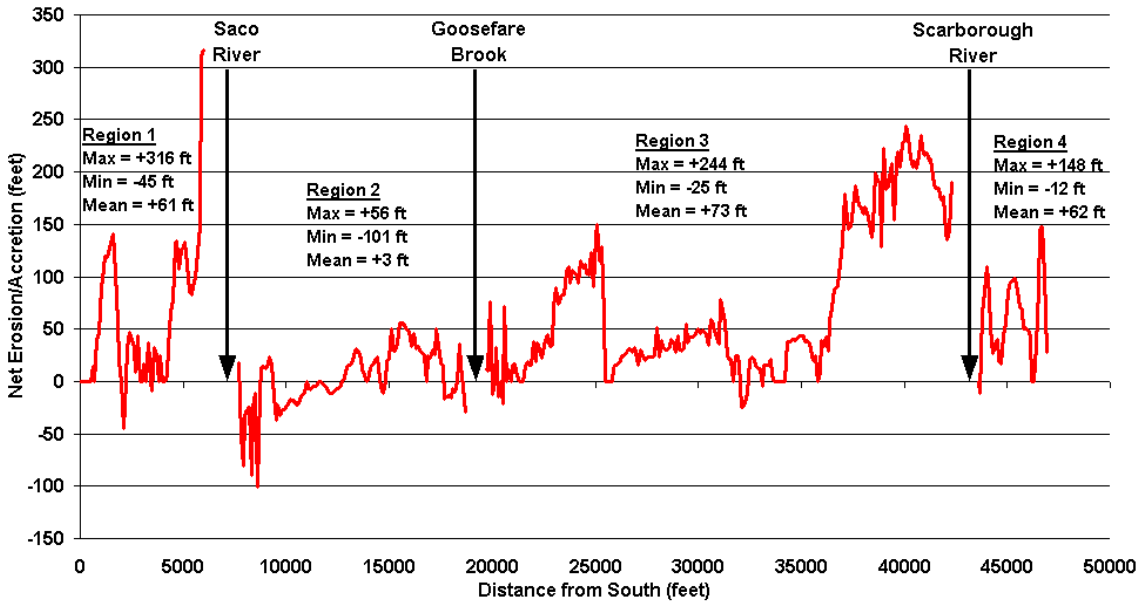

Figure 9. Variation of net erosion and accretion along Saco Bay, based on data from 1962-1995. Erosion is concentrated mostly within the southern part of region 2 (7,700-12,700 ft). Areas of highest net accretion are on the southern side of the Saco and Scarborough River jetties within Regions 1 and 3.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): The shoreline in this region has undergone the highest net erosion along Saco Bay based on data used for this study (Figure 9). The majority of erosion is concentrated within a 5,000 ft compartment (2A) north of the Saco River (7,700-12,700 ft), stretching roughly from Bay Avenue in Camp Ellis to near Pond Avenue in Ferry Beach. High erosion (up to 100 ft) is concentrated in a 1,000-foot stretch directly adjacent to the jetty, from Bay Avenue north to Lower Beach Avenue, while net erosion is generally on the order of -20 to -40 ft from 1,400-5,000 ft north of the jetty, from Sunrise Avenue in Camp Ellis to approximately 1,000 ft north of Pond Avenue in Ferry Beach, near Long Pond. A small pocket of generally stable shoreline extends from Lower Beach Avenue to Sunrise Avenue (8,700-9,200 ft) in Camp Ellis.

A zero crossing occurs near 12,800 ft (5,000 ft north of the jetty), in Ferry Beach. This designates the southern extent of compartment 2B. Accretion generally extends from north of Long Pond to Outlook Avenue in Kinney Shores (near 17,000 ft), with intermittent pockets of erosion and accretion adjacent to Goosefare Brook (17,000-18,700 ft).

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): The shoreline along region 3 is relatively stable to highly accretive, with only several small pockets of net erosion, generally 20 ft or less. Net accretion is generally 60 ft or less from 19,500-23,000 ft, generally from Goosefare Brook north to near Odessa Avenue in Ocean Park, and 25,500-36,400 ft, from Fernald Street in Old Orchard Beach northeast to near Little River Road in Grand Beach. Highest net accretion (>60 ft) occurs from 23,100-25,400, from Odessa Avenue in Ocean Park to Fernald Street in Old Orchard Beach, and from 36,500-42,300 ft, near Little River Road northeast to the southern Scarborough River jetty.

Region 4 (Western Beach): Western Beach underwent accretion over the 33-year study period. The majority of accretion has been concentrated along compartment 4B, nearer to Prouts Neck, while areas of less accretion are near the Scarborough River.

Shoreline Type, Dry Beach Width, and Total Landward Width

Figure 10 illustrates the variation of dry beach and total widths along the Saco Bay shoreline. Mean values for dry beach widths and total widths for Saco Bay as a whole, and for each region, are presented in Table 6. Region 4, Western Beach, has been excluded since no dry beach width data has been collected to date, and there are no habitable structures along this region. In terms of dry beach widths, for the overall bay, shorelines comprised of a combination of dune/seawall or seawall/dune are fronted by the widest dry beaches; surprisingly, the dry beach widths in dune-only shorelines are the thinnest. In terms of total widths (from the HWL to the first habitable structure), it seems that shorelines fronted by dunes are the widest.

Region 1 (Hills Beach): The Hills Beach shoreline is comprised of seawalls, rock outcrops, or vegetated dunes. Bedrock coastline dominates the southernmost portion, while the central section, from north of Surf Avenue to the narrowest part of the island (approximately 2,900-4,200 ft) is fronted by seawalls. The south-central and northern portions of region 1 are comprised of

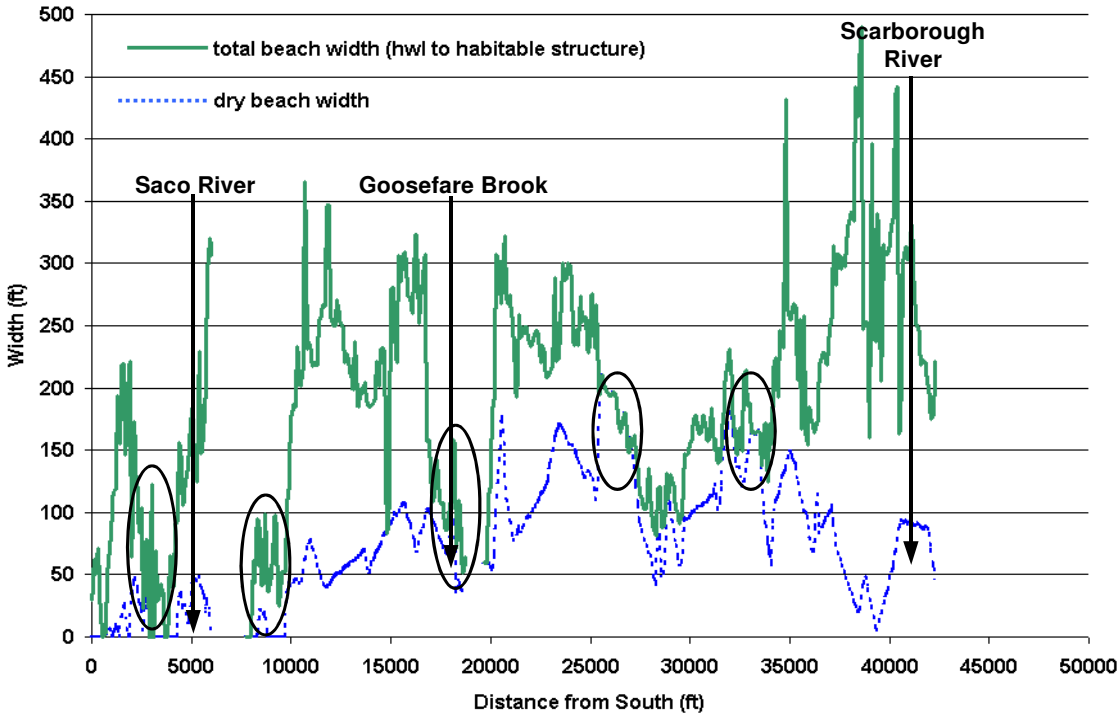

Figure 10. Variation of total width (from high water line landward to first habitable structure) and dry beach width (high water line to dune/seawall). Shoreline stabilized by seawalls only are circled. These segments exhibit the shortest total widths along Saco Bay. Region 4 was excluded because dry beach widths along Western Beach were not determined, and virtually no habitable structures exist along the shoreline of this region.

TABLE 6. A) Mean dry beach widths and total widths for overall bay.

	Overall Bay – mean values (ft)			
Characteristic	sw	sw+du	du+sw	du
Dry Beach Width	69	92	103	56
Total Width	97	180	201	232

B) Mean dry beach widths and total widths for each region. Region 4 was excluded since no habitable structures are located along shoreline. Highest values in each category are marked in bold.

	Region 1 – mean values (ft)				Region 2 – mean values (ft)				Region 3 – mean values (ft)			
Characteristic	sw	sw+du	du+sw	Du	sw	sw+du	du+sw	du	sw	sw+du	du+sw	du
Dry Beach Width	0	N/A	N/A	23	20	70	75	67	153	133	107	68
Total Width	40	N/A	N/A	151	60	180	192	241	164	179	203	274

Key: sw = seawall; du = dune; du+sw = dune and seawall; sw+du = seawall and dune

vegetated dune, and correspond with the widest distances to habitable structures. Distances from the seaward edge of dunes/structures appear largest in front of vegetated dunes, and smallest in front of the artificially stabilized stretches of shoreline along Hills Beach.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): Seawalls stabilize the first 2,000 ft of compartment 2A (Camp Ellis). Intermittent stretches of vegetated dune and vegetated dune backed by seawall extend from Beacon Avenue in Camp Ellis north to south of Stowe Avenue in Ferry Beach (9,600-13,800 ft). Vegetated dune and seawall combinations comprise the southern shoreline of compartment 2B (13,900-15,200 ft, Stowe Avenue north to Bay View Avenue). Naturally vegetated dune stretches from 15,300-16,900 (Bay View Avenue to Outlook Avenue). A mix of vegetated dune and seawall, seawall and vegetated dune, and only seawall completes the stretch of shoreline from 17,000-18,700 ft from Outlook Avenue north to Goosefare Brook. Vegetated dune segments of the shoreline are generally wider than stretches of shoreline stabilized with seawalls.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): The majority of region 3 shoreline includes a seawall in combination with a dune, although the northernmost stretch from near Grandview Avenue in Surfside north to the southern Scarborough River jetty (32,800-42,600) is fronted by vegetated dune only (compartments 3B and C). The widest distances from dune to habitable structure along the entire Saco Bay shoreline exist within compartment 3C, at the northern end of this region. Vegetated dune backed by a seawall is the most common shoreline type, although several stretches of seawall backed by vegetated dune, and seawall only are apparent.

Region 4 (Western Beach): Western Beach fronts a golf course and therefore supports very few structures or seawalls. Vegetated dune is the dominant shoreline type within compartments 4A and 4B.

Alongshore Variation of Beach Profile Shapes

Several distinct variations exist among beach profile shapes along the Saco Bay shoreline. In general, low profile elevations and relatively steep slopes dominate the southern portion of the bay (region 1 and part of region 2), from the entrance to The Pool in Hills Beach north to Long Pond in Ferry Beach (0-12,700 ft). Profiles tend to flatten and attain higher elevations from compartment 2B northward, past Goosefare Brook, to the south-central portion of Old Orchard Beach (compartment 3B). Here, profile elevations decrease dramatically, and profile slopes flatten substantially. Northwards, within compartment 3C, profiles appear to shallow seaward, but increase in overall elevation.

Alongshore variations in beach profile shapes are presented in three-dimensional line and color interpolated plots in Figure 11A and 11B for the entire Saco Bay. In addition, similar plots have been created illustrating variations within the compartments of each region (Figures 12-15).

Region 1 (Hills Beach): Hills Beach profiles (Figures 11, 12) appear relatively steep, especially within the central compartment (1B), and attain maximum elevations of generally 15 ft or less. Profiles in compartments 1A and 1C are slightly flatter. Profile maximum elevations dip to near 12 ft within the northern part of compartment 1C.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): Region 2 (Figures 11, 13) exhibits a dramatic alongshore variation in beach profile shapes, in both slope and elevation. Profiles nearest the Saco Bay north jetty (compartment 2A) are extremely steep, and generally attain depths of -3 ft within 200 ft of the dune or seawall crest. Profile elevations are generally less than 15 ft in the immediate vicinity of the jetty (~2,000 ft north of the jetty). Within compartment 2B (from Fairhaven Avenue northwards), there is an increase in profile elevations and decrease in slope. Closest to Goosefare Brook, however, profiles tend to steepen.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): Profiles along the central to northern portions of Saco Bay (Figures 11, 14) achieve their highest elevations from Goosefare Brook northeast to near Fernald Street in Old Orchard Beach (compartment 3A), and the 2,000 ft closest to the Scarborough River southern jetty (compartment 3C, from the Avenue Five Extension northeast to the Scarborough River). Compartment 3B, the central stretch of the region, exhibits relatively low (generally 15 ft maximum elevation or less), flat profiles. These profiles appear highly uniform in overall shape and slope.

Region 4 (Western Beach): Profiles along Western Beach (Figures 11, 15) are relatively steep nearest the Scarborough River (compartment 4A), and substantially flatten farther away from the river, to the southeast (compartment 4B).

Mean Profile Shapes

Mean beach profiles were computed for each region and their respective compartments. Regional mean profiles are presented in Figure 16. Compartmental mean profiles are shown in Figures 17-20. All mean profiles were offset to 0 NAVD for ease of comparison. Mean profiles from the different regions exhibit very different shapes, from steep and somewhat reflective, to gently sloped and dissipative. The mean profile from region 1 exhibits the steepest slope and lowest maximum elevation, while region 3 is the most dissipative profile overall. The region 2 mean profile achieves the highest elevation, and exhibits a slope in between those of the other regions. The region 4 mean profile falls in between the mean shapes of regions 1 and 2.

Region 1 (Hills Beach): Region 1 profiles fall into compartments 1A, 1B, and 1C based on overall profile shapes (Figure 12). Mean profiles calculated for each compartment exhibit different features (Figure 17). Compartment 1A (0-2,000 ft), exhibits the best-developed dune along Hills Beach. Compartment 1B achieves the same maximum elevation (14 ft), but is much steeper in slope. The mean profile, representing beach conditions from the thinnest part of the island north to the southern jetty of the Saco River, reaches a relatively low maximum elevation (12 ft) and has the flattest overall slope.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): Distinct profile shapes are apparent between compartments 2A and 2B (Figure 13). Profiles from the north Saco River jetty northwards approximately 5,000 ft (to near Long Pond) are relatively steep and low. Profiles from compartment 2B are much higher and show much more variability in their dune shapes. Mean profiles for the compartments are similar in overall shape and slope; however, the 2A mean profile reaches an elevation of only 13 ft, and is slightly steeper than the mean profile from compartment 2B (Figure 18).

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): The first profile compartment (3A) extends from Goosefare Brook northeast to near Fernald Avenue in Old Orchard Beach, and exhibits the best-developed dunes of

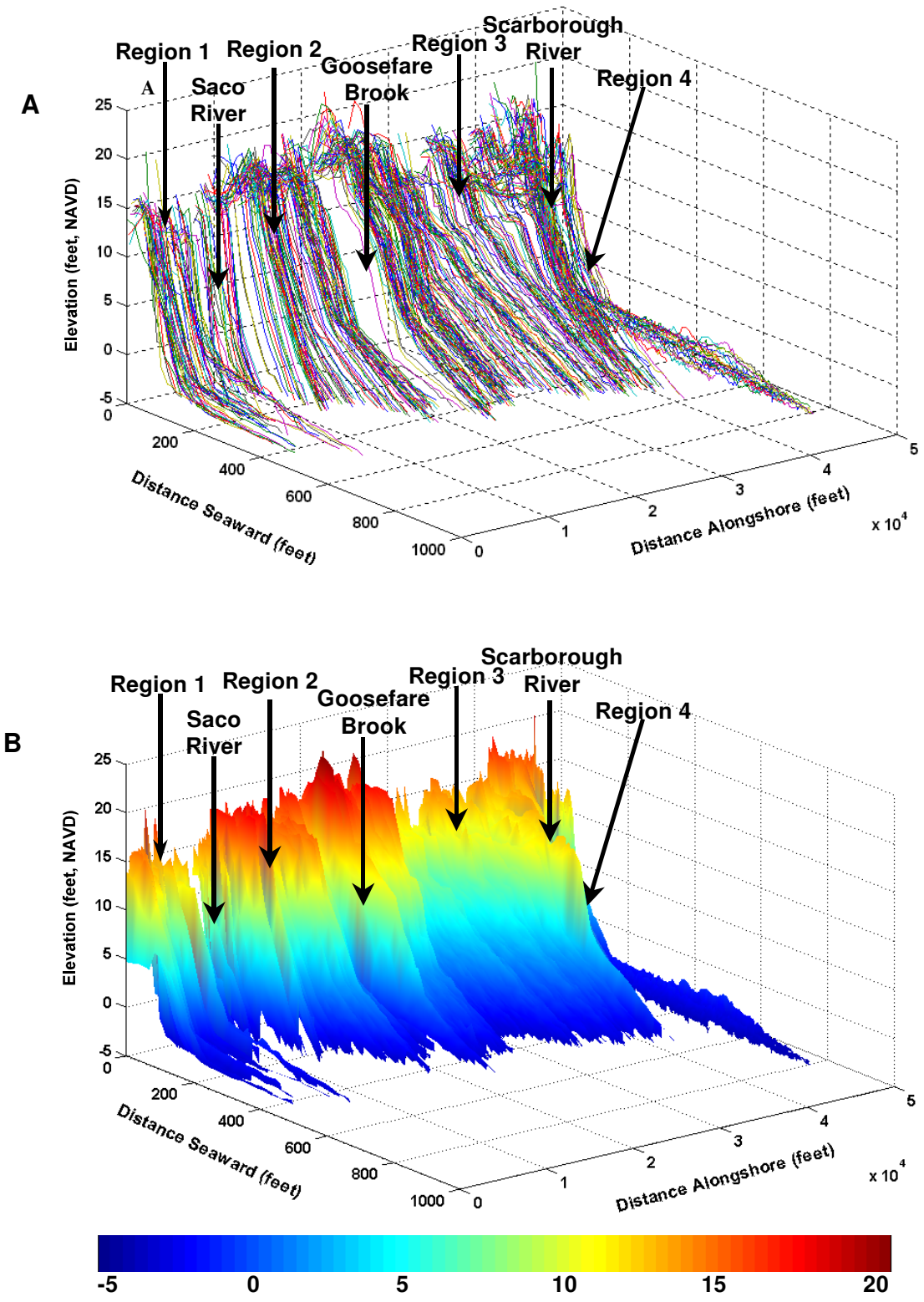

Figure 11. A) Three-dimensional plot of alongshore variation of beach profiles, from Hills Beach north to Western Beach, based on 2000 LIDAR beach profile data. B) Three-dimensional color-interpolated plot of beach profiles along Saco Bay. Note low profile elevations and steep slopes nearest to the Saco River. Profile elevations are low in region 3, however profile slopes appear to be quite gentle (near 30,000-35,000 ft).

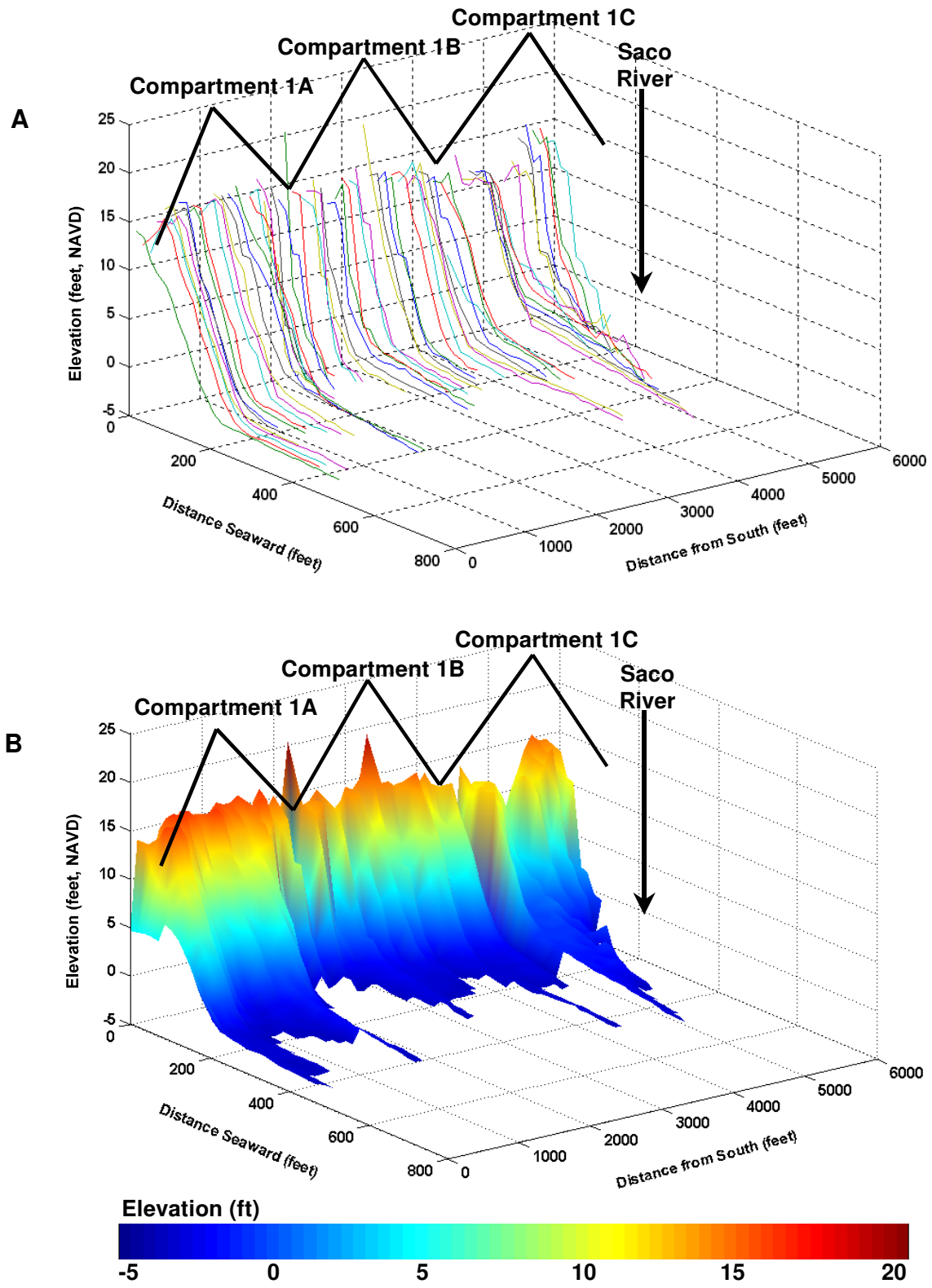

Figure 12. A) Beach profiles along region 1, stretching from rocky outcrop at the southern end of Hills Beach northwards to the southern Saco River jetty. B) Color-interpolated plot of beach profiles along region 1. Note the steeper profiles with, in general, lower elevations from near 2,000-5,000 ft, and the seaward progradation of profiles nearest the Saco River jetty, and at the southern end of Hills Beach.

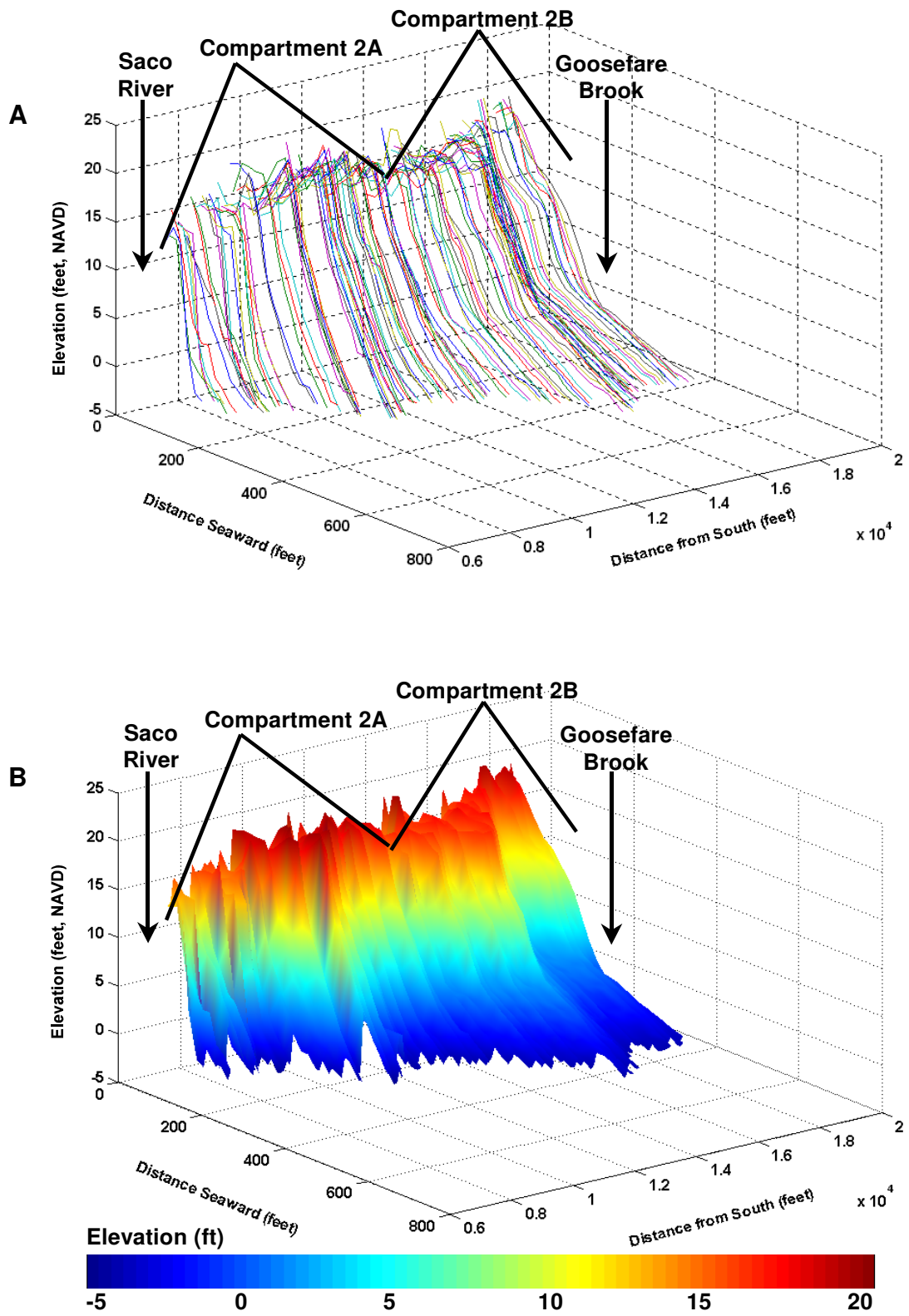

Figure 13. A) Beach profiles along region 2, stretching from the northern Saco River jetty northwards to Goosefare Brook. B) Color-interpolated plot of beach profiles along region 2. Profiles appear to be lowest and steepest within approximately 5,000 ft of the Saco River jetty, then gradually gain in elevation and decrease in slope northwards.

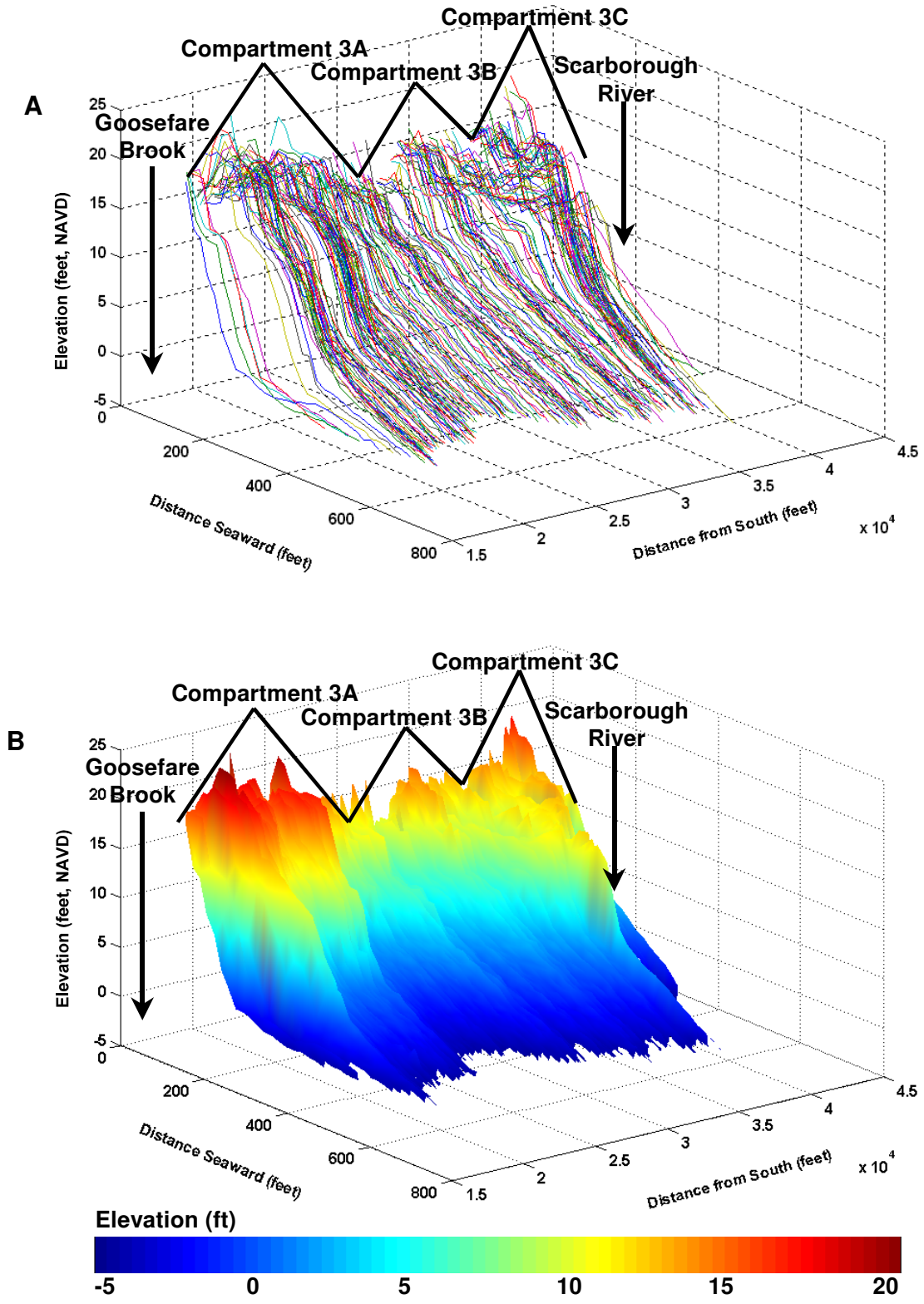

Figure 14. A) Beach profiles along region 3 (Goosefare Brook to Scarborough River jetty). B) Color-interpolated plot of beach profiles in region 3. Note high elevations of profiles in the southern part of region 3, while profiles in the central portion are low and relatively flat. High elevations may be attributed to the construction of an artificial dune, while seawalls stabilize the central section.

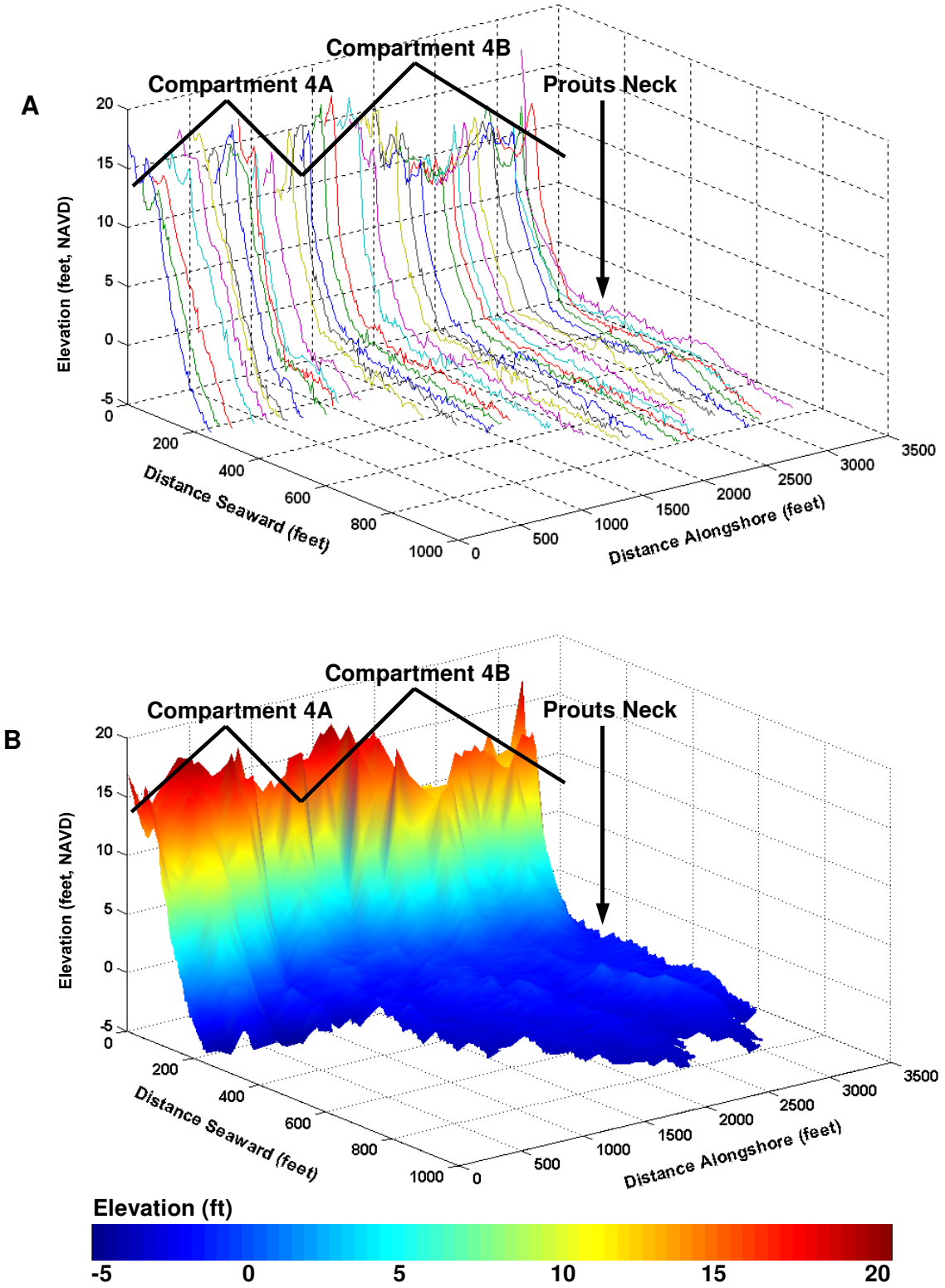

Figure 15. A) Beach profiles along region 4 (Western Beach), stretching from the Scarborough River jetty (0 in this figure) to the cliff at Prouts Neck. B) Color-interpolated plot of beach profiles along Western Beach. Note steep profiles from 0-1,100 feet, then much flatter profiles with lower elevations.

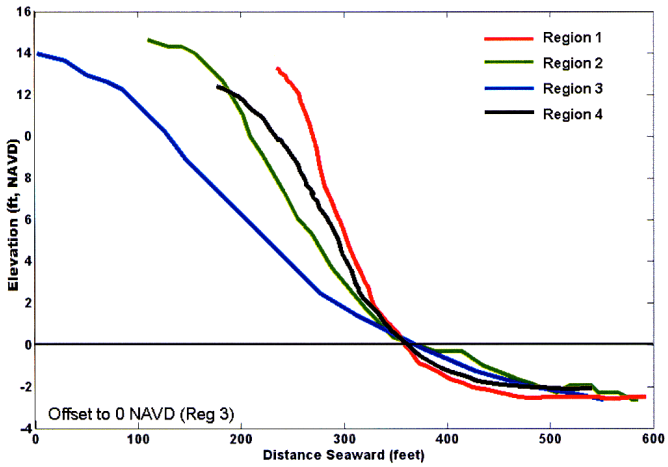

Figure 16. Mean beach profiles for regions 1, 2, 3, and 4. Note the steep, low profile of region 1, the intermediate shape of region 2, and the progradational shape of region 3. Profiles are based on 2000 LIDAR topographic data.

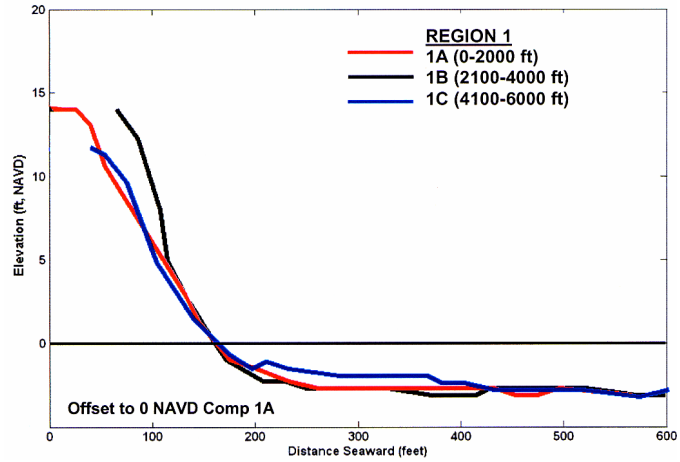

Figure 17. Mean profiles for compartments of region 1. Profiles from compartments 1A and 1B are similar in maximum elevations, but 1B mean profile is steeper. Compartment 1C profile has the lowest elevation. Profiles derived from 2000 LIDAR topographic data.

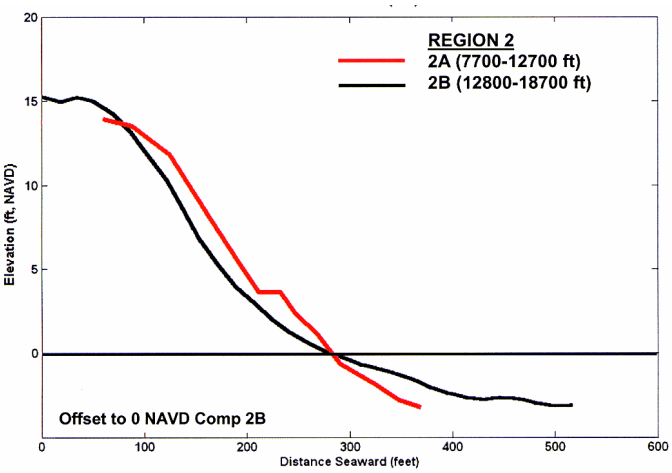

Figure 18. Mean profiles for compartments of region 2. Profile shapes are similar, yet mean profile from the beach nearest the Saco jetty (red) is lower and slightly steeper. Profiles were calculated from 2000 LIDAR topographic data.

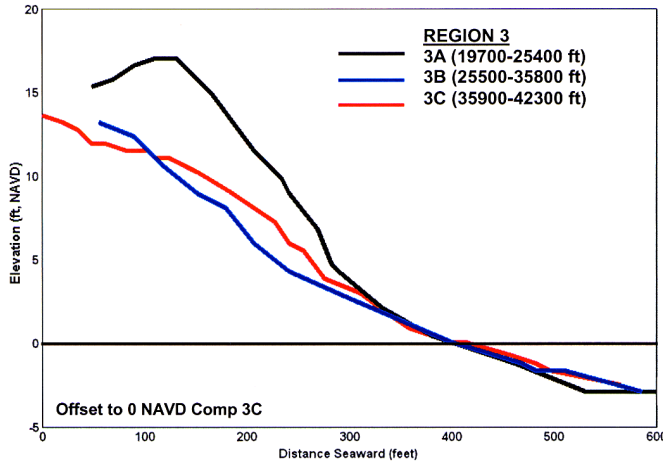

Figure 19. Mean profiles for the two different compartments of region 3. Note differences in profile slopes and maximum elevations, especially between compartments A and B. Profiles determined from 2000 LIDAR topographic data.

the region, with maximum elevation near 18 ft (Figure 14). Profiles from compartments 3B and 3C are generally much lower in elevation and much flatter. Mean profiles from each compartment reflect this trend; the mean profile for compartment 3B is very low and flat. The profile from compartment 3C, although low, exhibits a flat, dissipative shape, yet exhibits a larger volume of sediment within the upper portion of the profile than 3B (Figure 19).

Region 4 (Western Beach): Mean profiles for compartments 4A and 4B exhibit substantial differences in terms of slope, elevation, and dune/beach topography (Figure 20). Compartment 4A, although it achieves a higher elevation (near +15 ft), is much steeper than compartment 4B.

Variation of Maximum Profile Elevations (MPE) in Reference to Base Flood Elevations (BFE)

Figure 21 illustrates the alongshore variation of maximum profile elevations in relation to base flood elevations from FEMA Flood Insurance Rate Maps. Elevation data from FIRM maps were converted from NGVD29 to NAVD88 using the Vertcon conversion utility (NAVD88 values are approximately 0.7 ft greater than NGVD29 values in this geographic area) in order to compare with maximum profile elevations. Elevation data clearly identifies areas that are at risk for flooding during storm events along the Saco Bay shoreline. Approximately 61% of the region 1 shoreline is below BFE, while 17% of region 3 and less

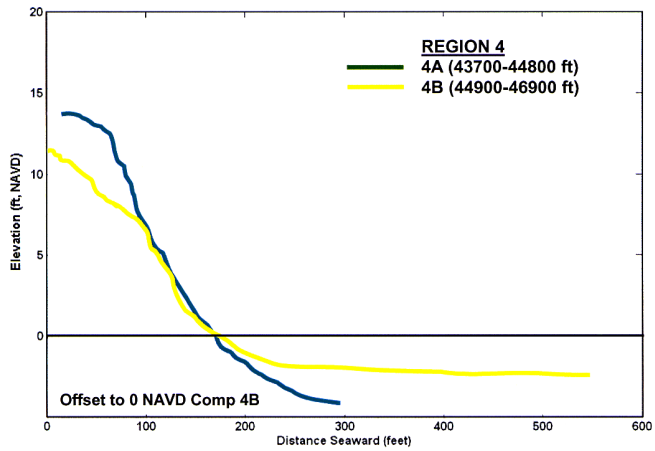

Figure 20. Mean profiles from the two compartments of region 4. 4A, nearest the Scarborough River, is much steeper. Profiles derived from 2000 LIDAR data.

than 4% of region 2 is below BFE. None of region 4 is below FEMA BFE values.

Region 1 (Hills Beach): Aside from the southernmost transect (near 0 ft), compartment 1A is above BFE. Profiles within compartment 1B are typically below BFE values (up to 6 ft), while elevations nearest the southern Saco River jetty (5,500-6,000 ft) are at or above BFE values.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): Profiles along the Camp Ellis Beach shoreline from the jetty north to near Island View Avenue (7,700-10,200 ft) exhibit MPE values that are slightly higher than BFE, except near Bay (7,700 ft) and Riverside Avenues (8,300 ft), where MPE values are about 1 ft below BFE. From Riverside Avenue northwards for approximately 1,000-ft, MPE values range from 1-2 ft above BFE. From Island View Avenue in Camp Ellis northwards to Goosefare Brook, MPE values are generally 2-6 feet higher than BFE values. Highest MPE values are from 9,800-12,800 ft within compartment 2A. Within compartment 2B, MPE values are typically 2-3 ft or greater than MPE values.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): MPE values within compartment 3A are 2-8 ft above BFE values (from Goosefare Brook northeast to near Fernald Avenue, 19,700-25,500 ft). Within compartment 3B, MPE values tend to follow the overall alongshore trend of BFE values, remaining at or several feet above BFE (north of Fernald Avenue northwards into Surfside). Values fall below BFE at the seawalled portion of Old Orchard Beach (26,300-27,200 ft). From 30,500 to 34,500 ft, MPE values are generally at or below BFE values. A transect near 33,600 ft is over 2 ft below BFE, corresponding with the former location of the Little River inlet. Compartment 3C profiles are generally 1-5 ft above BFE values along the remainder of the region 3 shoreline northeastwards to the Scarborough River jetty.

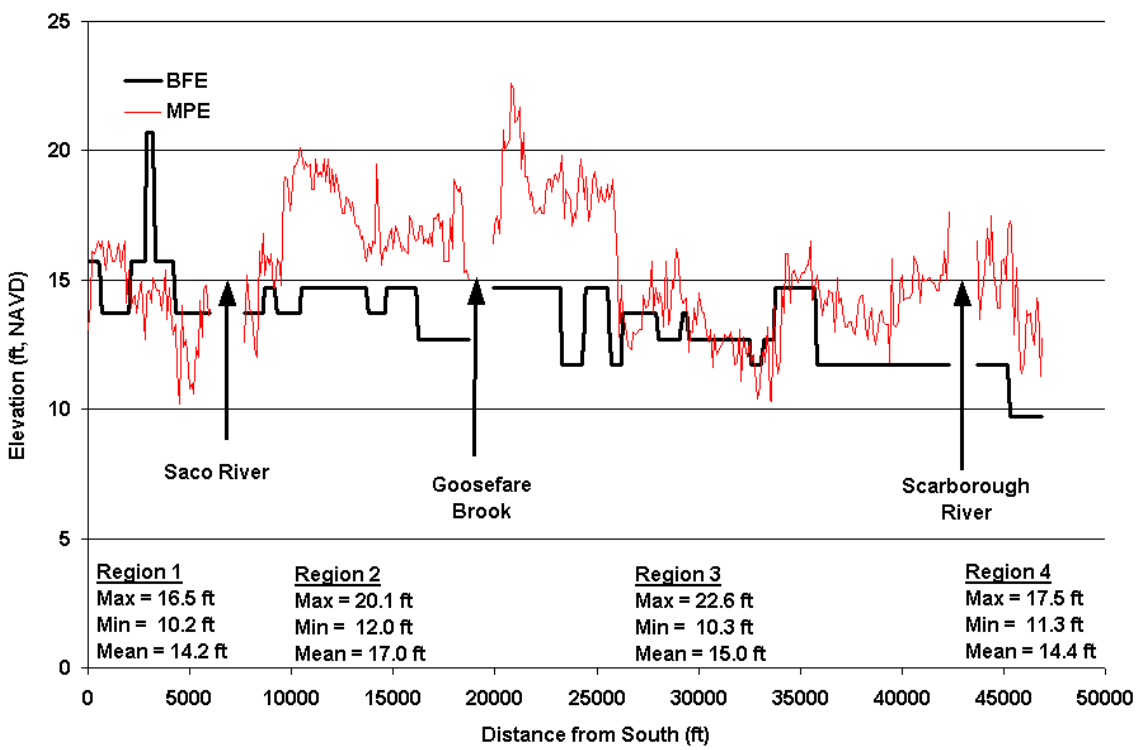

Figure 21. Variation of maximum profile elevations in relation to base flood elevations (BFEs). Most of the shoreline is at or above specified BFEs except for large segments of region 1. Elevations based on 2000 LIDAR topographic data.

Region 4 (Western Beach): MPE values are well above BFE values along the entire Western Beach shoreline. Within compartment 4A, MPE values are typically 3-7 ft above BFE, while in compartment 4B, elevations are 3-6 ft above BFE.

Variation of Overall Beach Profile Slopes

Region 1 (Hills Beach): Profile slopes range from 0.019 at the southern end of Hills Beach, to 0.193 north of Surf Avenue (near 2,300 ft), with a mean value of 0.071 (Figure 22). Lowest slopes (< 0.100) are concentrated in within compartment 1A (0-1,600 ft) and central to north-central portions of compartments 1B and 1C (2,600-5,500 ft). Steepest slopes occur just south and north of Surf Avenue (1,700-2,500 ft), and from Pleasant Avenue to the southern Saco River jetty (5,600-6,000 ft), while the mean value for the region is 0.072.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): In general, the steepest slope values along the entire Saco Bay shoreline are found in region 2. These are concentrated within compartment 2A. Slope values decrease accordingly with distance from the northern jetty, ranging from 0.237 near Pearl Avenue (8,000 ft) near the northern jetty, to 0.060 near Sylvain Avenue in Ferry Beach (10,700 ft). Slope values steepen from 0.06 near Sylvain Avenue to 0.09 near Pond Avenue (11,700 ft), followed by a subsequent flattening of slope values from 0.09 to 0.05 from Pond Avenue north to just north of Bay View Avenue (11,800-15,600 ft). Slopes stabilize to near 0.050 within Bay View and Kinney Shores (15,600-18,700 ft). The mean value for the region is 0.080.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): In contrast with region 2, this region exhibits the lowest slope values along Saco Bay. Slopes range from 0.025 to near 0.080 at the Scarborough River jetty and approximately 0.010 at the eastern end of Western Beach. The region has a mean value of 0.040. Values remain constant at 0.050 from Goosefare Brook north to Fernald Avenue (19,700-25,500 ft), with slightly steeper slopes (~ 0.060) nearest Goosefare Brook. In Old Orchard Beach, from Fernald Avenue north to Brisson Street (25,500-28,500 ft), slopes flatten slightly to ~0.040 and remain relatively constant. From Brisson Street north to Grand View Avenue in Surfside (28,600-32,000 ft), slopes steadily decrease to values near ~0.025, then remain constant to Parcher Avenue (32,100-33,700). There is a slight increase in slope values to 0.030 near Parcher Avenue, then slope values remain near 0.030 through Surfside and Grand Beach to Oak Street, near 38,100 ft. Slopes increase to ~0.050 in Pine Point, near Dunefield Road (40,400 ft), with a small segment of shoreline with increased slope values between Dunefield Road and Avenue Five Extension, then decrease to 0.050 from Avenue Five Extension east along Pillsbury Drive. Along Pillsbury, slopes abruptly increase to a maximum value of 0.080 at 41,600 ft, then decrease to 0.050 nearest the Scarborough River jetty.

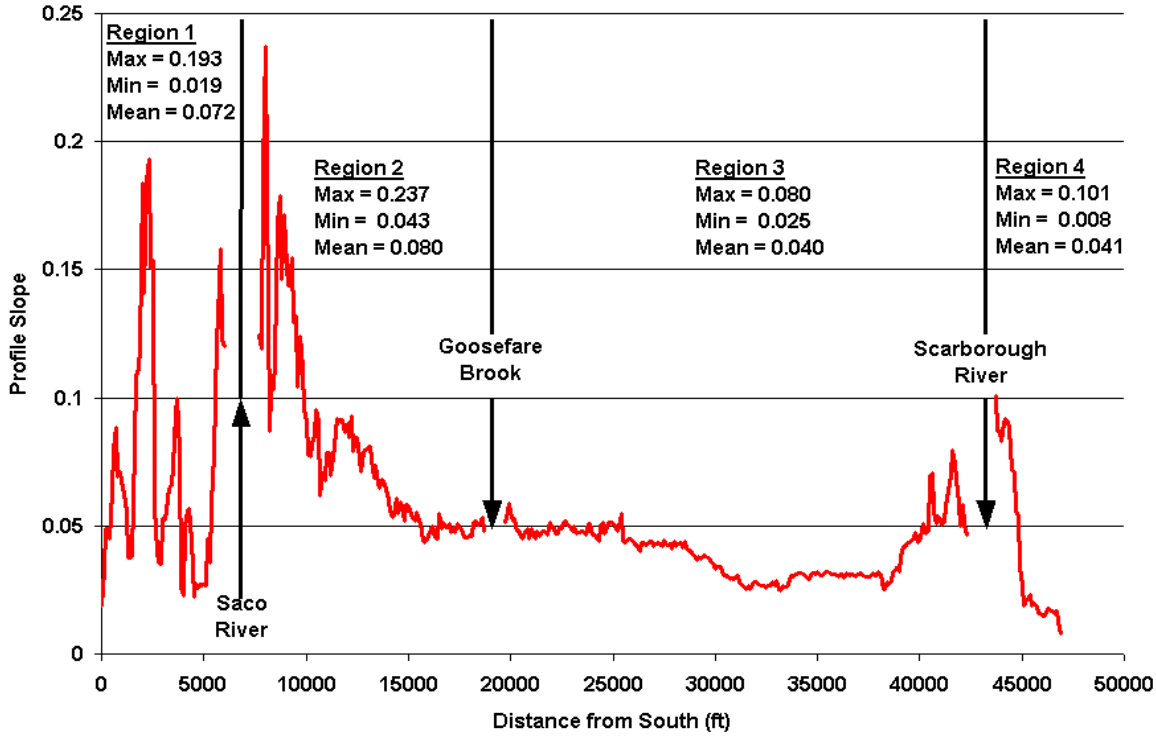

Figure 22. Variation of beach profile slopes. Steepest slopes are adjacent to the Saco River, and generally decrease from south to north. Steep slopes within the northern part of the bay are nearest the Scarborough River and along Western Beach. Slopes derived from 2000 LIDAR topographic data.

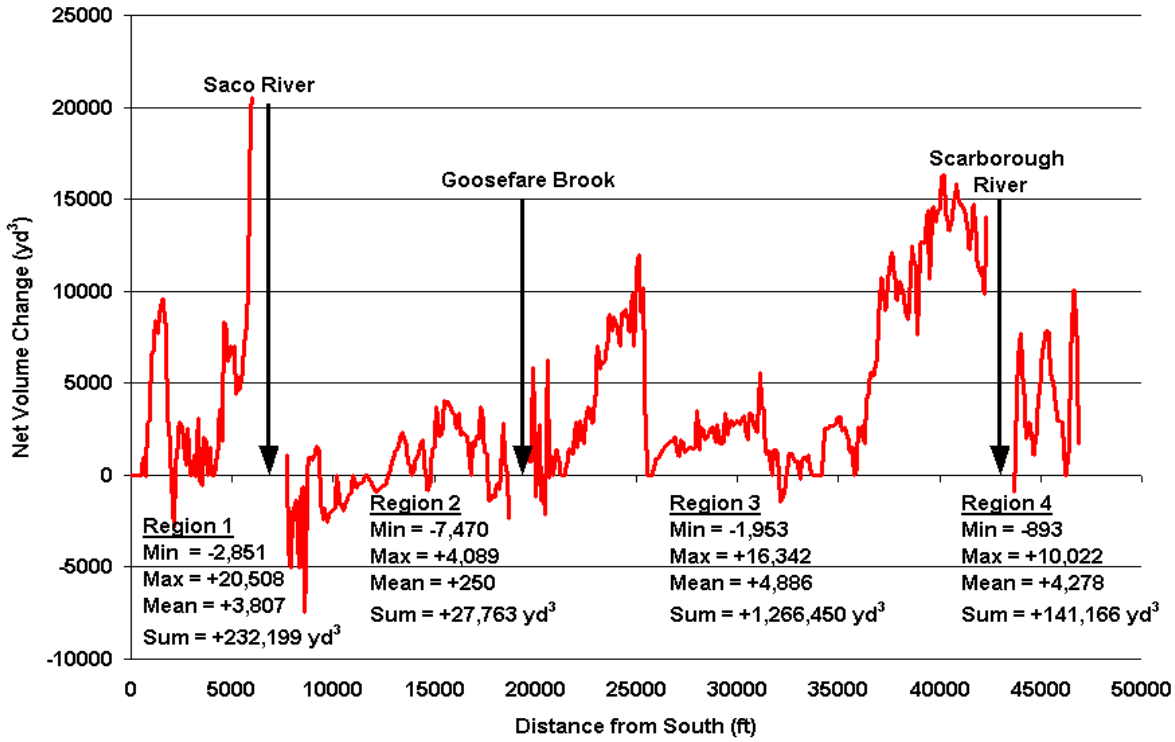

Figure 23. Variation of net volume changes along the Saco Bay shoreline, based on erosion-accretion rates (1962-1995) and 2000 LIDAR topographic data. Regions 3 and 1 have undergone the largest positive volume changes, while region 2 has experienced more negative changes, especially near Camp Ellis Beach.

Region 4 (Western Beach): Along Western Beach, profile slopes range from near 0.100 adjacent to the Scarborough River, to less than 0.010 at the beach's eastern extent.

Estimated Net Volume Changes (1962-1995)

As a whole, beach profiles along the Saco Bay shoreline appear to have undergone a positive net gain in sediment volume from 1962 to 1995 (Figure 23). This trend is also apparent for individual regions. Region 3 underwent the largest net volume gain, on the order of 1,266,450 yd^3, while region 2 gained the least (approximately 27,800 yd^3). Negative volume change (erosion) is generally concentrated within the Camp Ellis and Ferry Beach segments of region 2, from the northern Saco River jetty north to near Long Pond in Ferry Beach (7,700-12,800 ft). Table 7 summarizes the net volume changes for each region, and the smaller compartments defined within each region.

Region 1 (Hills Beach): Region 1 supports three separate compartments based on volumetric changes (Table 7). The southern compartment (entrance to The Pool north to near Surf Avenue), has a high net volume change on the order of 76,600 yd^3, while the central compartment (Surf Avenue north to the thinnest point of the island near 4,100 ft), is more stable, with a net volume change of near 18,700 yd^3 over the 33 year period. The northern compartment underwent the most accretion, with a net volume change of approximately 136,900 yd^3.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores): Two distinctly different net volume change patterns exist within this region. From Bay Avenue in Camp Ellis to north of Pond Avenue in Ferry Beach (7,700-12,700 ft), the compartment has a net volume change of approximately –55,400 yd^3, while the northern compartment, stretching from north of Pond Avenue to Goosefare Brook, has a net positive change near 83,200 yd^3, including a small segment of net negative volume change nearest to Goosefare Brook. The first 2,500 ft north of the Saco River jetty (7,700-10,200 ft) had a net loss of –37,400 yd^3, or approximately two-thirds of the loss within the southern compartment.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point): This region is highly accretive, with an overall net volume change of 1,266,450 yd^3. Several distinct compartments of high positive net volume change exist, along with several segments of little or almost no volume change. Segments of shoreline with little volumetric changes extend from Goosefare Brook northeast to near Tioga Avenue in Ocean Park (19,700-21,500 ft), and in Surfside, from Rosewood Street northeast to north of Parcher Avenue (31,700-34,200 ft). The largest positive volume changes occur from Ocean Park northeast to Parcher Avenue in Old Orchard Beach (21,500-31,700

TABLE 7. Summary of net volume changes for each region and compartment. Compartments defined by changes in morphologic trends and volumes.

Region	Distance (ft)	Volume Change (yd^3)	Compartment (ft)	Compartment #	Volume Change (yd^3)
1	0-2,000	+76,594	0-2,000	1A	+76,594
	2,000-2,200	-2,851	2,100-4,000	1B	+18,675
	2,200-3,000	+12,812			
	3,000-3,400	+4,131			
	3,400-3,500	-583			
	3,500-4,000	+5,166			
	4,100-6,000	+136,931	4,100-6,000	1C	+136,931
2	7,700-7,800	+1,067 *	7,700-12,700	2A	-55,384
	7,800-8,700	-29,486 *			
	8,800-9,300	+6,725 *			
	9,400-10,200	-15,714 *			
	10,300-11,000	-10,070			
	11,100-11,600	-2,410			
	11,700-12,700	-5,495			
	12,800-13,800	+14,149	12,800-18,700	2B	+83,147
	13,900-14,500	+6,677			
	14,600-14,700	-1,286			
	14,800-16,700	+52,297			
	16,800-17,600	+16,314			
	17,700-18,300	-6,269			
	18,400-18,500	+3,966			
	18,600-18,700	-2,700			
3	19,700-19,900	+5,835	19,700-25,400	3A	+246,195
	20,000-20,100	-1,048			
	20,200	+2,718			
	20,300	-1,287			
	20,400-20,500	-1,953			
	20,600-20,700	+6,285			
	20,800-20,900	+997			
	21,000-21,500	+3,173			
	21,600-25,400	+231,475			
	25,500-31,700	+125,693	25,500-35,800	3B	+171,563
	31,800-32,000	+4,025			
	32,100-32,400	-4,319			
	32,500-33,000	+5,567			
	33,100	-249			
	33,200-33,600	+4,039			
	33,700-35,800	+36,808			
	35,900-42,300	+705,892	35,900-42,300	3C	+705,892
4	43,700-44,800	+39,997	43,700-44,800	4A	+39,997
	44,900-46,900	+101,168	44,900-46,900	4B	+101,168

*A 2,500-foot stretch of beach just north of the northern Saco River jetty experienced a net volume change of -37,408 yd^3, approximately 2/3 of the total loss within the southern compartment (7,700-12,700 feet) of region 2. This 2,500-foot stretch is the proposed Corps Section 111 Project Area.

ft), and from Little River Road in Grand Beach northeast to Pillsbury Drive in Pine Point (35,800-42,300 ft), combining for a net positive volume change of approximately 1,063,100 yd^3.

Region 4 (Western Beach): Net volume changes along Western Beach are also largely positive, with a change of approximately 141,200 yd^3, the majority of which is concentrated along the easternmost portion of the beach (44,900-46,900 ft).

DISCUSSION

Saco Bay is generally considered to be an enclosed littoral cell. Previous work by others (e.g., van Heteren and others, 1996; Kelley and others, 1995; Barber, 1995) have estimated sand budgets and inferred sediment transport directions along the Saco Bay shoreline. Such work has established a general

northerly-directed sediment transport direction along the Bay, with the source of the majority of the sediment being the Saco River. Stabilization of the river entrance has undoubtedly influenced the sediment budget of the beach system.

Results of the current study suggest that the Saco Bay system can be further divided into four distinctly different geographic regions (regions 1 to 4) based on general beach morphology (Figure 1). Both regions 1 and 2 appear to be influenced by the stabilized Saco River channel. Region 3 seems to be outside of the direct influence of the Saco River jetties; however, it does appear to be influenced by the Scarborough River and its jetty. Tidal currents of the Scarborough River heavily influence the morphology of Region 4 (Western Beach).

The southern jetty of the Saco River positively influences the updrift Hills Beach region for approximately 2,000 ft, while the northern jetty negatively influences approximately 5,000 ft of the downdrift shoreline. These trends are evidenced by dramatic changes in overall beach profile shapes, slopes, and erosion/accretion trends. Region 3 as a whole is highly accretive, receiving the majority of sediment within the Saco Bay system and resulting in the largest positive net volume changes along the bay's shoreline.

Because Saco Bay can be divided into four different regions, the remainder of this section will be separated into a regional discussion of the parameters and characteristics investigated.

Region 1 (Hills Beach)

Estimated Net Erosion and Accretion (1962-1995). The majority of region 1 is generally stable to accretive (Figure 9). These trends may be attributed to the following factors: the sheltering of Hills Beach from incoming wave energy from the south by Fletchers Neck and Biddeford Pool and several offshore islands, and from the north/northeast by the northern Saco River jetty), and the trapping of sediment by the southern jetty.

The southern portion of this region, nearest Fletcher Neck, exhibits little shoreline change due to a shoreline stabilized by natural rocky outcrops and seawalls. Pocket accretion exists from 700-2,000 ft, to just south of Surf Avenue, probably attributable to wave shadowing by Stage and Basket Islands.

Net accretion near the northern end of the beach (4,000-6,000 ft), adjacent to the jetty, is on the order of ~ 130 ft with an average rate of 4 ft per year. This indicates that over the time period of study (33 years), sediment has accumulated and substantially widened the dunes. Hulmes (1980) suggested that no new sediment (aside from beach nourishment by the Corps, although amount unspecified) has been introduced into the Hills Beach system since the Saco River jetties were emplaced. Therefore, a distinct deficit in the sediment budget exists; the actual source of sediment for such shoreline progradation is unknown, however several possibilities exist.

It is possible that the accretion seen is a result of the slow, landward migration of ebb-tidal delta shoals due to wave action. This process most likely occurred several years to several decades following construction of the southern jetty in the late 1890's (USACE, 1961).

However, some ebb-tidal shoals may continue to periodically nourish the system. It is also possible that the accretion seen in the northern portion of Hills Beach is a result of material reworked within the Hills Beach littoral cell. Portions of Hills Beach that appear to be relatively stable (e.g., the central portion, 2,000-4,000 ft) are in actuality eroding; the erosion signal is simply not present due to the reconstruction of seawalls along this stretch of shoreline in order to 'hold the line'. Over time, sediment lost in front of these seawalls may be diverted northward by currents due to wave refraction around the Hills Beach cell. A Corps study conducted in 1961 focused on erosion problems at Hills Beach. Part of the study utilized shoreline positions from 1859, 1871, 1913, 1954, and 1960 in order to describe accretion and recession along the Hills Beach shoreline. The largest net accretion along Hills Beach occurred between 1871-1913. The Corps concluded that this was '…attributable to impounding of material by the south jetty following initiation of construction in 1891' (USACE, 1961).

It is important to note that the central portion of the shoreline (near 4,000 ft) that is fully stabilized by a continuous seawall corresponds with the thinnest portion of the entire beach, and may have been previously breached and connected with a tidal inlet to a back-barrier tidal creek. This area, because of its narrow width and relatively low topography, remains extremely susceptible to washover and erosion. This segment of shoreline probably has eroded; however, due to the erosion reference feature utilized in this study (seaward extent of seawall), the shoreline exhibits relative stability.

The dramatic increase in net accretion within 2,000 ft adjacent to the southern jetty (0 at 4,000 ft to almost 320 ft adjacent to the southern jetty) may also relate to elevation variations along the length of the southern jetty. The 4,800-ft long jetty is constructed to +11 ft MLW for 1,760 ft, then at +5.5 ft MLW for the remainder of its length. The continuously exposed portion of the jetty (1,760 ft) influences the adjacent beach for a distance of its approximate length by interrupting the northward flow of sediment.

Shoreline Type, Dry Beach Width, and Total Landward Width. The region 1 shoreline is comprised of rocky outcrops, seawalls, or vegetated dunes. Approximately 38% of the shoreline is stabilized, while the remaining 62% is vegetated dune. Dry beach widths along region 1 are consistently less than 50 ft. Minimum widths (0 ft) are adjacent to stabilized (seawalls) portions of the shoreline. Total distances to habitable structures are widest for naturally vegetated dune portions of the shoreline. It is clear that segments of the shoreline fronted by seawalls and rocky outcrops are those with the shortest total distances to habitable structures. Along the southernmost stretch, habitable structures are constructed close to the rocky coastline. A pocket of relatively wide vegetated dune (~ 1,000-1,800 ft) exists due to wave sheltering and protective sandy shoals associated with

Stage and Basket Islands. The seawalled shoreline and subsequent short distances to habitable structures from 2,700-4,200 ft may exist because of shoreline erosion caused by wave focusing within the Hills Beach area. Although dry beach widths are narrow at the northern end, the overall dune system is wide, leading to a relatively wide total width from HWL to habitable structures.

Alongshore Variation of Beach Profile Shapes. Beach profiles within the Hills Beach region are highly variable due to the influences of sand shoals, rock outcrops, seawalls, and the southern Saco River jetty (Figures 11 and 12). Profiles within the southern compartment of Hills Beach (0-2,000 ft) have dune crests that are situated above the BFE, which ranges from near 13 ft to about 15 ft (Figure 21). The relatively flat slopes in the southern section may be attributed to sheltering from wave action by large shoals and Basket Island, just offshore. This southern compartment also exhibits a stretch of exposed rock outcrops in the surf zone. Beachfront homes within this stretch are not only above the BFE, but also have a horizontal buffer (see *Shoreline Type, Dry Beach Width, and Total Landward Width to Structures*) that serves to dissipate floodwater energy.

Profiles within the central compartment are generally below BFE, and beachfront structures are generally less than 100 ft from the seaward edge of dune or structure. The stretch of steepest slopes (1,700-2,500 ft) corresponds with a change in shoreline orientation that relates to the loss of the protective shoals associated with Basket Island (Figures 6, 7, and 22). The steeper slopes in this segment may be the result of wave energy focusing on this stretch of beach due to deeper water offshore. Profile slopes tend to flatten near 2,600 ft, and steepen from 3,000-3,700 ft. This trend may relate to a stretch of seawalls that have been constructed along the beach from 3,000 to near 4,000 ft.

Dune crests are generally below BFE along the central to northern stretch of Hills Beach (2,000-5,500 ft), although the width of dunes seaward of structures substantially increases from near 100 ft at 4,300 ft, to 300 ft at 6,000 ft, adjacent to the jetty. Profile slopes tend to flatten corresponding with substantial beach progradation up to about 5,100 ft. Nearest the jetty, profile slopes steepen, though the beach exhibits an accretive trend.

Estimated Net Volume Changes (1962-1995). Beach profiles within region 1 exhibit a net overall positive volume change of approximately 232,200 yd^3 over the 33-year period of study, and appear to support three separate compartments based on volume change (Figure 23, Table 7). The southern compartment, with net positive volume change on the order of 76,600 yd^3, corresponds with the wave-sheltered portion of the coastline. The relatively small positive net volume change of about 18,700 yd^3 over the 33-year study period seen within the central compartment may be due to the presence of seawalls, most of which have been maintained, and may not reflect actual shoreline changes since the shoreline has been artificially held in place. In all likelihood, erosion of the submerged beach has occurred along this stretch. Also, several Corps nourishment projects have added sediment to Hills Beach as beneficial use of dredged material from the Saco River, although the exact amount is unknown. The northern compartment, as discussed under *Estimated Net Erosion and Accretion*, has undergone substantial accretion with a positive net volume change on the order of 136,900 yd^3.

Region 2 (Camp Ellis Beach, Ferry Beach, Bay View, and Kinney Shores)

Estimated Net Erosion and Accretion (1962-1995). Net erosion dominates the initial 5,000 ft of the shoreline with the highest net erosion (40-100 ft) confined to an approximate 1,000-foot (7,700-8,700 ft) stretch of beach near the northern jetty (Figure 9). This stretch corresponds with a section of shoreline that has been heavily stabilized with seawalls, with unstabilized pockets experiencing more net erosion than those that have been continually maintained. A pocket of slight net accretion (20 ft) occurs from 8,900-9,300 ft, corresponding with a stabilized stretch of beach between Lower Beach Avenue and Sunrise Avenue. North of this, the shoreline is erosive from Sunrise Avenue north to Morris Avenue (9,400-10,600 ft), and relatively stable to slightly erosive from Morris Avenue north to near Long Pond in Ferry Beach (10,600-12,700 ft). The different patterns along this stretch may relate to the shoreline types; vegetated dune and seawall along the stretch of beach from Sunrise to Morris Avenues, and natural dune with no seawall from Morris Avenue to near Long Pond.

The pattern becomes accretive near Long Pond (12,700 ft), and extends north through Bay View and Kinney Shores to Goosefare Brook, although some short lengths of shoreline display erosive trends. These pockets appear to coincide with several small yet abrupt changes in shoreline orientation. Pockets of accretion (noted as distinct bulges in the shoreline) near 13,700 and 15,700 ft (north of Bay View Avenue) correspond with wave shadowing associated with bedrock outcrops in the subtidal beach.

Shoreline Type, Dry Beach Width, and Total Landward Width. Approximately 25% of this region is stabilized by seawalls alone; while some combination of seawalls and vegetated dunes account for an additional 31% of the shoreline. The remaining 44% is vegetated dune only. Seawalls are concentrated along a stretch closest to the Saco River jetty (7,700-9,700 ft), with distances to habitable structures generally less than 100 ft and dry beach widths less than 25 ft. North of this, a mixture of naturally-vegetated dune and seawall/dune combinations extend from Fairhaven Avenue north to Outlook Avenue (9,800-17,000 ft), with distances to habitable structures generally greater than 100 ft except for an oceanfront condominium south of Bay View Avenue (near 15,000 ft), which is located just landward of the seawall/dune. The remaining shoreline within the region includes some form of stabilization. The northern end exhibits relatively short distances to structures, generally fifty feet or less due to proximity of Goosefare Brook, which has a high tendency

to shift position on its south side. It is apparent that homes in this area are constructed right at the seawall.

Alongshore Variation of Beach Profile Shapes. Beach profiles within this region appear to be heavily influenced by both the northern Saco River jetty and stretches of privately constructed seawalls (Figure 13). The stabilized shoreline along Camp Ellis Beach, which extends roughly 2,000 ft northwards from the jetty, constitutes the steepest profile slopes along Saco Bay (Figure 22). The slopes flatten from south to north as a result of fewer shorefront structures and a decrease in the influence of reflected waves from the northern jetty. The jetty, in conjunction with numerous seawalls, influences beach profile slopes for a distance of almost 6,000 ft, from the jetty to north of Long Pond (7,700-13,700 ft), assuming that the slope of the 'natural' beach is roughly 0.050. This is also apparent in the maximum profile elevations, especially for those profiles within approximately 2,000 ft of the jetty.

Beach profiles approach a constant slope value of 0.050 near 13,700 ft, which corresponds with a bulge in the coastline, probably resulting from wave shadowing by an exposed bedrock outcrop. Aside from abrupt profile flattening near 15,700 ft, attributed to another bedrock outcrop that has trapped sediment, slopes remain at values near 0.050 north to Goosefare Brook. This general alongshore stability in profile slope, and distinct increase in maximum profile elevations may be attributed to: 1) the fact that profiles north of 13,700 ft appear to be outside the influence of the northern jetty of the Saco River; and 2) shoreline stabilization structures are not as abundant along this stretch of beach.

Estimated Net Volume Changes (1962-1995). Although region 2 exhibits a relatively small positive net volume change for the study, it includes a compartment that shows the largest negative volume change along the Saco Bay shoreline, on the order of 55,400 yd^3 (Figure 23). This stretch of beach, roughly from Bay Avenue north to near Long Pond (7,700-12,700 ft), corresponds with highly erosive portions of Camp Ellis and Ferry Beaches and is heavily stabilized with sea walls. In reality, the reconstruction and maintenance of seawalls along Camp Ellis Beach, especially along Surf Street, has probably decreased the calculated net volume and net erosion of the shoreline. This is a result of using the seaward extent of a seawall as the erosion reference feature in determining net shoreline erosion or accretion. If a seawall is maintained, apparent horizontal erosion of the immediate seaward shoreline may be abated; however, vertical erosion of the profile may be accelerated, and is immeasurable using techniques employed herein. *Therefore, net volume changes may be grossly underestimated in this section.*

The distinct shift from negative net volume change to positive net volume change occurs at the same location as a sudden increase in coastline orientation associated with a small bulge in the shoreline. This bulge is located in line with Eagle Island to the east, and may result from wave shadowing by that island.

Region 3 (Ocean Park, Old Orchard Beach, Surfside, Grand Beach, Pine Point)

Net Accretion/Erosion (1962-1995). Adjacent to Goosefare Brook, frontal dune growth and retreat varied within Ocean Park, from roughly 19,600-20,800 ft, probably associated with periodic migration and shoaling of Goosefare Brook (Nelson, 1979; Farrell, 1972). The shoreline underwent little change near 21,000 ft, and becomes accretive along Old Orchard Beach, from 21,400-25,400 ft (Figure 9). The shift from variable, to stable, to accretive coincides with small changes in coastline orientation. The progradation of the frontal dune along 21,400-25,400 ft may be attributed to artificial dune construction for emplacement of a sewer pipeline (within the frontal dune) along portions of Ocean Park and Old Orchard Beach.

A stretch of unvegetated, stabilized shoreline extends from near Fernald Avenue north to Brisson Street (25,500-28,000 ft), coinciding with a heavily developed section of Old Orchard Beach. Accretion is relatively minimal, on the order of 20 ft. Accretion slightly increases from Brisson Street to near Rosewood Street, associated with small artificial dunes constructed as part of the northern extension of the sewer pipeline. From near Rosewood Street to near Parcher Avenue (approximately 31,000-34,000 ft), the shoreline has been continuously stabilized with seawalls and has undergone little change. From just north of Parcher Avenue northeast to just north of Little River Road (34,000-36,000 ft), small dunes have grown seaward of the 1962 line (established by a seawall), with net accretion near 50 ft. Net accretion increases to over 100 ft near 36,400 ft and continues to increase to a peak of near 250 ft near Oak Street in Grand Beach (40,000 ft), decreasing slightly northwards to the Scarborough River jetty. The accretion in this region corresponds with the distinct crescent shape of the shoreline, changing abruptly from 50-60°, then increasing to 90° at the peak of the accretion.

This distinct increase in accretion may relate to the reworking of sediments trapped in the Scarborough River ebb-tidal delta. Sediment most likely migrates northwards into the Pine Point area and becomes trapped within the Scarborough River ebb tidal delta. Over time, waves refracting around Prouts Neck rework the sediment and spread shoals in a landward (and slightly southern) direction until they weld onto the beach at Pine Point and Old Orchard Beach. It seems that the southern limit of this accretion is just north of the old Little River Inlet, near Grandview Avenue in Surfside (~ 32,500 ft); this southern limit corresponds with wave refraction patterns illustrated in an aerial photograph from Goldsmith (1976) (Figure 24).

Shoreline Type, Dry Beach Width, and Total Landward Width. Approximately 75% of region 3 (including Western Beach, 69%) is fronted by either stabilization structures, or structures combined with vegetated dunes. Portions of the shoreline that are solely stabilized (25,500-27,100 ft in Old Or-

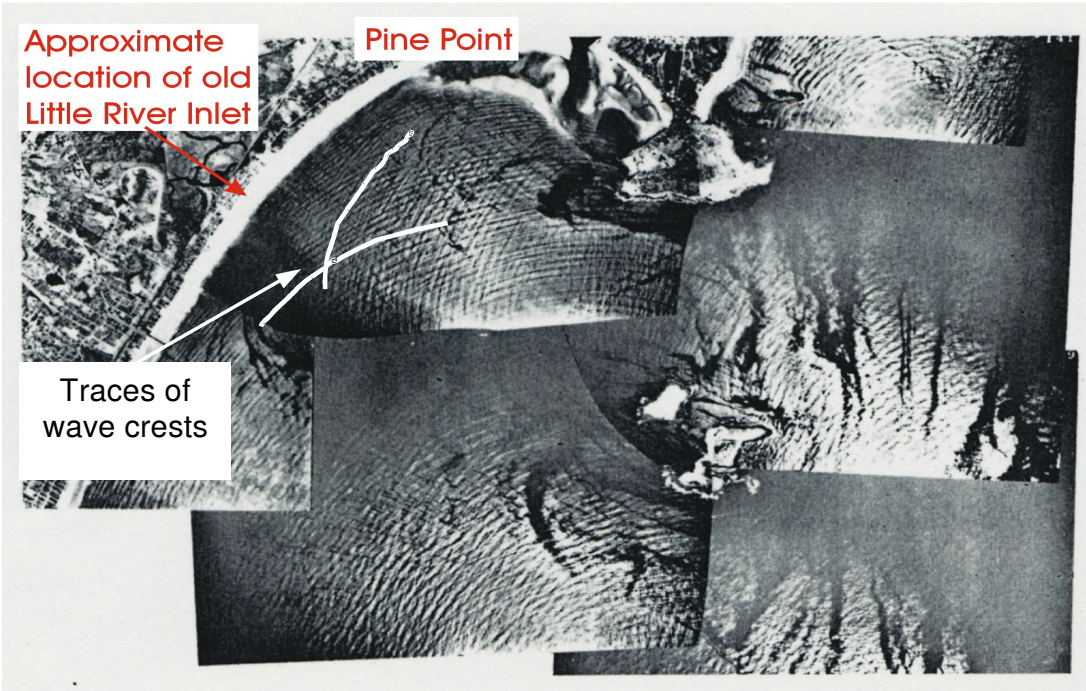

Figure 24. Aerial photograph showing wave refraction patterns along the central to northern portions of the Saco Bay shoreline (regions 3-4). Note refraction patterns in reference to the approximate location of the old Little River Inlet (modified from Goldsmith, 1976).

chard Beach) are generally those with habitable structures constructed right at the landward extent of the dry beach/seawall (Figure 10). Although this stretch has no dune whatsoever, it does coincide with the highest dry beach widths along the bay, ranging from 150 to over 200 ft. This stretch is part of the heavily developed "downtown" section of Old Orchard Beach. Shoreline along 27,300-29,500 ft is fronted by vegetated dune and seawall, yet has dry beach widths near 50 ft and total widths approaching 100 ft. The shoreline adjacent to the former location of the Little River Inlet (near 32,500 ft) is fronted by seawalls, yet the total width (and subsequent dry beach width) is between 150 and 200 ft. This is a result of the former migratory nature of the Little River Inlet, which incised paleochannels through the beach during migration. Due to this historical instability, such areas typically become erosion prone (i.e., erosion 'hot spots'). Such is the case for other historically unstable areas along the east coast such as the 'Washout' at the northern end of Folly Beach, South Carolina (Gayes and others, 1998).

The northern portion of the region exhibits extremely large distances to habitable structures and no shoreline structures are located at the landward edge of the beach. This stretch is the most naturally protected shoreline along Saco Bay, even though dry beach widths tend to decrease from a point at 35,100 ft northwards. This stretch, however, exhibits a wide vegetated dune (and subsequent distances to structures ranging from 150 ft to near 500 ft) and maximum profile elevations that exceed BFE values.

Alongshore Variation of Beach Profile Shapes. In general, region 3 beach profiles (Figures 11 and 14) exhibit flat slopes generally on the order of 0.050 or less, except for along the western portion of Western Beach (Figure 22). This may be attributed to the general accretive nature of the shoreline. From 19,700-25,400 ft, the shoreline supports a vegetated dune and a constant slope on the order of 0.050, with high maximum profile elevations (from just below to over 20 ft). These elevations are the result of an artificially constructed dune that covers a sewer line for portions of Ocean Park and Old Orchard Beach.

A stabilized portion of Old Orchard Beach exists from 25,500-28,500 ft, and beach profile slopes tend to flatten slightly in front of this stretch, in addition to dramatically decreasing in maximum profile elevations. The crests of the seawalls that front the beach along this stretch are sometimes below BFE (Figure 21). It is interesting that beach profile slopes decrease in this stretch, considering the influence of structures on the beach profile slopes adjacent to Camp Ellis (dramatic increase in profile slopes). This difference in beach response may be attributed to sediment supply: Old Orchard Beach is relatively sand-rich, while Camp Ellis is starved of sediment. Profile flattening may also be attributed to wave action, in which waves reflected off of the seawall transport sediment in a seaward direction, thereby decreasing overall profile slope.

North of this stretch, small dunes are developed and beach profiles gently flatten to 0.025 near 32,000 ft. The flattest profiles of all exist from near Rosewood Street to just south of

Parcher Avenue (32,000-33,700 ft); this stretch corresponds with a slight change in shoreline orientation and the location of another seawall. An increase in shoreline compass-bearing occurs near 32,500 ft, and seems to correspond with the former location of the Little River Inlet, which was closed in the 1870's by the construction of a railway through Old Orchard Beach (Farrell, 1972). Closure of the inlet is probably partly responsible for the abrupt jump in net accretion seen north of this area due to the abandoning of ebb tidal shoals (Kelley and others, 1995). This location also coincides with the lowest profile elevations (near 10 ft), well below BFE. The substantial decrease in maximum profile elevations along this entire stretch may be a result of the historical migratory nature of the Little River Inlet, prior to its artificial closure. Evidence of the inlet still exists in the aerial photographs, and existing geomorphology of the coastline indicates a northward transport of sediment. The shoreline has subsequently been heavily developed and stabilized with seawalls. In addition, the thickness of dune sand in this area is also the thinnest of any between the Saco and Scarborough Rivers (van Heteren and others, 1996).

North of this section, slopes slightly steepen, but maximum profile elevations increase to above 15 ft and stay at or above BFE values (Figure 21). This stretch includes an old seawall that has been fronted by a large, accretive dune that stretches from northeast of Little River Road to about Oak Street (36,500-38,100 ft). The growth of this dune may be attributed to the welding of historic sediment shoals associated with the old Little River Inlet.

Beach profiles continue to steepen from Oak Street east into Pine Point (38,300-41,200 ft), corresponding with a curvature of the coastline towards 90° from North (Figure 6). An abrupt change in shoreline orientation and distinctly steeper beach profile slopes near 41,300 ft may be the result of a shore perpendicular trough between shoals of the Scarborough River ebb delta. This shoal structure may cause wave focusing, resulting in the steeper profiles and change in orientation. Profile flattening north of this is attributed to shoaling adjacent to the Scarborough River jetty.

Estimated Net Volume Changes (1962-1995). Beach profiles within region 3 exhibit the highest positive volume changes along Saco Bay (Figure 23). Stretches with very little volumetric change over the period of study are concentrated between 25,500-36,000 ft, corresponding with the heavily stabilized sections of the Old Orchard Beach, Surfside, and Grand Beach shorelines. This makes sense based on the technique used to determine erosion/accretion and subsequent volume changes, since the seaward edges of structures were measured in areas with no frontal dune vegetation.

The largest positive net volume changes within region 3 occur within compartment 3C, downdrift (northeast) of Goosefare Brook, and updrift (southwest) of the Scarborough River. Both Goosefare Brook and Scarborough River act as sediment sinks (van Heteren and others, 1996). Goosefare Brook has actually closed several times in recent history, most recently in 1992, when dredged material used to nourish the beaches at Camp Ellis migrated northwards. The inlet of the brook also has a history of meandering periodically to the north and south, which is evident in both the 1962 and 1995 photographs. These variations may be attributed to wave refraction patterns and currents in the vicinity of Goosefare Brook (Kelley and others, 1995), and probably cause the instability seen at the immediately adjacent shorelines.

The Scarborough River also acts as a sediment trap, and receives the majority of the sediment moving northwards along the Saco Bay shoreline, supplied mostly by the Saco River. As mentioned previously, Kelley and others (1995) estimate that the Saco River supplies approximately 10,500-21,000 yd^3 (8,000-16,000 m^3) of sediment annually to Saco Bay (Kelley and others, 1995; Barber, 1995). According to their work, from 1955 to 1991, Pine Point received a minimum of 11,117 yd^3/yr (8,500 m^3/yr) of sediment from both erosion of the shoreface and alongshore drift.

Based on volume changes within the subaerial-intertidal beaches of Grand Beach northeast into Pine Point (approximately 36,000-42,300 ft), there was an overall net volume gain of near 705,900 yd^3. This equates to approximately 21,000 yd^3/yr volumetric gain from 1962-1995. Barber (1995) estimated that the total volume of accretion at Pine Point over a 96-year period from 1859-1955 was on the order of 5.8×10^6 yd^3 (4.46×10^6 m^3), with approximately 31% (1.798×10^6 yd^3) of this going into spit accretion at Pine Point. If the annual volumetric gain of 21,000 yd^3/yr from the current study (1962-1995) is used to compute a net 96-year period for comparison, a net volume change of $+2.016 \times 10^6$ yd^3 is recorded, similar in magnitude to Barber's (1995) net volume gain at Pine Point.

Region 4 (Western Beach)

Estimated Net Erosion and Accretion (1962-1995). Shoreline changes indicate, in general, substantial amounts of accretion along Western Beach. Aside from some small pockets of little change or slight erosion (e.g., nearest the Scarborough River jetty, and near 44,600 ft at a tee location of the golf course), net accretion averages around 60 ft, with the stretch of beach from 43,700-44,800 ft having an average net accretion of 47 ft, while the remainder of the beach has an average of 70 feet. This difference may be attributed to the influence of the Scarborough River channel on this section of beach nearest the Scarborough River jetty. This area is proximal to the main channel of the river; because of this, current velocities are most likely higher in this area, making sediment accumulation and subsequent accretion more difficult.

Shoreline Type, Dry Beach Width, and Total Landward Width. Since Western Beach borders the Prouts Neck Country Club, there are very few habitable structures along the shoreline, and hence, very few stabilization structures to protect them, although a clubhouse and several smaller structures are located at

the southeastern end of Western Beach. The majority of the shoreline type is therefore vegetated dune. Western Beach, however, does border several holes of the Country Club. Therefore, distances were measured from the vegetation line to the nearest green or fairway, since shoreline changes may impact course locations. Distances to the golf course, in general, are well over 100 feet aside from several pockets near 44,500 ft that are near 50 feet (near Tee #2). No dry beach widths were measured for this section.

Alongshore Variation of Beach Profile Shapes. Along Western Beach, beach profiles appear to be impacted by the Scarborough River, especially those most proximal to the river's main channel. Beach profiles along the first 1,100 ft stretch adjacent to the Scarborough River jetty are relatively high in elevation (near 15 ft) and quite steep (slopes on the order 0.100), achieving depths of -3 feet within 200 feet of the dune line. Beach slopes tend to flatten with distance away from the jetty, as the main channel migrates farther offshore. This trend may be due to the influence of tidal currents on beach profile shape. In general, currents within the main channel move at greater velocities than those outside the main channel, prohibiting sediment accumulation that permits the formation of a wide, flat beach. Farther east, beach profiles flatten and extend much farther offshore (greater than 500 feet) in order to achieve depths of -3 feet.

Estimated Net Volume Changes (1962-1995). As a whole, the shoreline along Western Beach has gained approximately 141,200 yd^3 of sand over the 33-yr study period, or approximately 4,300 yd^3/yr. However, the 2 separate compartments within the region have undergone different net changes. Only 28% (40,000 yd^3) of the net volume change is accounted for in the first 1,100-ft stretch (compartment 4A) of beach east of the Scarborough River. The morphology of this compartment is heavily influenced by tidal currents associated with the Scarborough River. Ebb and flood currents probably divert sediments into the ebb and flood deltas, leaving little sand for accumulation adjacent to the main channel. The majority of positive net volume change occurs in the easternmost 1,900-ft (compartment 4B) of shoreline. This is probably due to sediment entrapment by Prouts Neck and a weakening in the impacts of tidal currents from the river.

General Discussion

An imbalance exists in the sediment budget along the Saco Bay shoreline. Part of this may be a result of the method employed to determine erosion/accretion and subsequent volumetric gains and losses. By using the visible seaward edge of vegetation, or a stabilization structure in the absence of vegetation, false stability may be represented when in fact erosion has occurred. This is most likely the case along the Camp Ellis Beach and portions of the Hills Beach shoreline, which are heavily engineered with seawalls; these stabilized sections, especially in the case of Camp Ellis Beach, have been rebuilt several times between 1962 and 1995. Therefore, the seaward edge of structure, for the overall time period of 1962-1995, appears to not have changed even though it has most likely undergone episodes of substantial erosion.

It is unlikely, however, that the sole source of material for the accretion seen at Pine Point is eroded and reworked material from the Camp Ellis shoreline. Sediment originating from the Saco River may be migrating northwards and feeding the beaches to make up for the apparent sediment budget deficit. It is also possible that sediment from the subtidal portion of the beach along Camp Ellis is being eroded and reworked northwards, although this trend is impossible to decipher given that existing profile data only extends to near the low water mark. Kelley and others (1995) and Barber (1995) estimated an annual range of 10,500-21,000 yd^3 of sediment input from the River. This accounts for 346,500-693,000 yd^3 of sediment over the 33-year period of this study. The upper limit of this range is comparatively close to the approximate 705,900 yd^3 gain seen at the subaerial-intertidal portions of beaches at Pine Point during the current study, although it is unlikely that all sediment introduced to Saco Bay by the Saco River ends up at Pine Point.

Interestingly, if the amount of sediment dredged and used for either beach nourishment (at Camp Ellis Beach) or disposed of inshore/offshore (Tables 2, 3) during the study period is taken into account, the numbers relate well. Approximately 473,700 yd^3 of sediment was used for nourishment at Camp Ellis Beach, and approximately 427,500 yd^3 of sediment was dredged from the Scarborough River and disposed of in either the nearshore or the offshore, equaling 901,200 yd^3 of sediment added to the Saco Bay nearshore system. Assuming that the overall gain in sediment volume for region 3 (at Pine Point) was 1,125,300 yd^3, this leaves a deficit of about 224,000 yd^3 of sand, well below the range for total input of sediment from the Saco River over a 33-year period (using Kelley and others, and Barber's numbers, above). Since the current study only accounts for sediment volumes incorporated in the subaerial-intertidal portion of the beach profile, this variation may be justified. The process of upwelling may also rework some of this sand onshore during westerly gales (Dickson, 1999) through a regular exchange with the nearshore (Heinze, 2001).

As a whole, Saco Bay beach profiles (from Hills Beach north to Western Beach on Prouts Neck) have experienced an overall net volumetric gain of approximately 1,526,400 yd^3 for the 33-year study period. This summed value falls in between values for total sediment entering the nearshore system (including volume of dredged materials added), which range from 1,247,700-1,594,200 yd^3.

Identification of Regions of Potential Concern

Net erosion or accretion values were used to estimate annual rates for the time period of study. By multiplying calculated annual rates by a time period of 100 years (a 100-year time frame was selected since Maine's Coastal Sand Dune Rules, Chapter

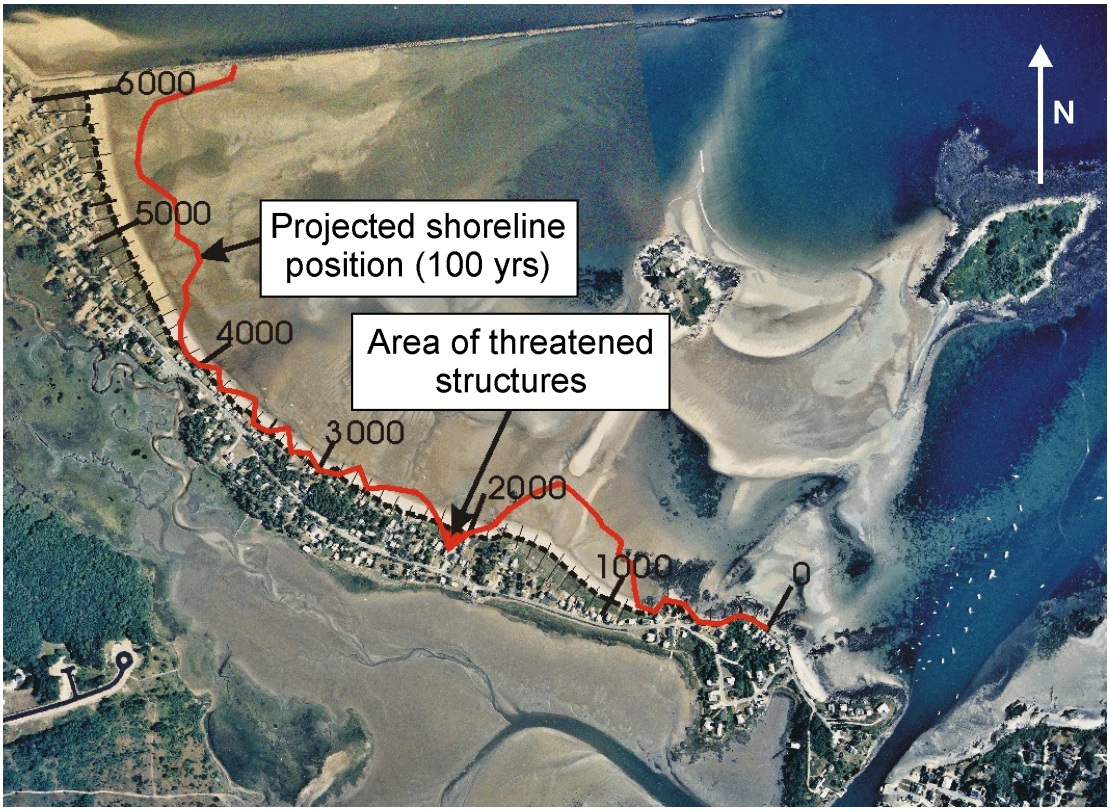

Figure 25. 1995 aerial photograph of region 1 depicting the projected 100-year shoreline position (red line), with areas of threatened structures identified. The shoreline may be stable to accretive, with only a small pocket of projected erosion that threatens existing structures. The central portion, although it may appear stable, is maintained by rip-rap and wooden seawalls (not to scale).

355, reference a 100-year erosion standard), future estimates of shoreline position for each 100-foot alongshore transect were made and areas with potential future erosion problems were identified (Figures 25-28). Areas where existing structures may be threatened by projected erosion of the shoreline were identified. As expected, areas with existing erosion problems (e.g., Camp Ellis Beach), exhibit the farthest landward shift in shoreline position. It is important to note that future projected shoreline changes are based solely on shoreline change data (erosion and accretion rates) calculated from the 1962 and 1995 data (see *Data and Method Limitations*).

Based on this method, the future shoreline of region 1 (Figure 25) will be relatively stable to highly accretive, with only one small pocket of projected erosion that threatens existing structures. The sandy shoreline of Hills Beach, from the entrance to The Pool north to near Surf Avenue, may accrete several hundred feet seaward as a result of wave shadowing by numerous shoals and a tombolo that stretches seaward to Basket Island. Extensive accretion is also projected to occur from 4,200-6,000 ft along the shoreline, associated with continued shoaling along the southern Saco River jetty. Shoreline stability, albeit artificial stabilization-induced, is projected for the central section of the shoreline (2,200-4,200 ft), with one pocket of erosion threatening a structure near 2,100 ft, north of Surf Avenue. However, historically documented erosion (e.g., Hulmes, 1980; USACE, 1961) of this portion of the shoreline will probably continue unless stabilization structures are continually rehabilitated into the future. The actual source of sediment for projected shoreline accretion is not known; however, based on existing data, it appears that sediment in front of the central portion of the shoreline may be reworked by waves to the north and south, and the existing nearshore tombolo and shoals may continue to accrete (evident in a 2002 GPS survey of the Hills Beach dry beach widths).

In region 2 (Figure 26) segments of the shoreline within 1,000 ft of the northern jetty of the Saco River, from Bay Avenue north to Lower Beach Avenue, may experience up to 400 ft of erosion over the next 100 years. Such changes to the shoreline may jeopardize numerous existing habitable structures. Minimal shoreline accretion may occur for a short stretch of shoreline between Lower Beach Avenue and Sunrise Avenue (8,800-9,300 ft) within Camp Ellis Beach. This projected accretion is probably inaccurate, resulting from the reconstructed seawall that fronts this portion of the shoreline along Surf Street. Shoreline stability may be maintained through the maintenance of the existing seawalls. Substantial shoreline erosion may occur north of this stretch, from Sunrise Avenue in Camp Ellis

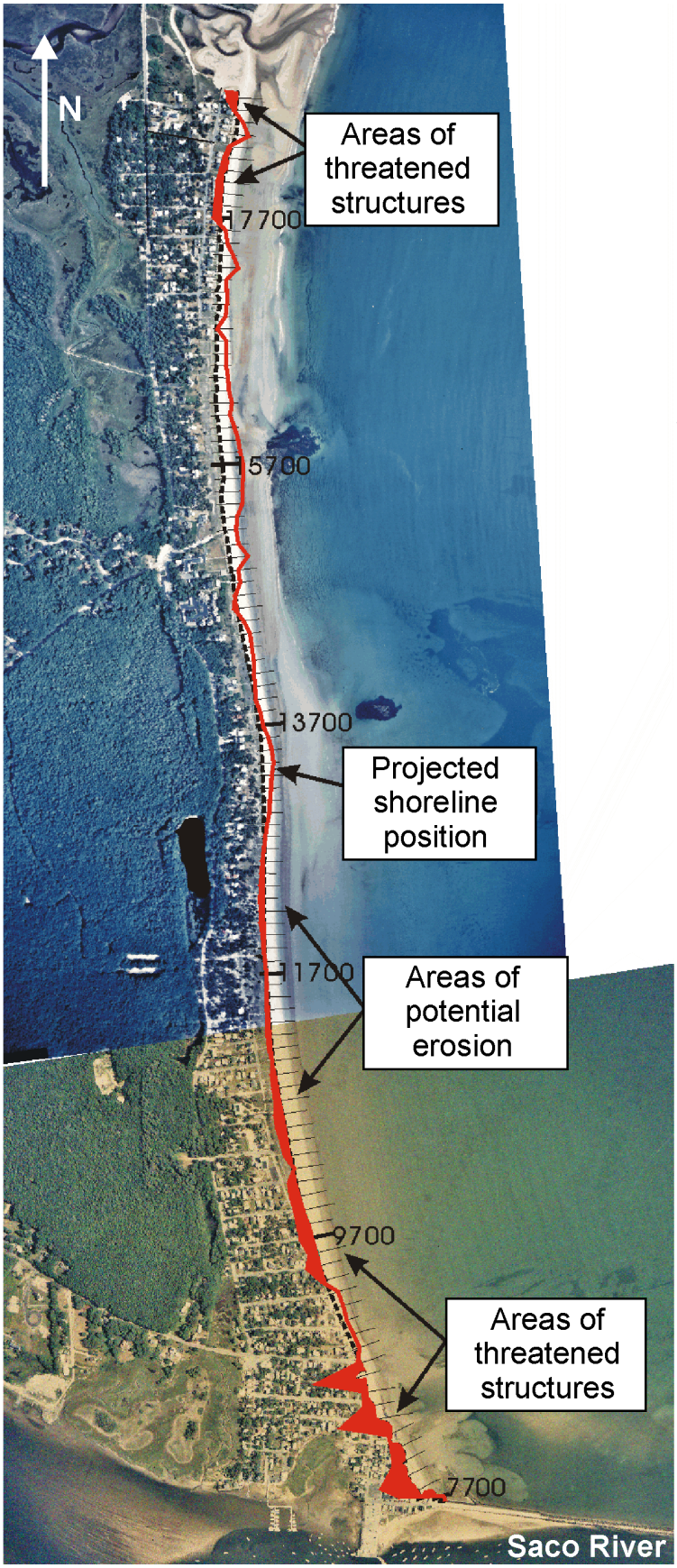

Figure 26. 1995 aerial photograph showing projected 100-year shoreline position along region 2. Large pockets of erosion threaten the Camp Ellis Beach shoreline and adjoining existing structures. The projected erosion appears to dissipate near 12,700 ft (5,000 ft north of the jetty), although additional pockets of erosion exist nearer Goosefare Brook (not to scale).

north to the shoreline adjacent to Long Pond in Ferry Beach (9,300-12,700 ft), although no existing structures appear to be affected. Within Kinney Shores, several structures along the southern seawalled side of Goosefare Brook appear to be threatened by future erosion.

Future shoreline positions within region 3 show dominant accretion and stretches of general stability for the majority of the region (Figures 27A, B). The shoreline adjacent to Goosefare Brook within Ocean Park, from 19,700-21,700 ft, is fairly stable, while future shoreline positions show projected accretion from Tioga Avenue northeast to Fernald Avenue (21,800-25,400 ft). It is imperative to note that the projected future accretion along this stretch is a direct result of artificial dune construction associated with the sewer line installation, and therefore may not reflect any natural accretion rate or a sustainable trend. Shoreline stability and slight accretion is projected for the seawalled shoreline along Old Orchard Beach and Surfside, from 25,500-33,700 ft. A small pocket of erosion that may threaten several oceanfront structures is projected within Surfside (near 32,000 ft), corresponding with the old location of the Little River Inlet. North of this stretch, future shoreline positions project high accretion from Grand Beach into Pine Point (34,200-42,300 ft), on the order of several hundred ft to over 700 ft of accretion over the next 100 years assuming recent accretion rates and a continuing sand supply from the southern part of the Bay.

Based on existing trends used herein, large portions of Western Beach may also accrete over 200 feet in the next 100 years (Figure 28). Areas with projected accretion of 50 feet or less are located directly adjacent to the Scarborough River, adjacent to a tee of the golf course, and in the vicinity of the practice green. The cause of lower projected accretion along compartment 4A of Western Beach may be an old abandoned tidal channel situated adjacent to the shoreline (Figure 28). This channel is slightly deeper than adjoining shoals to the east, and inhibits beach accretion due to higher currents. As a result, this stretch of beach coincides with the steepest beach profiles along Western Beach, and very low accretion rates over the study-period. This lends to the relatively small accretion projected along this stretch. The remaining portions of Western Beach appear to be fed by the adjacent shoal. It is important to note that estimating future shorelines along a stretch of beach heavily influenced by a tidal channel is difficult (see *Data and Method Limitations*).

Areas of projected substantial potential accretion or erosion are also identified in aerial photographs of the different regions in the context of other physical characteristics that correspond with the *Recommendations* section (Figures 33-38). In addition to projected erosion or accretion areas, these figures identify beach areas that may be vulnerable to shoreline change due to any of the following characteristics: maximum elevations below base flood elevations (BFE); dry beach widths of less than 25 feet; total widths of less than 100 feet; areas stabilized with shoreline structures; and areas proximal to tidal inlets. Refer to the *Recommendations* section for further discussion of these characteristics in relation to each region.

Data and Method Limitations

Estimated Net Erosion and Accretion (1962-1995). There are several limitations to the methods employed within this study in determining net erosion and accretion. In general, there are three types of aberrations that should be corrected, when possible, if aerial photographs are used for shoreline change: variable scale, tilt, and radial lens distortion. To account for scale, common control points (e.g. homes, road corners, etc.) were set in each photograph, and the 1962 photograph was "rubbersheeted" (stretched) linearly to assigned control points of the 1995 photograph. However, rubbersheeting does not account for displacements due to tilt and radial lens distortion. Therefore, errors may be introduced into the shoreline data by tilt and radial lens distortion. Because of this, the shoreline change values should be used for overall trend determination and guidance only, and not taken as exact values.

The method used to determine net erosion or accretion is called the "end point" method since it only uses shorelines from two years (1962 and 1995). Although this method is widely utilized by state coastal management agencies, it cannot take into account yearly or decadal fluctuations in shoreline position as a result of different erosion or accretion rates (Crowell and others, 1991). It is, however, less complicated and time consuming, and by some researchers (Leatherman and Anders, 1999) has resulted in the same shoreline change rate as the "linear regression" method. Therefore, results should be used for general planning only, and cannot indicate exact erosion or accretion rates, which may vary from year-to-year or more frequently due to storm events. Future technical reports on shoreline change (data permitting) will utilize the "linear regression" method rather than the "end point" method.

The seaward edge of vegetation was chosen as the erosion reference feature (ERF) because it is an indicator of the first point of longer-term stability than high water or wrack lines (Leatherman and Anders, 1999). However, using seaward edge of vegetation may be inaccurate at times due to unnatural (human) impacts to vegetation, such as planting, artificial construction or beach scraping. Such is the case with the stretch of beach along Ocean Park and Old Orchard Beach that underwent sewer line emplacement within an artificially constructed frontal dune planted with beach grass. This gives a false signal of natural accretion that must be either discounted, or at a minimum, duly noted.

Using the seaward edge of a seawall as an ERF may also cause errors in net erosion or accretion calculations. Shorelines may be naturally eroding, yet "stabilized" by a seawall (e.g., compartment 2A, Camp Ellis, and compartment 1B of Hills Beach). The seawall, if maintained over the time period of study, provides a signal of shoreline stability, while an adjacent unprotected shoreline may be undergoing erosion. In addition, along erosive shorelines fronted by seawalls (where the HWL is at the seawall), wave reflection can erode the beach vertically, not horizontally, since the beach cannot retreat in a landward direction.

Figure 27A. 1995 aerial photograph showing projected 100-year shoreline position along southern part of region 3. Accretive trend from 19,700-25,500 ft may be attributed to artificial dune construction, and may not occur naturally. From 25,500 ft northwards, there is little change expected (possibly minor accretion) due to shoreline stabilization with seawalls (not to scale).

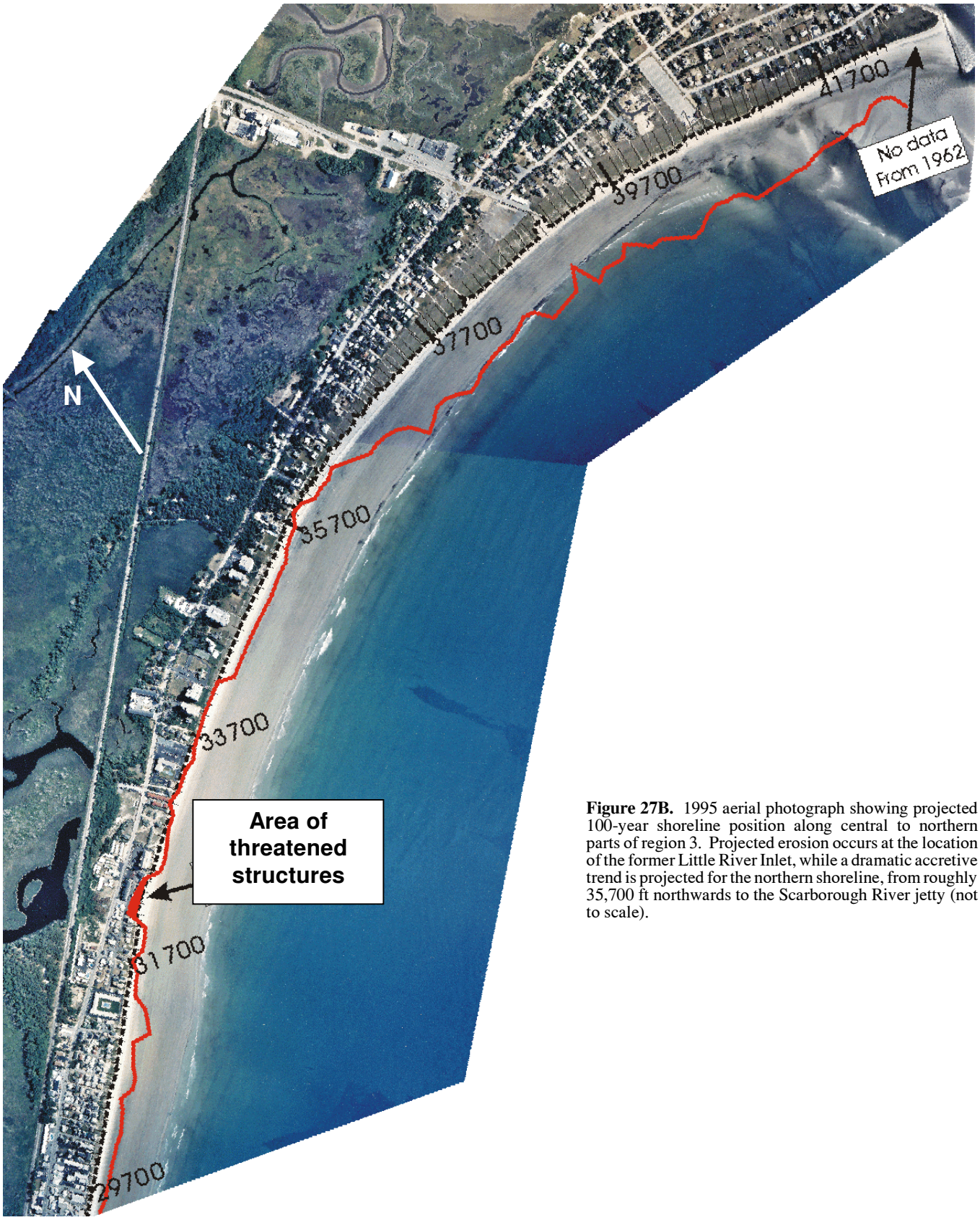

Figure 27B. 1995 aerial photograph showing projected 100-year shoreline position along central to northern parts of region 3. Projected erosion occurs at the location of the former Little River Inlet, while a dramatic accretive trend is projected for the northern shoreline, from roughly 35,700 ft northwards to the Scarborough River jetty (not to scale).

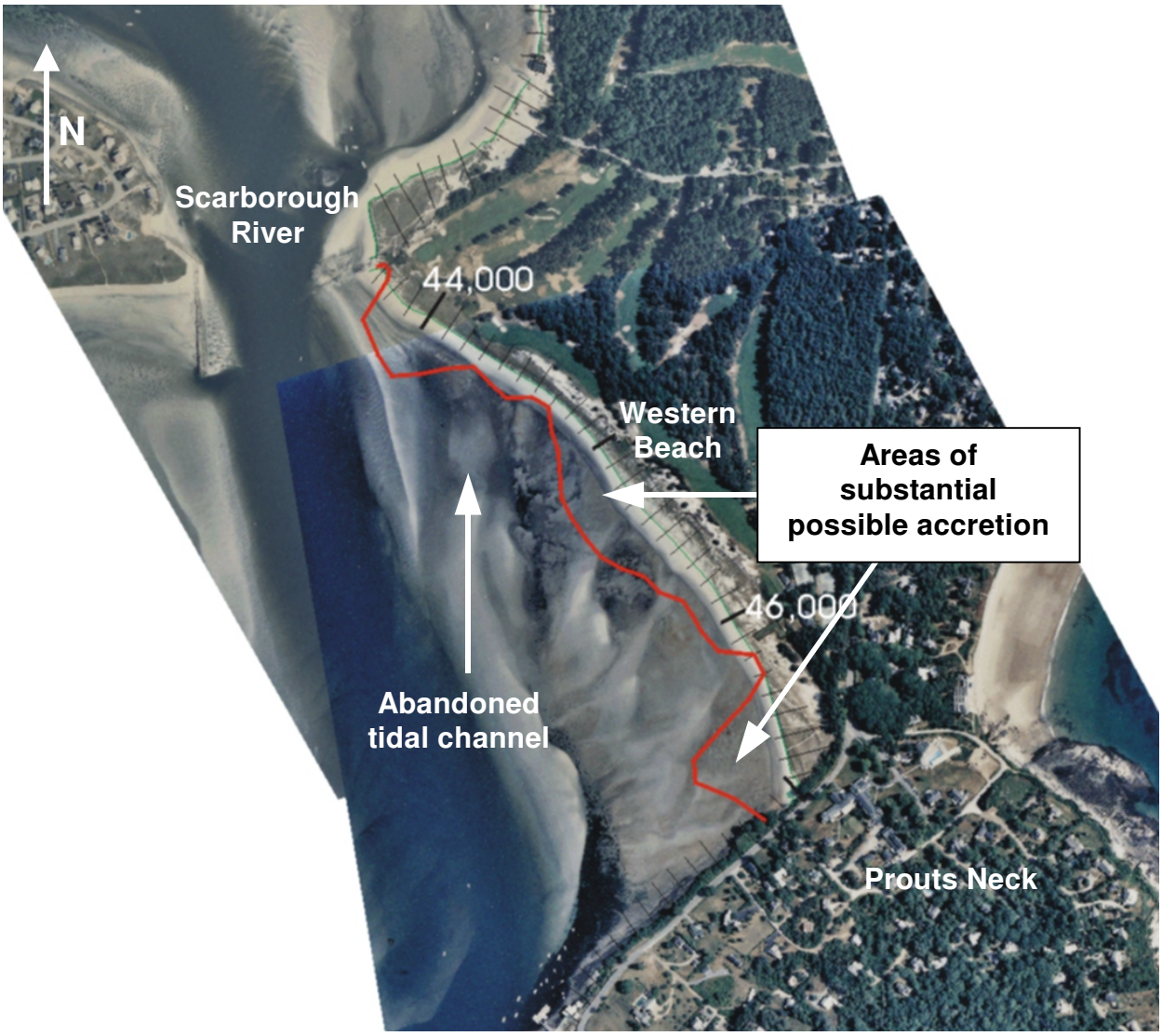

Figure 28. 1995 aerial photograph showing projected 100-year shoreline position along the Western Beach shoreline. Projected accretion is dominant from 43,800-44,200 ft, from 45,000-45,800 ft, and 46,500-46,900 ft (not to scale).

Estimation of Net Volume Changes. The method for estimating net volumetric changes for 1962-1995 also has limitations. Since Saco Bay lacks adequate beach profile data, beach profiles from a 2000 LIDAR flight were utilized. For calculating volume changes, it was assumed that the 2000 profiles represented beach profile conditions from both 1962 and 1995. Other authors have used a similar technique to estimate volumetric changes along the South Carolina shoreline, lacking present beach profile data (Kana and Gaudiano, 2001). Although this assumption is largely inaccurate, lacking beach profile data from these time periods, it was one that had to be made. However, it must be noted that beach profiles are highly variable (Heinze, 2001) and one single snapshot from 2000 may not accurately represent beach profile shapes from either 1962 or 1995. In addition, the current study only looks at variations in the subaerial-intertidal beach, not the subtidal beach where the majority of sediment is located.

Projection of 100-yr Shoreline Positions. Projection of future 100-yr shoreline positions is based on average annual erosion rates (AAER) calculated from net erosion/accretion using the end point method. Therefore, yearly or decadal trends in shoreline change are not taken into account. For example, in the 33-yr period of study, a shoreline may have accreted 50 ft in 10 years, eroded 70 ft the next 10, then accreted 20 ft over the next 13 yrs. However, the only data available from the 1962 and 1995 photos are the beginning and ending shorelines, yielding a "stable" net shoreline change of 0 ft even though the shoreline underwent large fluctuations and was anything but stable. Using an AAER of 0 ft projected 100 yrs from now indicates a very stable shoreline. In areas prone to highly variable shoreline conditions

(e.g., directly adjacent to a highly migratory tidal channel), this method may yield inaccuracies. Such may be the case with the shoreline at Western Beach (region 4), which historically has been highly variable due to its proximity to and the influence of the Scarborough River tidal channel. However, using 1962-1995 data, projected shorelines indicate accretion over the next 100 yrs. Therefore, future shoreline projections should be used for guidance purposes only.

Correlations

This section presents and discusses notable correlations, or a lack thereof, between certain beach profile characteristics and overall shoreline trends. For example, an erosive beach should exhibit different beach profile characteristics than an accretive beach. Such relationships were investigated along the Saco Bay shoreline.

Coastline Orientation. Coastline orientation (Figures 6, 7) is an important characteristic of shoreline morphology since it dictates those portions of the shoreline that receive direct, incoming wave energy, and those portions that may be protected from dominant wave conditions. Wave energy in many cases is a driving factor controlling beach profile shape and dominant alongshore geomorphic characteristics (e.g., erosion or accretion). Therefore, the relationships between coastline orientation and different beach and shoreline characteristics were investigated.

Figure 29 illustrates the inverse relationship between coastline orientation and beach profile slope for the general regions identified. In general, beach profile slope generally decreases with an increase in coastline orientation. This trend is most evident in region 2, and barring several outliers, also within region 1. Slopes within region 1 are highest from 100°-120° orientations probably due to the fact that these profiles are located at the southern end of Hills Beach where they are more exposed to waves arriving from the northeast, around the southern jetty of the Saco River. The other slopes in region 1 generally decrease with increasing compass bearing. This relates to wave sheltering from the northeast by the jetty, and may permit smaller, longer-period, summer wave conditions to help build the beach.

Profile slopes are highest within region 2 at orientations between 150°-180° from TN. This may be a result of several factors. First, summer wave conditions (approaching from the S and SE) that generally move sand onto the beach are completely blocked by the northern jetty. This orientation exposes the shoreline to erosive, large, short-period storm waves that approach from the E and NE.

This relationship within region 3 is harder to discern due to the general flatness of beach profiles along the stretch from Goosefare Brook north to the Scarborough River. However, a distinct trend does emerge. As coastline orientation increases, there is a negative relationship from 200°-220°, with a slight decrease in profile slopes. For profiles located at orientations of 220°-250°, there is a consistent slope. A large portion of profiles with these orientations falls within the heavily seawalled section of Old Orchard Beach. There is then a direct relationship between orientation and slope for orientations ranging from 250°-275° from TN. This may relate to an increase in maximum profile elevations (dune crests) at the northern end of the bay where the sand dunes are relatively high. In addition, a distinct

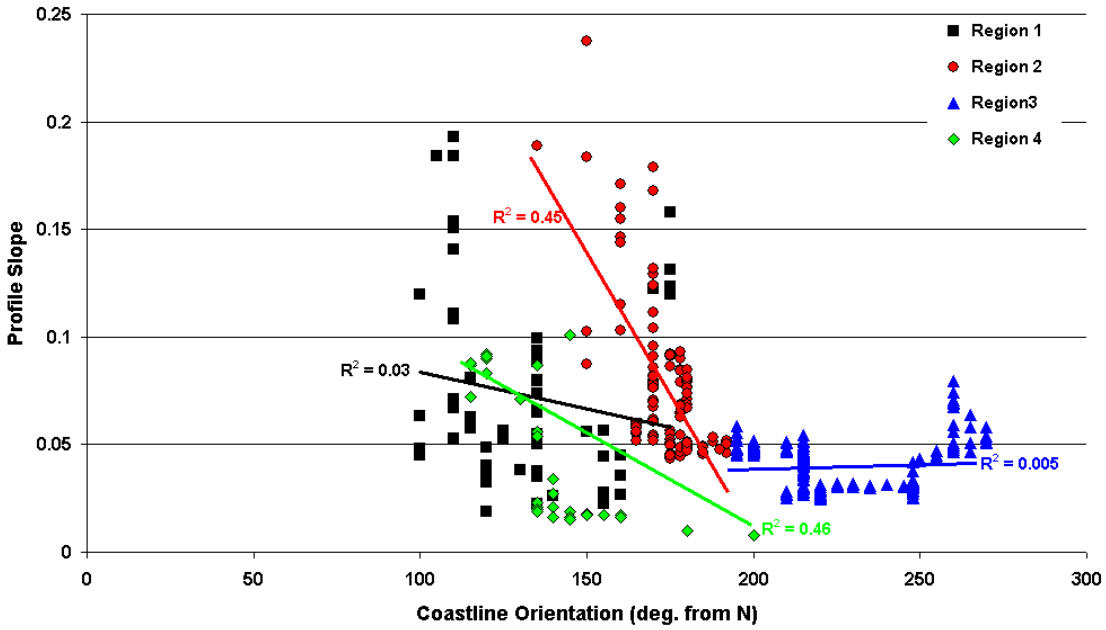

Figure 29. Relationship between coastline orientation and profile slope. Generally, regions 1, 2, and 4 show inverse relationships. Region 3 shows a weakly direct relationship.

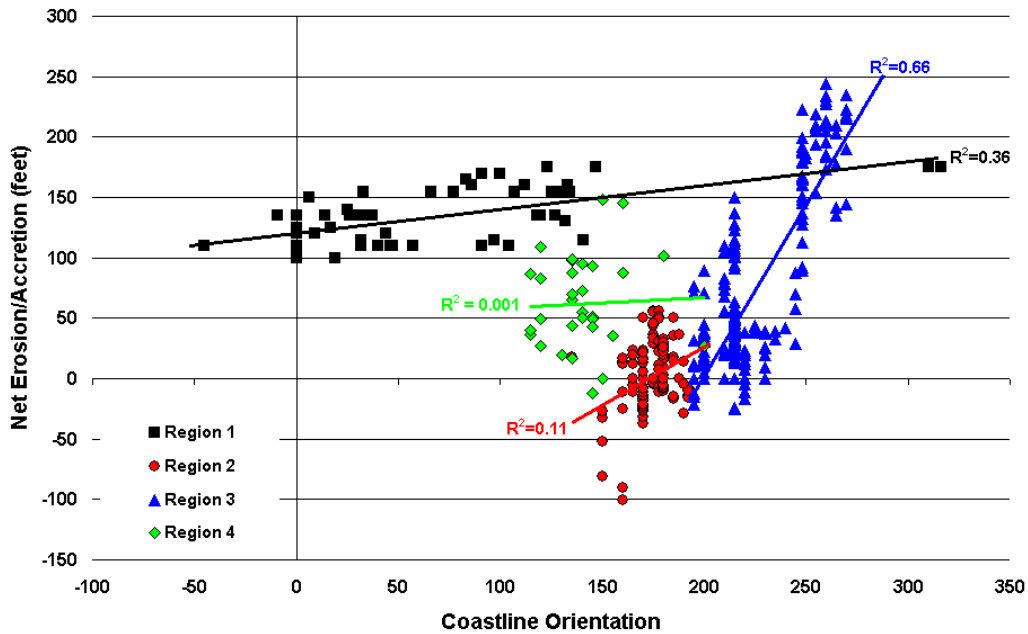

Figure 30. Relationship between coastline orientation and net erosion or accretion. All regions show a direct relationship of increasing accretion with increasing coastline orientation, although the relationship for region 4 is weak. The strongest relationship occurs in region 3.

negative relationship is apparent for region 4 beach profile slope values from along Western Beach (centrally located on Figure 29 between 100-160° from TN).

There is a direct relationship between coastline orientation and net erosion/accretion (Figure 30). This is partly due to the steady increase in orientation of the coastline from south to north, combined with the general increase in accretion from south to north. This relationship is also positive for each region, signifying the dominant northerly transport of sediment throughout the Saco Bay area. A relatively strong relationship is seen within region 3, where the highest net accretion occurs at Pine Point (linear regression coefficient, $R^2 = 0.66$). The weakest relationship is for region 2 ($R^2 = 0.11$). Region 1 has a relatively strong positive relationship due to the shoaling that occurs on the southern side of the Saco River jetties. The relationship for region 2 is weakest due to the fact that there is no littoral barrier that aids in trapping sediment, aside from the natural sink at Goosefare Brook.

Estimated Net Erosion and Accretion (1962-1995). The relationship between the distance from the northern Saco River jetty (jetty being a distance of 0 ft) and net erosion/accretion along the Saco Bay shoreline is illustrated in Figure 31. Regions 1 (Hills Beach) and 4 (Western Beach) have been removed because they have very different trends, and act as their own littoral cells. Although a direct linear relationship exists, it is not overly strong (R^2=0.49). If artificial accretion, caused by the construction of dunes to protect a sewer line within Ocean Park/Old Orchard Beach, is removed (points circled), the relationship becomes slightly more direct (R^2=0.53). However, the overall trend of net erosion/accretion along Saco Bay does not appear to be linear; it is best represented by a third order polynomial expression (R^2=0.80). This expression represents well the distinct variations in shoreline changes of the shoreline from the Saco River northwards to the Scarborough River. The shoreline is generally erosive from the Saco River jetty northwards approximately 5,000 feet. From 5,000-30,000, the shoreline is generally stable to mildly accretive. This section represents a "conveyor belt" of sand, where sediment is moving along the beach on its journey northwards. Subsequently, the northern end of the bay, nearest the Scarborough River jetty (30,000-35,000 feet), is highly accretive. High accretion in this section is associated with the trapping of sediments by the Scarborough River ebb tidal delta, which generally forms the northern boundary of the Saco Bay littoral cell.

The relationship shows several other important features. First, the Pine Point shoreline has accreted much more than the Camp Ellis/Ferry Beach shoreline has eroded, illustrating an imbalance in the sediment budget (see *General Discussion*). This clearly indicates sediment input other than eroded sediments from compartment 2A being reworked and transported northwards along the bay. Other sources of sediment may include the Saco River, reworked sediments from the subtidal beach of compartment 2A, and a sand shoal south of Prouts Neck. Second, the different slopes of the polynomial may provide some insight into

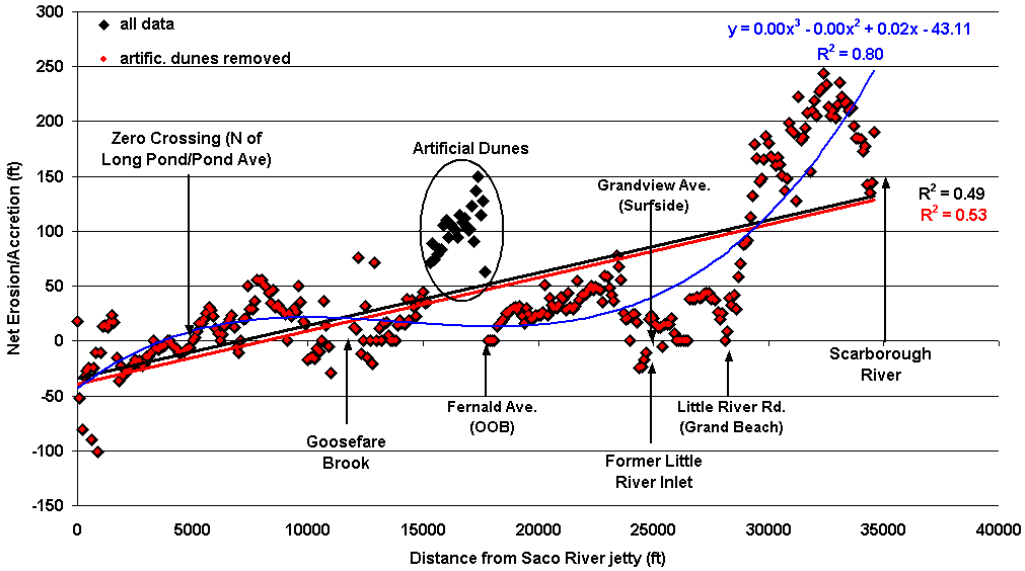

Figure 31. Graph showing trend of alongshore increase in net accretion (1962-1995) with distance from the Saco River jetty, excluding data from regions 1 (Hills Beach) and 4 (Western Beach). Regions 1 and 4 have been excluded from this figure because they tend to act as their own littoral cells, and have trends very different from the remainder of the bay. Several roads have been included for geographic reference. The relationship is clearly positive, indicating an increase in net accretion at the northern end of Saco Bay, confirming a northerly dominant sediment transport direction. Black points indicate net erosion/accretion data for all transects within regions 2 and 3 (linear fit, black line, R^2=0.49). If artificial dune data (within Ocean Park and Old Orchard Beach, constructed as part of sewer line emplacement) is removed and remaining data is plotted (small red circles), the relationship increases slightly (linear fit, red line, R^2=0.53). The overall alongshore trend is best represented by a third-order polynomial expression (blue line, R^2=0.80), fit to the data with artificial dunes removed. This expression takes into account the general stability (little shoreline change over the 33-yr period) of the central portion of the Saco Bay shoreline, yet also portrays the erosive portion of region 2 (0-5,000 ft) and the accretive region 3 (30,000-35,000 ft).

the gradients of alongshore drift and may relate to different forcings that cause the three different trends seen. These topics are not within the scope of this report, and will be discussed further in different papers.

Beach Profile Slope. An exponential relationship consistently exists between beach profile slope and distance from an updrift and downdrift jetty (Figure 32). The relationships are closest between portions of region 1 (Hills Beach, denoted as 'S of Saco River') and region 4 (Western Beach, 'E of Scarborough River'). This is unexpected, as one is considered an updrift beach (region 1), while the other is a downdrift beach (region 4). This relationship may be explained by the fact that both regions may be considered their own enclosed littoral cells found at the ends (south and north, respectively) of the larger, log-spiral shaped Saco Bay littoral cell. Also, both appear to be influenced more by tidal currents than regions 2 or 3, which are located along the spine of the log-spiral shoreline.

RECOMMENDATIONS

The current study has identified certain morphologic trends along the Saco Bay shoreline. Net erosion and accretion, and subsequent subaerial-to-intertidal beach volumetric changes were determined at 100-foot beach profile transects along the shoreline. Certain beach features, such as maximum dune elevation, are important safety features in protecting developed shorelines from storm events. As a result, shorefront communities may find portions of this document useful for planning purposes. The following recommendations are solely based on trends seen within the current study. *It is suggested that communities use this document for preliminary guidance only, and contact appropriate consultants in order to receive additional guidance regarding shoreline studies and subsequent planning. It is also recommended that communities along Saco Bay work to develop federally approved hazard mitigation plans in order to deal with both short and long-term coastal hazards.* Recommendations include the following:

Regional Sediment Management

Communities within the Saco Bay littoral cell should consider implementation of a regional sediment management plan. Sediment, in general, originates from and is confined within the bay. Sand "recycling" may therefore be an extremely effective measure in dealing with areas of erosion and accretion. Previous authors (e.g., Kelley and others, 1995) have proposed such a sediment management plan. Since there are two federal navigation projects located at both ends of the bay (one at the source, the Saco River; and one at Scarborough River), communities should look to couple their efforts with federal dredging projects (under

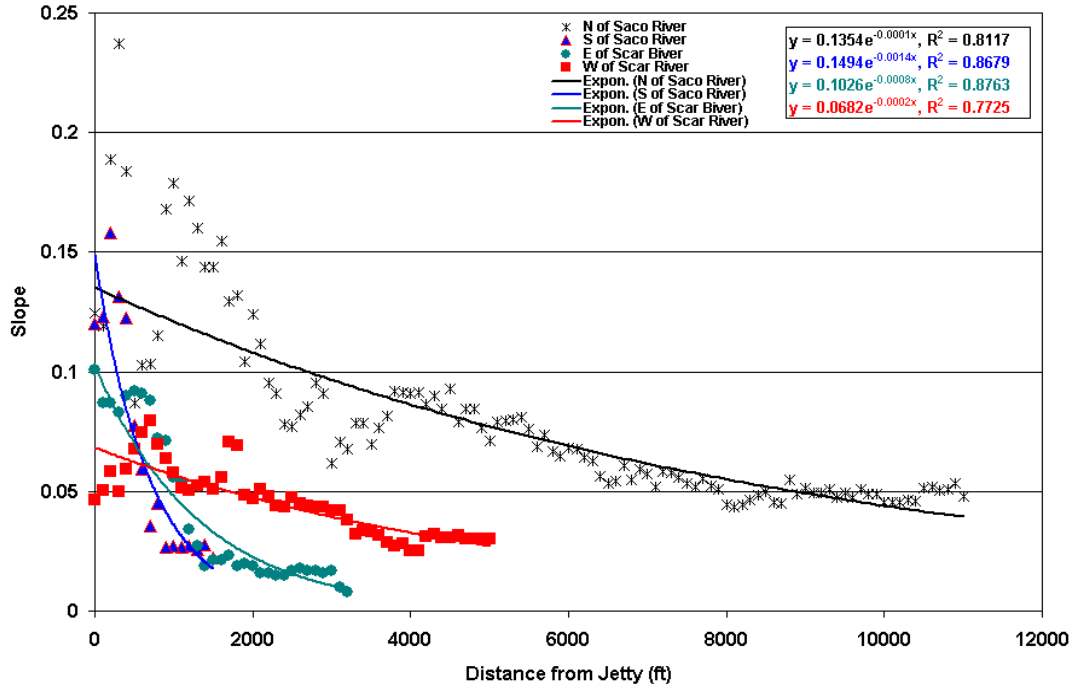

Figure 32. Graph showing different relationships between distance from a jetty and beach slope for shorelines adjacent to the Saco and Scarborough Rivers. The relationships are clearly best represented by exponential, not linear, expressions. It is interesting that the updrift (accreting) shorelines, e.g., S of Saco River (blue) and W of Scarborough River (red), are not similar in slope, as one may expect. However, data for E of the Scarborough River (green) and S of the Saco River (blue) are very similar. This may relate to the fact that both regions 1 and 4 act as individual littoral cells

Corps Operations and Management funding) for sediment backpassing from northern, highly accretive beaches, to southern erosive beaches. Saco Bay seems to be a perfect location to implement the Corps' new Regional Sediment Management (RSM) program, and funding may be available through this program (Rosati and others, 2001).

Elevating Above Base Flood Elevations

Communities exhibiting maximum profile elevations (e.g., dune or seawall crests) below established FEMA base flood elevations should take mitigation actions to create more protective frontal dunes, or in the case of existing rocky shoreline outcrops, elevating existing structures above the base flood elevation (BFE). This should be applicable even to those areas that have a relatively wide landward distance to structure. Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* intermittently from 2,400-3,900 ft, but especially just north of Surf Avenue, near 2,800 ft; and from near the thinnest part of the island (near 4,500 ft) northwest to near Pleasant Avenue (5,100 ft), see Figure 33.
- ***Region 2,*** *Camp Ellis Beach:* in the vicinity of Riverside Avenue (8,300 ft), see Figure 34.
- ***Region 3,*** *Old Orchard Beach:* possibly near Old Orchard Street (26,700 ft); *Surfside:* several pockets stretching from near Grandview Avenue (33,600 ft) northeast to just north of Parcher Avenue (34,000 ft), see Figures 36 and 37.
- ***Region 4:*** no areas apply.

Widening Dry Beach Widths

Communities exhibiting dry beach widths less than 25 ft should consider some form of beach restoration (especially those stretches of shoreline that have dry beach widths of less than 25 ft and total landward distances of less than 100 ft). Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* from 0 to 1,900 ft, and from near 2,500-4,300 ft, see Figure 33.
- ***Region 2,*** *Camp Ellis Beach:* from the northern jetty to 9,700 ft (near Eagle Ave.), see Figure 34.
- ***Region 3:*** no areas apply.
- ***Region 4:*** unknown, although no areas appear to apply
-

Increasing Total Landward Widths

Communities with total landward widths from HWL to the seaward edge of the first habitable structure of approximately

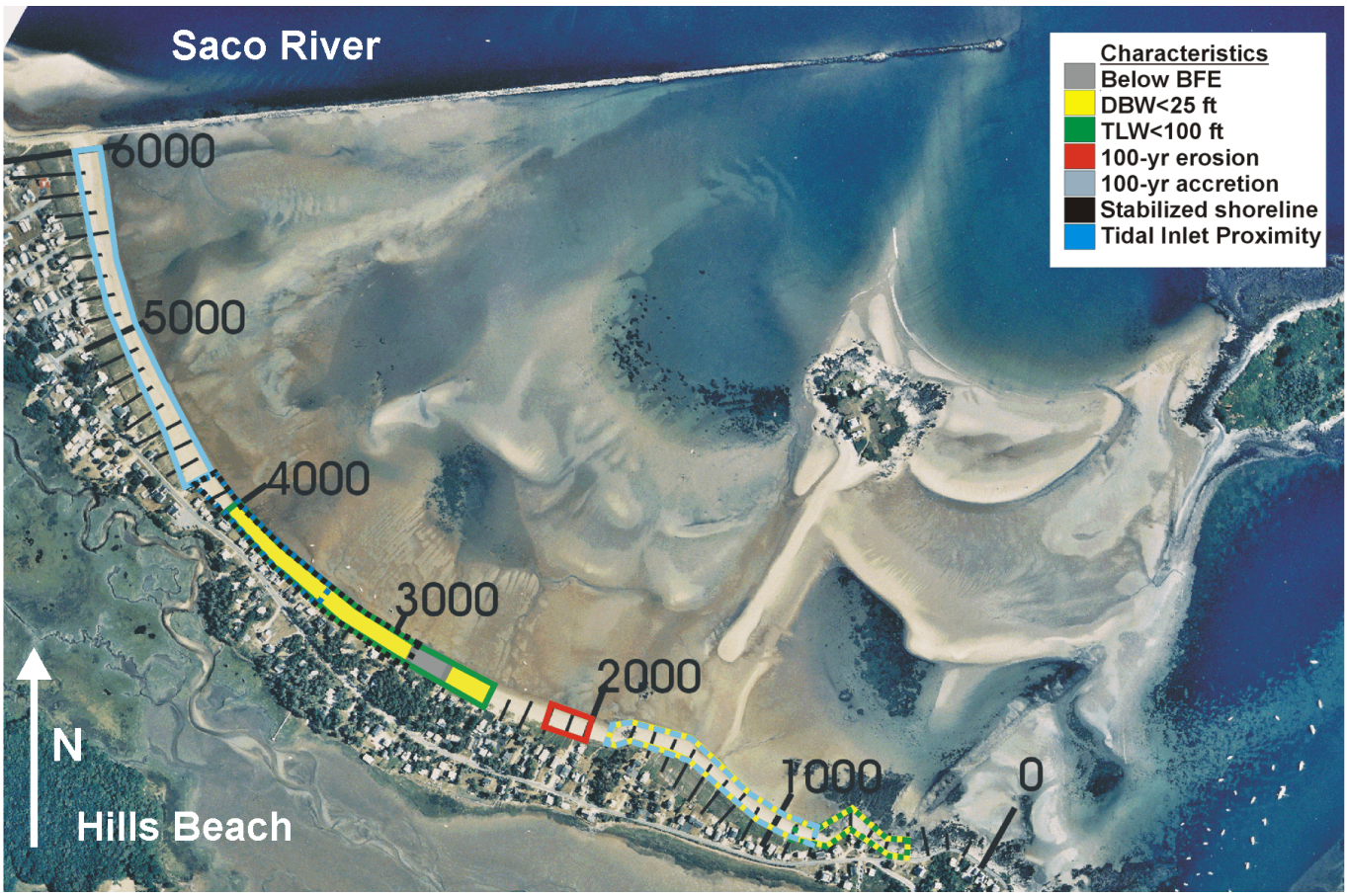

Figure 33. Identified areas that may require management within region 1 (Hills Beach) based on physical characteristics of the beach. The central portion of Hills Beach (approx. 2,500-4,200 ft) appears most vulnerable to shoreline change due to low elevations, and thin dry beach and total widths. In areas of multiple overlap, base layers are solid colors, while overlaying colors are lined or dotted.

100 ft or less should consider some form of beach and/or dune restoration in order to provide a larger natural buffer between dunes or seawalls and habitable structures. This recommendation does not apply to habitable structures fronted by exposed rocky shorelines (e.g., southern Hills Beach). Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* near the southern end of Hills Beach Road (400-900 ft); in the central-northern section of the beach (2,400-4,200 ft), see Figure 33.
- ***Region 2,*** *Camp Ellis Beach:* from Bay Avenue north to near Fairhaven Avenue (7,700-9,700 ft); *Bay View:* in the vicinity of the condominiums just south of Bay View Avenue (14,800-14,900 ft); *Kinney Shores:* near Goosefare Brook (17,700-18,700 ft), see Figures 34 and 35.
- ***Region 3,*** *Ocean Park:* immediately adjacent to the north side of Goosefare Brook (19,700-19,900 ft); *Old Orchard Beach through Surfside:* intermittently from 28,100-29,700 ft, see Figures 36 and 37.
- ***Region 4:*** no areas appear to apply.

Plan for 100-yr Erosion

Communities with projected 100-year shorelines showing areas of erosion that may adversely affect habitable structures should consider advance beach restoration and/or structure relocation or acquisition measures. Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* in the vicinity just north of Surf Avenue (near 2,000-2,200 ft), see Figure 33.
- ***Region 2,*** *Camp Ellis Beach to Ferry Beach:* from Bay Avenue north to Island View Avenue (from 7,700-10,200 ft); *Ferry Beach:* from Island View Avenue to seaward of Long Pond (10,200-12,900 ft), although no structures appear to be impacted; *Kinney Shores:* from near Pinewood Avenue north to Goosefare Brook (17,700-18,700 ft), see Figures 34 and 35.
- ***Region 3,*** *Ocean Park:* possibly from just south of Sandpiper Avenue to near Colby Avenue (20,000-20,500 ft); Surfside: from near Grandview Avenue northeast to near

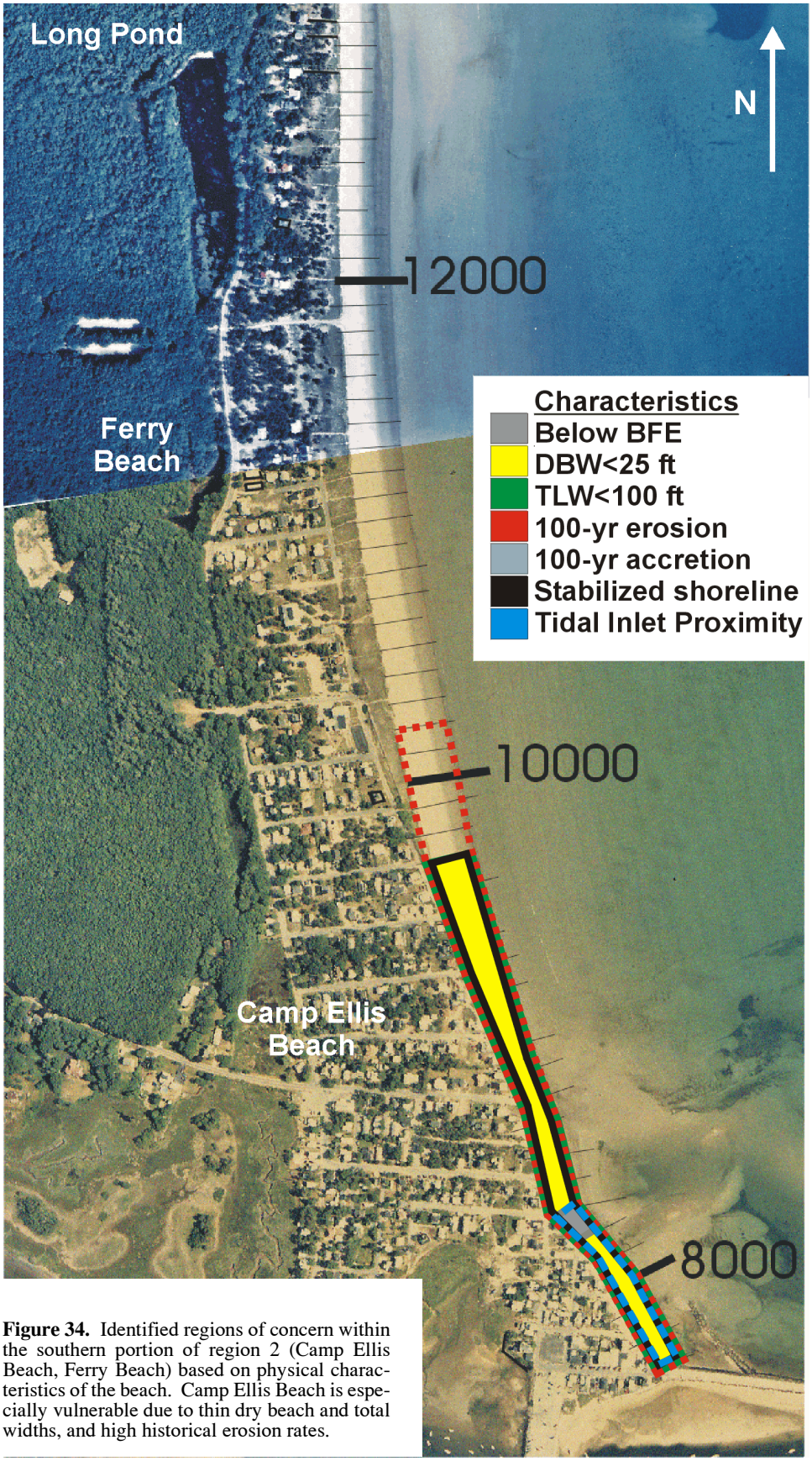

Figure 34. Identified regions of concern within the southern portion of region 2 (Camp Ellis Beach, Ferry Beach) based on physical characteristics of the beach. Camp Ellis Beach is especially vulnerable due to thin dry beach and total widths, and high historical erosion rates.

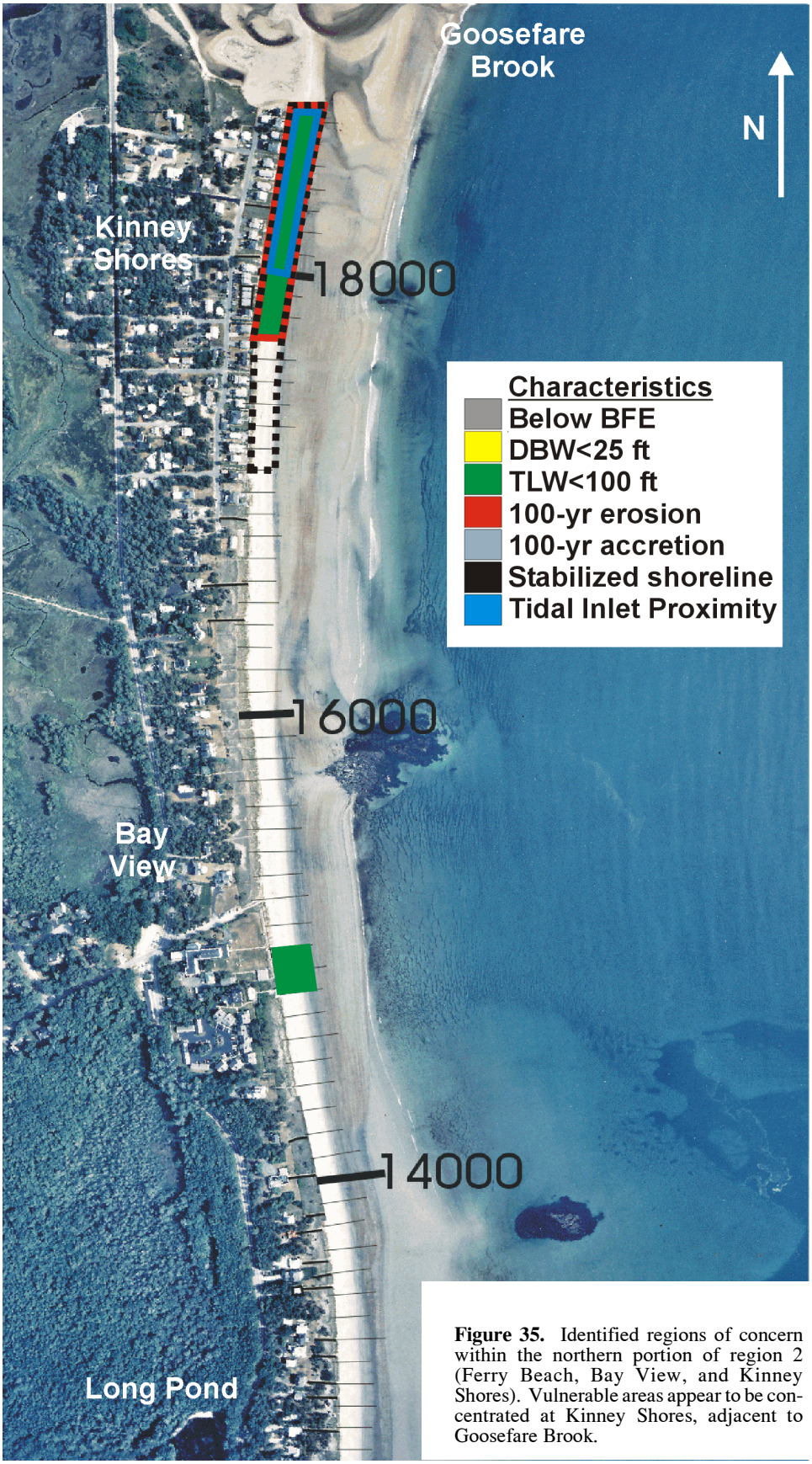

Figure 35. Identified regions of concern within the northern portion of region 2 (Ferry Beach, Bay View, and Kinney Shores). Vulnerable areas appear to be concentrated at Kinney Shores, adjacent to Goosefare Brook.

Figure 36. Identified regions of concern within the southern portion of region 3 (Ocean Park, Old Orchard Beach). The area of 100-yr accretion between Ocean Park and Old Orchard Beach is an artificial signal from the dune construction project associated with sewer line emplacement.

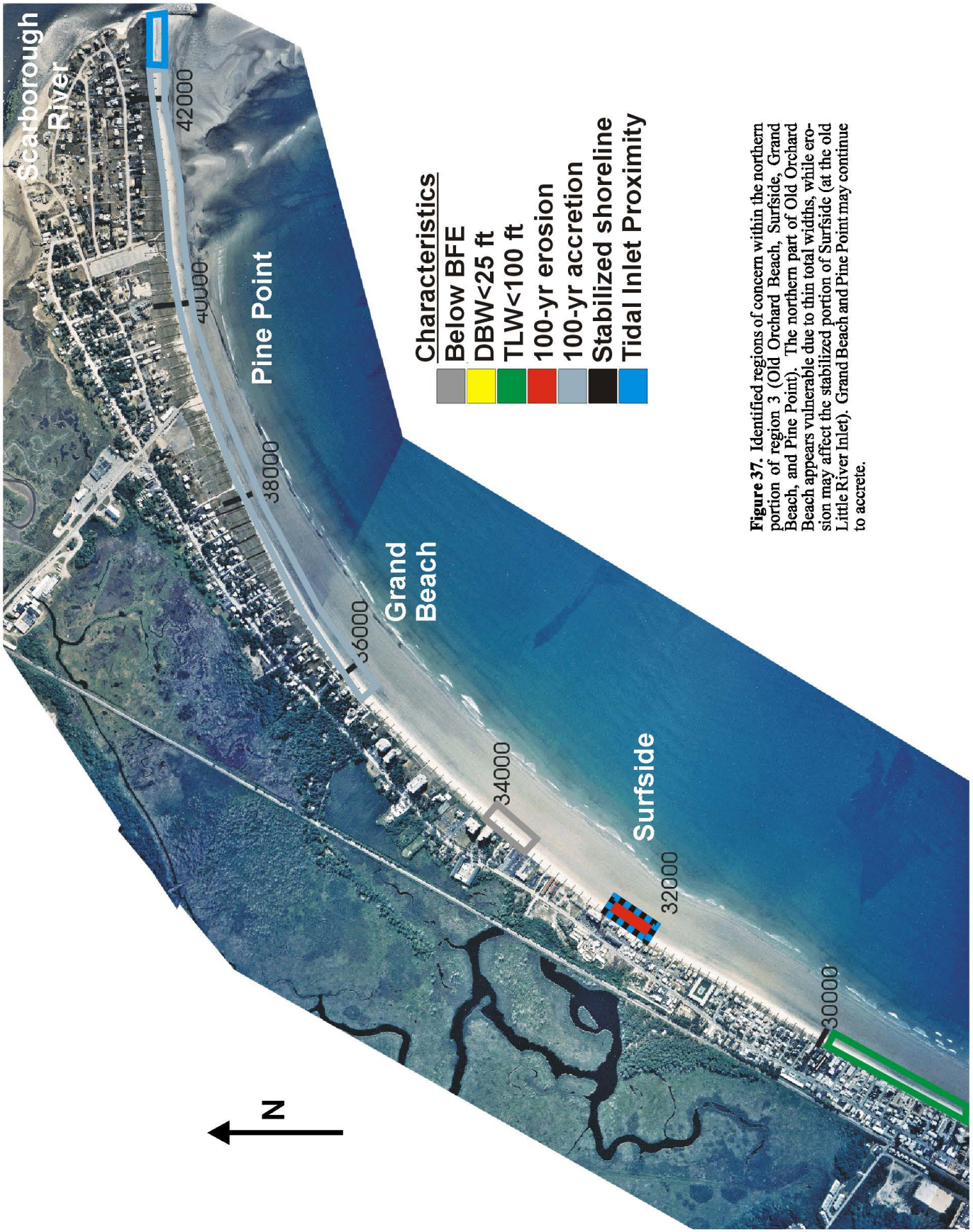

Figure 37. Identified regions of concern within the northern portion of region 3 (Old Orchard Beach, Surfside, Grand Beach, and Pine Point). The northern part of Old Orchard Beach appears vulnerable due to thin total widths, while erosion may affect the stabilized portion of Surfside (at the old Little River Inlet). Grand Beach and Pine Point may continue to accrete.

Figure 38. Identified regions of concern within region 4 (Western Beach). Although data suggests the area has undergone historic accretion (1962-1995, and therefore projected future accretion), trends suggest that areas of possible future erosion problems are located near Tee #2 and at the practice green.

Parcher Avenue, in the vicinity of the former Little River Inlet (32,000-32,500 ft), see Figures 36 and 37.

- ***Region 4,*** *Western Beach:* adjacent to the Scarborough River jetty, near Tee #2 (44,700 ft), and near the practice green (46,300 ft), although no structures appear to be impacted, see Figure 38.

Plan for 100-yr Accretion

Communities with projected 100-year shorelines showing areas of substantial potential accretion must plan accordingly. As shorelines build seaward, community planners should be prepared to address ownership, access, zoning, and development issues that may result. Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* from near the roundabout of Hills Beach Road northwest to near Surf Avenue (800-2,000 ft); and from near the thinnest portion of the island northwest to the southern Saco River jetty (4,200-6,000 ft), see Figure 33.
- ***Region 2:*** no areas appear to apply.
- ***Region 3,*** *Ocean Park to Old Orchard Beach:* from the vicinity of Tunis Avenue northeast to Fernald Avenue (21,900-25,500 ft); *Grand Beach to Pine Point:* from Little River Road northeast into Pine Point (35,700-42,300 ft), see Figures 36 and 37.
- ***Region 4,*** *Western Beach:* the majority of the beach, aside from areas noted with potential erosion, see Figure 38.

Consider Shoreline Structure Maintenance or Removal

Communities with existing seawalls should evaluate the effectiveness of the structures in protecting development, the future rehabilitation/renovation expenses associated with structure maintenance, and investigate additional shoreline protection options. Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* central portion of the beach, from 2,900-4,200 ft, see Figure 33.
- ***Region 2,*** *Camp Ellis Beach:* from Bay Avenue north to Fairhaven Avenue (7,700-9,700 ft); *Kinney Shores:* from Outlook Avenue to Goosefare Brook (17,100-18,700 ft), see Figures 34 and 35.
- ***Region 3,*** *Old Orchard Beach:* from Fernald Avenue northeast to near Linwood Street (25,500-27,900 ft), see Figure 36.
- ***Region 4:*** no areas apply.

Proximity to Tidal Inlets

Communities with areas situated within or directly adjacent to the limits of a tidal inlet should pay close attention to historical and existing erosion trends, as such areas are generally erosive 'hotspots,' are generally lower in elevation, and are subsequently prone to periodic overwash. Sections of shoreline that should consider this recommendation are:

- ***Region 1,*** *Hills Beach:* in the vicinity of the thinnest portion of the island, from 3,500-4,200 ft (abandoned oxbows and meandering tidal channel in back marsh), see Figure 33.
- ***Region 2,*** *Camp Ellis Beach:* adjacent to the north jetty, from Bay Avenue to Main Avenue, 8,000-8,400 ft (marsh landward of Camp Ellis pier); *Kinney Shores:* from near Pinewood Avenue north to Goosefare Brook, 17,700-18,700 ft (abandoned, meandering channels of Goosefare Brook), see Figures 34 and 35.
- ***Region 3,*** *Surfside:* from near Grandview Avenue northeast to near Parcher Avenue, 32,000-32,500 ft (in the vicinity of the abandoned channel(s) of Little River Inlet); *Pine Point:* adjacent to the Scarborough River, see Figure 37.
- ***Region 4,*** *Western Beach:* adjacent to Scarborough River jetty southeast towards Prouts Neck, associated with abandoned channel (43,700-44,500 ft), see Figure 38.

Section 111 Plan Alternatives: Coastal Engineering and Mitigation at Camp Ellis

Based on the analysis in this report, erosion problems along the Saco Bay shoreline appear to be localized to Camp Ellis Beach and portions of Ferry Beach, and also appear to be a direct result of the negative influence of the Saco River jetties. Upon jetty construction, the downdrift beach first accreted due to landward ebb-delta shoal migration; however, once this sediment moved landward, it was slowly eroded and reworked northward. With the jetties in place, no new sediment was available to adjoining beaches, and they have faced continual erosion since approximately 1900.

A 1992 Section 111 study by the Corps presented several alternatives to deal with the erosion problems along the southernmost 2,500-foot stretch of Camp Ellis and Ferry Beaches. Original alternatives included 6 Plans: A) beach nourishment; B) revetment/seawall; C) roughening jetty face and beach nourishment; D) larger spur jetty; E) larger spur jetty with beach nourishment; and F) acquisition and demolition of structures within a projected 50-year erosion zone. Subsequent cost-to-benefit analyses by the Corps determined that none of the options were economically justified at the time (USACE, 1992).

In 1995, the Corps' Waterways Experiment Station (WES) laboratory completed a model study of the Camp Ellis Beach erosion problems. WES analyzed existing conditions in addition to some of the alternatives (and several variations) presented by the 1992 study. Conclusions indicated that *any beach-fill plan would only be a temporary solution that would require periodic nourishment,* and that an approximate 3,000 linear foot spur jetty was most effective in significantly reducing wave heights and beach erosion along Camp Ellis Beach.

In 2001, the Corps updated its 1992 Section 111 study at the request of the City of Saco and Congressman Thomas Allen.

This study reviewed the original plans proposed in the 1992 study and found that Plan C, which included roughening approximately 1,000 linear ft of the shoreward most portion of the jetty and placement of approximately 275,000 cubic yards of beach-fill, was economically justifiable (USACE, 2001).

To date, the Saco Bay Implementation Team has been meeting to determine the most physically effective alternatives to alleviate the high erosion rates seen at Camp Ellis, while attempting to minimize impacts to the rest of the Saco Bay littoral system. At the time of the publication of this document, the Corps is in the process of collecting real-time wave and current data for the purposes of groundtruthing a nearshore numerical wave model. This model will be utilized to analyze several different structural alterations to the northern federal jetty, including several spur jetty configurations, roughening the innermost 1,000 feet of the existing jetty, removing the seaward end of the jetty, and several T-groin configurations along the shoreline. Results of the numerical model may indicate the most effective alternative for reducing storm wave heights, and subsequent erosion, along Camp Ellis beaches.

A successful overall long-term mitigation solution must not only take actions to substantially *decrease* existing erosion rates along Camp Ellis Beach (which range from 1-3 ft/year based on the data utilized in this report), but must also take into account the regular addition of sediment to the currently starved system. However, without a successful decrease in the existing erosion rate, any addition of beach nourishment material will only be a short-term, temporary solution. In order to help deal with this issue, it is recommended that the community of Camp Ellis address long-term coastal hazard issues through the development of a hazard mitigation plan, which would improve the community's resistance to flooding and coastal damage from storm events.

CONCLUSIONS

This study was initiated to research some of the geomorphic trends along the Saco Bay shoreline in hopes of gaining more understanding of the impacts of the Saco River jetties on the Saco Bay littoral cell. Due to a lack of adequate historical beach profile data, aerial photographs were used in conjunction with recent LIDAR data to estimate shoreline changes (and volumetric changes) along Saco Bay. Results generally indicate that:

- The Saco Bay littoral cell as a whole is relatively stable to accretive; volume changes for the subaerial-intertidal beach from 1962-1995 indicate that the Saco Bay shoreline, from Hills Beach to Pine Point, has gained approximately 1.53 x 10^6 yd^3 of sediment, not including material discharged as part of harbor/channel dredging or beach nourishment.

- A 5,000-foot erosive shoreline exists immediately adjacent to the northern Saco River jetty, directly influencing Camp Ellis Beach and Ferry Beach. The highest erosion is concentrated within approximately 2,500 ft of the jetty; this stretch accounts for approximately 2/3 of the 55,390 yd^3 of sediment lost within the 5,000-foot length of erosive shoreline.

- Using beach profile characteristics and calculated net erosion and accretion, a 100-year future shoreline was projected along Saco Bay; future shoreline positions were used to identify areas of erosion and accretion where future impacts to structures could be expected;

- Morphologic trends were used to identify stretches of shoreline that may require future planning actions, including beach and dune restoration.

RECOMMENDATIONS FOR ADDITIONAL STUDY

Considering the length of Corps involvement and numerous studies completed on the Camp Ellis region, there is little data regarding beach or hydrodynamic conditions or processes along Saco Bay. Such long-term monitoring data is very useful in beach nourishment project design and modeling of hydrodynamic and morphologic conditions. In development of current project alternatives, the Corps has recently conducted bathymetric, topographic, and geophysical surveys to document pre-project conditions. In order to insure project success and prepare to address future erosion problems, should they arise, a detailed post-project monitoring program should be implemented. The monitoring should focus on studying the fate of sediment placed as part of the beach nourishment project (should it be undertaken), and the impacts of jetty alterations/additions on the existing hydrodynamic processes. Since Saco Bay is considered an enclosed littoral cell (Kelley and others, 1995), post-nourishment monitoring should encompass the entire Bay. The Bay is approximately 43,000 ft in length (along the shoreline) from Hills Beach north to Pine Point, with approximately 3,500 ft comprised of the Saco River and Goosefare Brook waterbodies (e.g., inlet widths). The proposed Section 111 Mitigation Project site extends approximately 2,500 linear ft north of the northern jetty of the Saco River. It is suggested that the monitoring program include:

- ***Beach Profiles***
  - *Spatial Coverage:* Due to the relatively small size of the project, profiles should be established at a high density (e.g., every 100 ft) along project length than the remaining Saco Bay shoreline. The remaining shoreline should be sampled at random 2,000-3,000 foot spacing, allowing for the total number of profiles to range from 19-25. Siting of profile benchmarks should take into consideration ease of access, and documentation of entire active profile is imperative. Profiles should extend from benchmarks of known elevation, generally from the

back-dune seaward to 'depth of closure' or 3,000 ft seaward of the MHWL, whichever is farther (Dean and Campbell, 1999), with survey points at an average spacing of 10-15 ft horizontally and 0.1-0.2 ft vertically (Kriebel, 1995).

- *Temporal Coverage:* Profiles should be completed at a minimum annually at one-year, two-year, and three-year post construction intervals, and biennially thereafter (Dean and Campbell, 1999). In order to document shorter-term profile variations and seasonal fluctuations, if possible, profile monitoring should be completed 6 times a year for the initial two years post-construction, then annually thereafter. Profile collection should occur as close to low-tide as possible. Monitoring should also occur post-storm (e.g., 20 year storm minimum) to document beach response, when possible (USACE, 1995b).

- ***Mean High Water Line (MHWL) Variation:*** The alongshore variation of the MHWL should be surveyed in order to document fluctuations in dry-beach width at the project site and within study boundaries. Surveys should correspond with times of beach profile collection.

- ***Aerial Photography:*** Aerial photograph flights documenting the immediate project area and study boundaries should be flown prior to, and immediately after completion of construction. Biennial flights thereafter should be sufficient to document overall geomorphologic changes.

- ***Sediment Sampling:*** Samples should be collected prior to and immediately post-construction. Collection should then correspond with timing of cross-shore surveys. Sampling should occur at toe-of-dune, vegetation or seawall line, mid-berm location, and at mean high water contour (Dean and Campbell, 1999). Samples should be analyzed for grain size, color, texture, and percent organic material matter.

- ***Current and Wave Sampling:*** It is suggested that modern, efficient and effective monitoring equipment be employed, such as a personal watercraft outfitted for hydrodynamic sampling (e.g., Dugan and others, 1999). An Acoustic Doppler Current Profiler (ADCP) can be mounted on the personal watercraft to provide current measurements during nearshore surveys. Wave gauges and ADCPs could be installed at seaward end of northern jetty and adjacent to the spur jetty for certain monitoring periods to monitor effectiveness of whatever structural solution, if any, is used, in lessening northerly-directed alongshore currents and wave heights. If an offshore borrow site is chosen as the source of sediment for the nourishment, additional monitoring should include the borrow site. If cost inhibits the installation of wave gauges and ADCPs, it may be possible to implement a Littoral Environment Observation (LEO) program with members of the Camp Ellis community (USACE, 1995b).

CONTINUED RESEARCH

The Maine Geological Survey (MGS), in conjunction with scientists at the University of Maine (Orono), recently received a Maine Sea Grant award for a project titled *Monitoring Coastal Dynamics at the Saco River Mouth Near Jetty Modification and Beach Nourishment Projects*. The project will span 2 full years and will test the hypotheses that proposed engineering alterations to the north jetty at the Saco River mouth will significantly reduce incident wave energy at Camp Ellis and reduce the rate of alongshore transport (erosion) away from that area, in addition to confirming that the Saco River is a major source of sand to the beach and nearshore system, and that alongshore drift carries sand to the north along the Saco Bay littoral system, through observation of the redistribution of the beach-nourishment material.

MGS also received an award from the Maine Marine Research Fund for an additional project, *Three Dimensional Beach and Nearshore Bathymetric Surveys and Sand Budgets*. Funds will be used to construct a Nearshore Survey System (NSS) based on a personal watercraft platform outfitted with a high precision Real-Time Kinematic (RTK) Global Positioning System (GPS) and high accuracy fathometer. The extremely mobile system will enable detailed three-dimensional surveys within the highly dynamic surf zone, which will allow much more precise quantification of nearshore sediment budgets.

These projects will provide data vital to understanding sediment migration pathways within Saco Bay, and will develop a hydrodynamic framework for the processes governing sediment movement within the bay.

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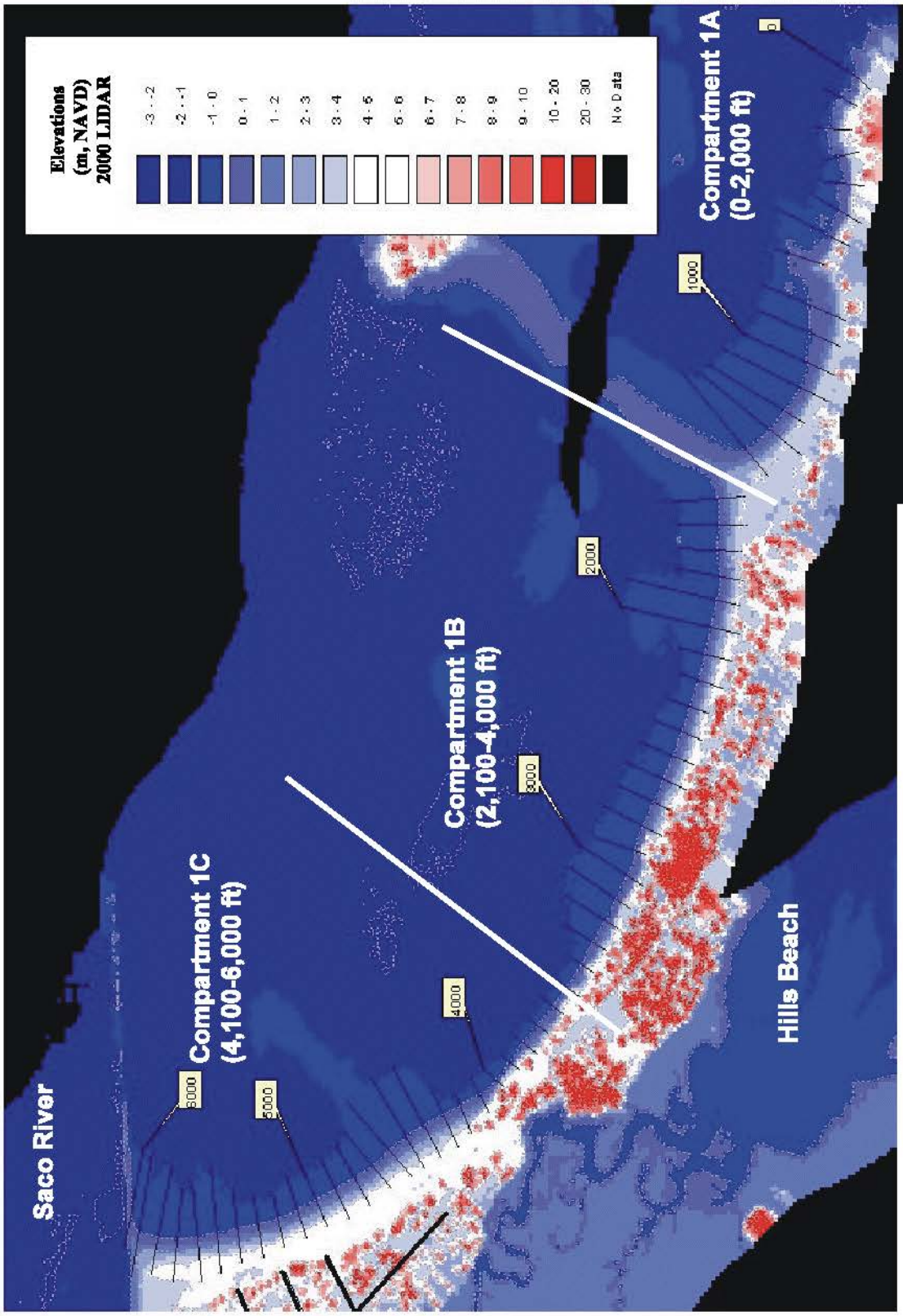
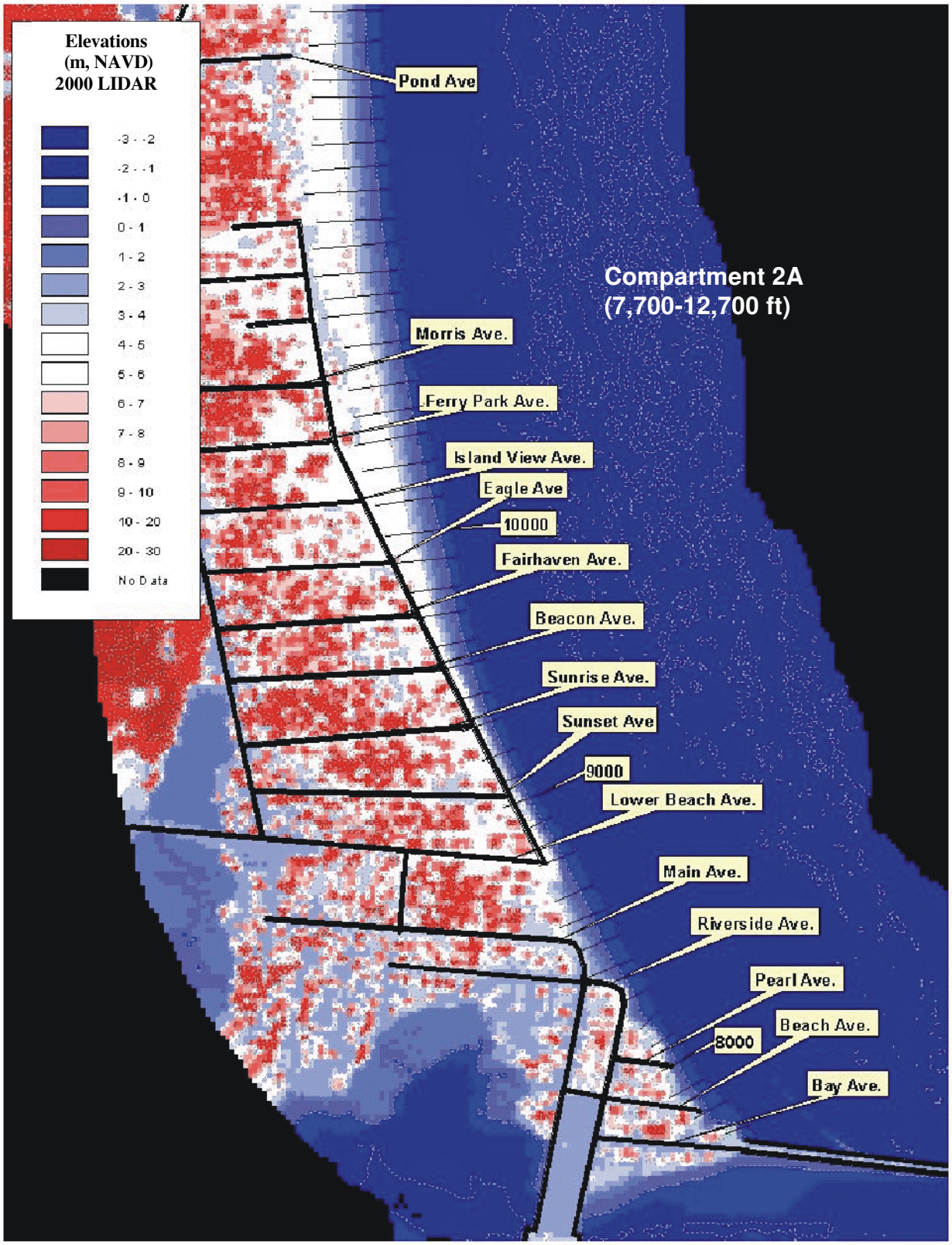
APPENDIX A

LIDAR IMAGES

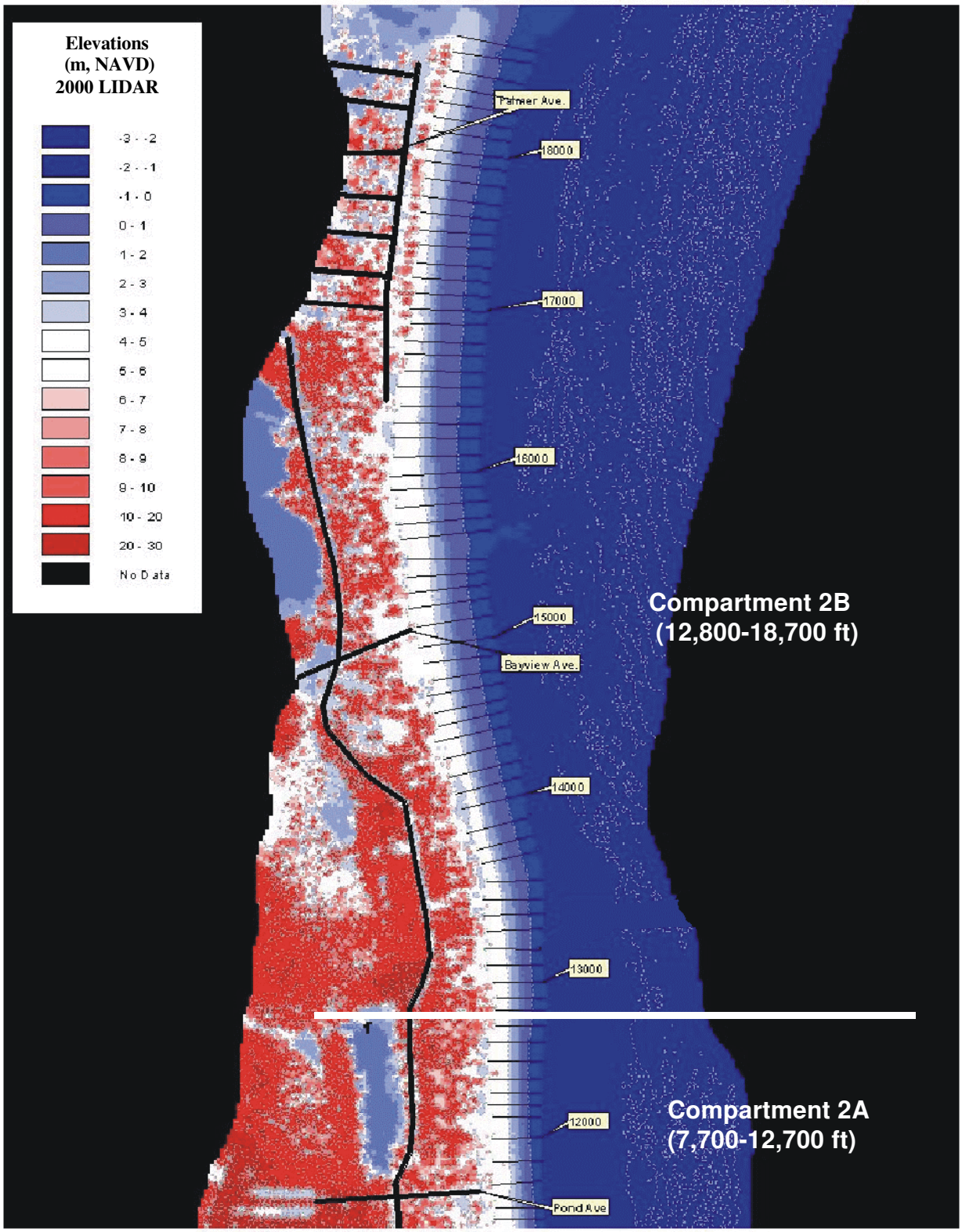
(not to scale)



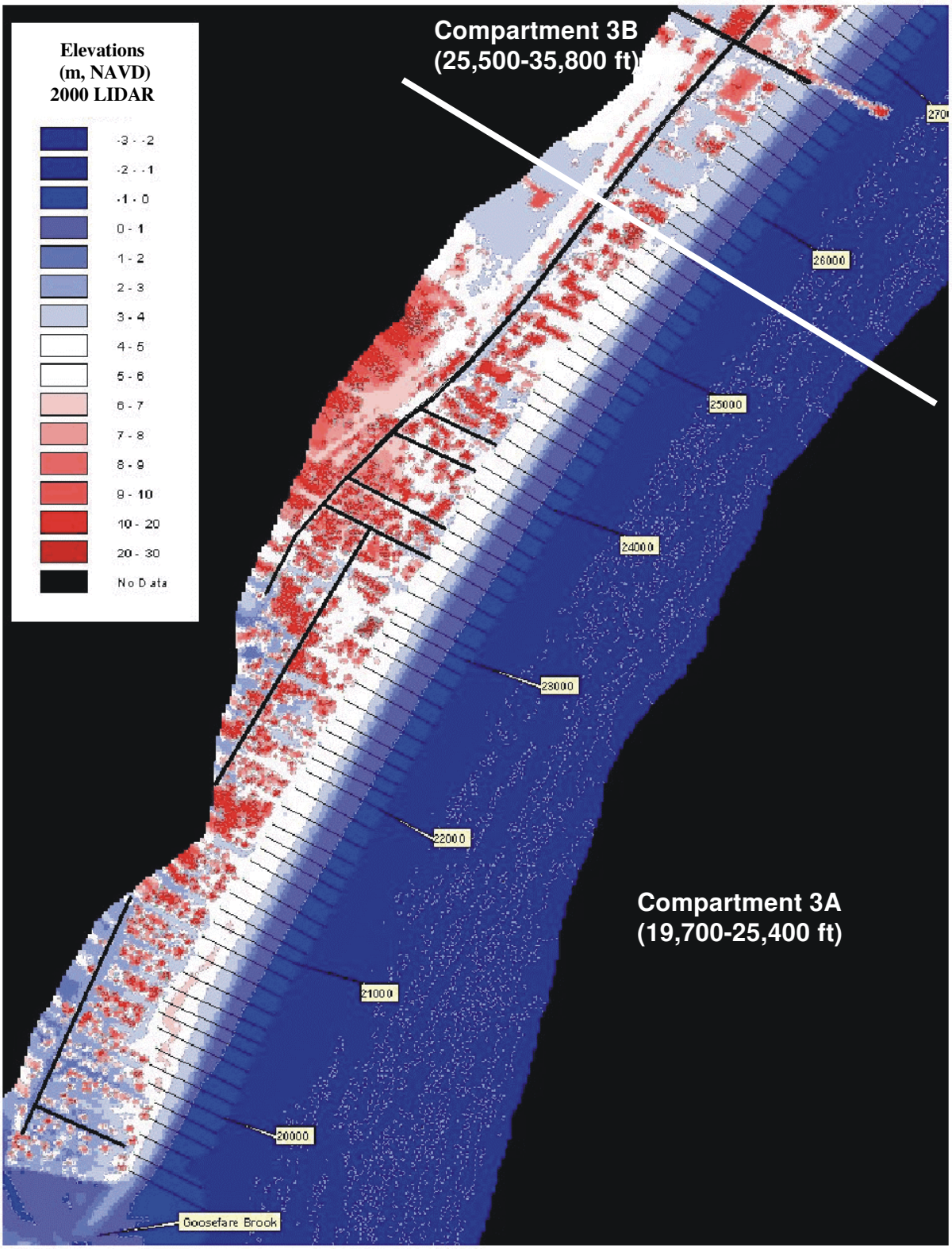
Region 1. LIDAR image illustrating topographic variations along region 1, Hills Beach in Biddeford. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



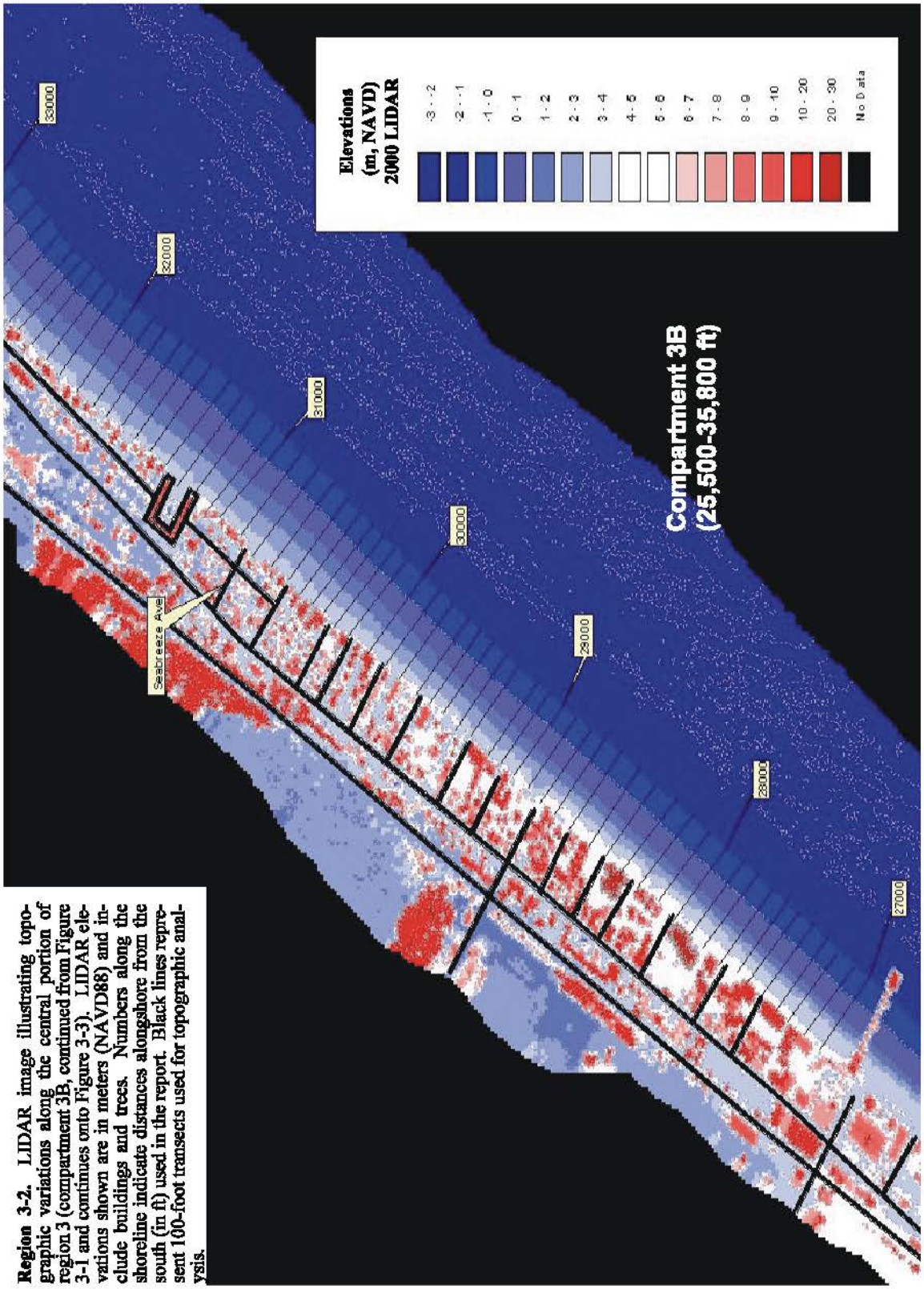
Region 2A. LIDAR image illustrating topographic variations along Camp Ellis and Ferry Beach in compartment 2A. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



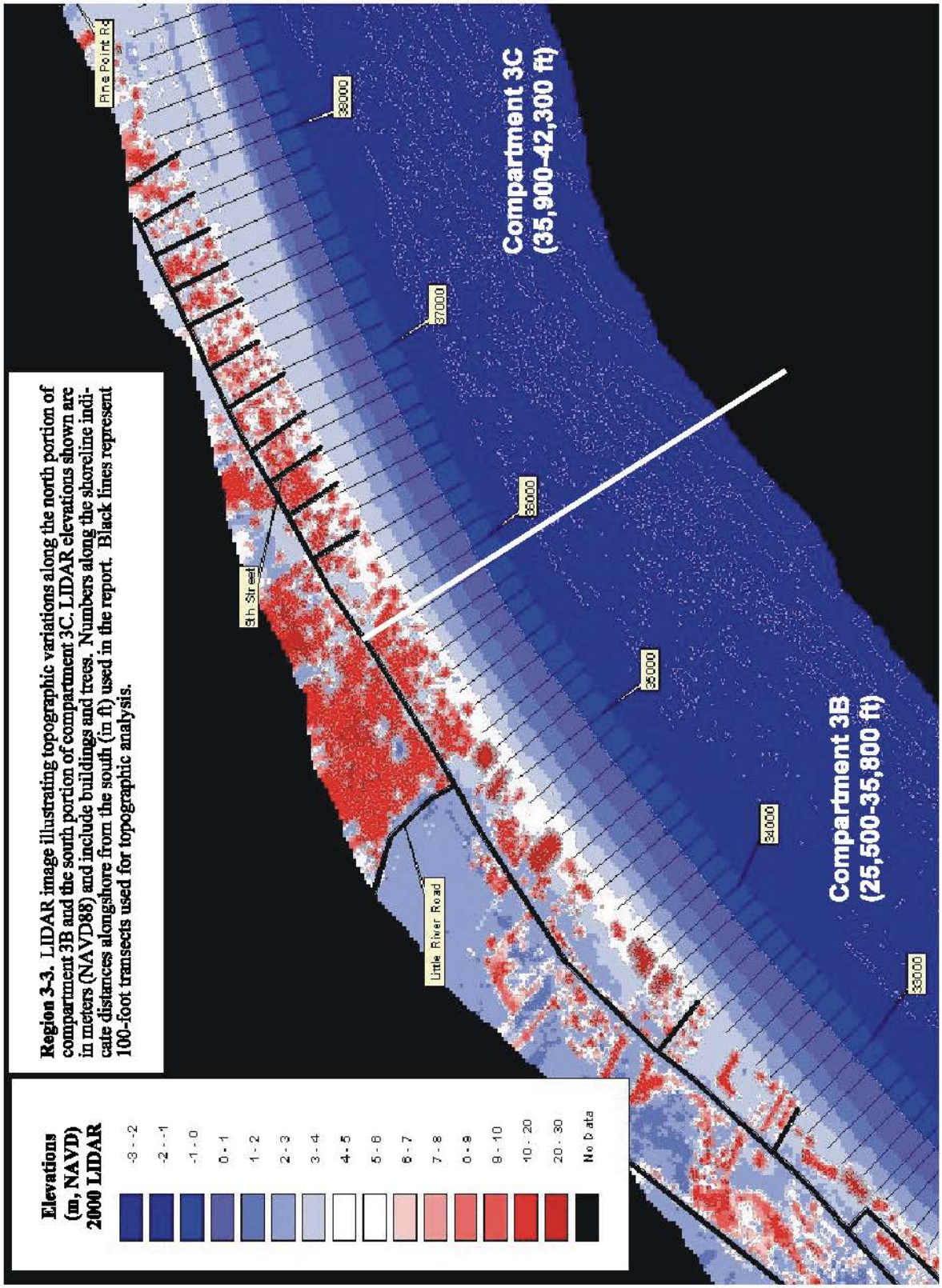
Region 2B. LIDAR image illustrating topographic variations along the northern portion of compartment 2A, and compartment 2B. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



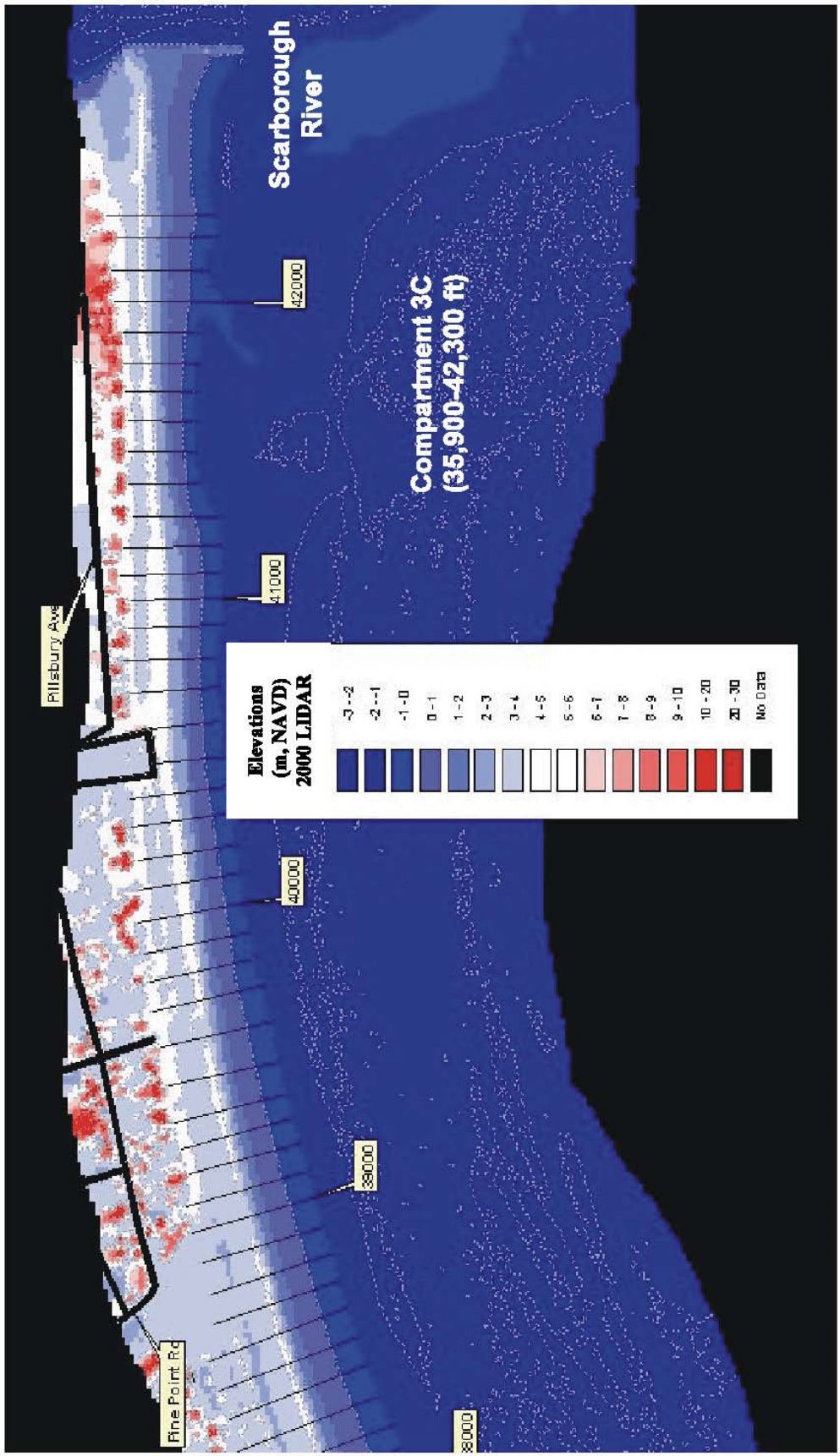
Region 3-1. LIDAR image illustrating topographic variations along region 3, compartment 3A and the southern portion of compartment 3B. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



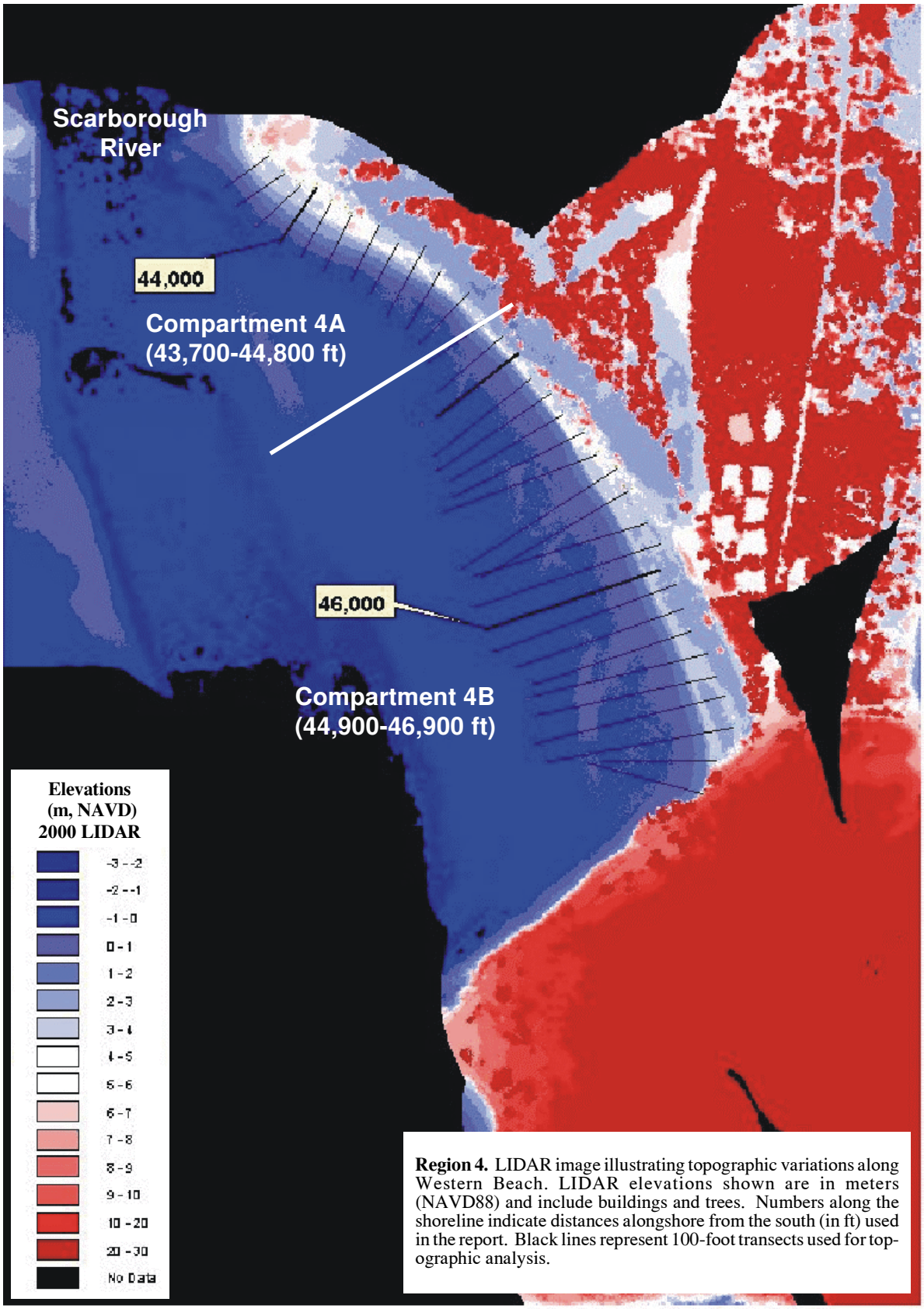
Region 3-2. LIDAR image illustrating topographic variations along the central portion of region 3 (compartment 3B, continued from Figure 3-1 and continues onto Figure 3-3). LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



Region 3-3. LIDAR image illustrating topographic variations along the north portion of compartment 3B and the south portion of compartment 3C. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



Region 3-4. LIDAR image illustrating topographic variations along the northernmost portion of Region 3 (compartment 3C). LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.



Region 4. LIDAR image illustrating topographic variations along Western Beach. LIDAR elevations shown are in meters (NAVD88) and include buildings and trees. Numbers along the shoreline indicate distances alongshore from the south (in ft) used in the report. Black lines represent 100-foot transects used for topographic analysis.