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ANTHROPOGENIC INFLUENCES AND METEOROLOGICAL EFFECTS: HOW THEY ARE CHANGING THE SAND BEACHES IN SOUTHERN MAINE

By

Heather W. Heinze

B.A. Albion College, 1999

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Geological Sciences)

The Graduate School

The University of Maine

December, 2001

Advisory Committee:

Joseph T. Kelley, Professor of Geological Sciences, Marine Sciences, and Quaternary Studies, Advisor

Daniel F. Belknap, Professor of Geological Sciences, Marine Sciences, and Quaternary Studies

Stephen M. Dickson, State Marine Geologist, Maine Geological Survey, Augusta, Maine

ANTHROPOGENIC INFLUENCES AND METEOROLOGICAL EFFECTS: HOW THEY ARE CHANGING THE SAND BEACHES IN SOUTHERN MAINE

By Heather W. Heinze

Thesis Advisor: Dr. Joseph T. Kelley

An Abstract of the Thesis Presented
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Although sand beaches in southern Maine comprise only a small segment of the coastline, they are economically important to the state. From September 1999-March 2001, volunteers made monthly topographic profiles along nine beaches in southern Maine to monitor changes. The volunteers used the Emery Method of beach profiling to take simultaneous measurements at spring low tide. The beaches are significantly different with respect to physiography, incident wave energy and direction, available sediment supply and extent of development.

An average of the profiles for each category demonstrates that the undeveloped beaches experienced regular seasonal fluctuations and a consistent berm elevation from one fall to the next. The moderately and developed beaches also showed seasonal fluctuations, but the berm during the fall 2000 was close to 0.5 m higher than the berm in fall 1999, a response that was not observed on the undeveloped beaches.

Weather, particularly storms, are one of the most important controls on the cycle of erosion and accretion. Current meters placed in shoreface locations of Saco Bay and Wells Embayment, Maine, recorded bottom currents during the winter months of 2000

and 2001. The current meters documented three unique types of storms: frontal passages, southwest storms, and northeast storms. In general, frontal passages and southwest storms were responsible for bringing sediment towards the shore, while northeast storms resulted in a net movement of sediment away from the beach.

A northeast storm on March 5-6, 2001, resulted in currents in excess of one m/sec and wave heights that reached six meters. The storm persisted over 10 high tides and caused coastal flooding and damage to property. Topographic profiles made before and after the storm demonstrate that developed beaches experienced a loss of sediment during the storm, while sediment was redistributed along the profile on moderately developed and undeveloped beaches. Two months after the storm, the profiles along the developed beaches had not reached their pre-storm elevation. In comparison, the moderately developed and undeveloped beaches reached and exceeded their pre-storm elevation and began to show berm buildup characteristic of the summer months.

The amount of sediment available to the system was another factor that played a role in the changes observed along the profiles. The expected high sand volumes in the summer and low volumes in the winter were generally not observed along any of the barriers. Eight out of the nine beaches showed a net gain in the active volume of sediment during the sampling interval.

Results from the past year and a half suggest that profiling efforts need to continue into the future to minimize the effects of seasonal and other short-term changes and to determine whether the beaches are in a stable state. It is probable that the barriers are currently in equilibrium with human-induced alterations and a significant storm event is necessary to cause extreme erosion and movement of the shoreline.

ACKNOWLEDGMENTS

Funding for this research project came from the Maine Sea Grant College Program, sponsored by the U.S. Department of Commerce-National Oceanic and Atmospheric Administration. They provided resources for all field work and travel money for presentation of results. Partial funding, in the form of a Research Assistantship, was also provided by Maine Sea Grant.

I express gratitude to my advisory committee members from the Department of Geological Sciences, J.T. Kelley and D.F. Belknap for their guidance, discussions, patience and understanding. I also thank my third committee member, S.M. Dickson, from the Maine Geological Survey, for his encouragement and support in all aspects of my project, particularly the current meter work. I express sincere appreciation to my fellow students Rebecca Nestor, Allen Gontz and John Nelson for their assistance in the field, as well as to everyone else who has assisted along the way.

Lastly, although most importantly, I would like to thank my husband, Randy for his love and understanding throughout this project. He took the brunt of my frustrations for the past two years and never let me give up. The support from my parents has been tremendous and encouraging, as well.

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Chapter 1

INTRODUCTION

PURPOSE

The sand beaches of southern Maine are dynamic features that respond to a variety of forcing mechanisms. As these barrier systems naturally migrate landward in response to sea-level rise, homes and businesses located along the waterfront become more susceptible to flooding and other damage caused by major storms. The implications of these hazards increase as a greater number of people move to the coast. Over 43% of Maine's population currently lives in coastal areas and this number is expected to rise in the next several decades (Maine State Planning Office, 2001).

In addition to supporting private and public property, the beaches of southern Maine are major tourist attractions for the state. Over 80% of tourist money is spent along the coast, although not all in southern Maine (Maine State Planning Office, 2001). The beaches also provide habitat for a diversity of wildlife, particularly shorebirds. For these economic and environmental reasons, it is important to study and comprehend the changes that are occurring to the beach systems.

It is also necessary to educate the public on beach behavior. Few people understand why some southern Maine beaches are gaining sediment (i.e., Pine Point), while others are losing it (i.e., Camp Ellis) (Kelley *et al.*, 1995a). More research can justify why the current laws in Maine do not allow new engineering structures to be built to protect property and why buildings that are destroyed by a storm must be removed (MNRPA, 1993). Conversely, further study may provide an argument against these current laws. We need to achieve a balance between human use of the sand beaches and protection of one of Maine's natural resources.

In an attempt to lay the foundation for studying the southern Maine beaches, the Maine Sea Grant Program funded a two-year project that involved collaboration between coastal citizens and scientists/government regulators. Trained volunteers made monthly topographic profiles across nine barrier systems in Saco Bay and Wells Embayment, Maine (Figure 1.1) to monitor changes. Some goals of the Sea Grant project were met through two State-of-Maine's beaches meetings (Portland Press Herald, 2000) and a website (University of Maine Geological Sciences, 2000), but the task of evaluating the beach profile data remains.

The purpose of this study is to analyze that profile data to determine short and longer-term fluctuations (within the two-year data collection) along each beach and to draw some preliminary conclusions regarding the mechanisms responsible for the changes. It is unknown whether the beaches in southern Maine demonstrate the classic response of beach behavior with a summer berm buildup and a winter concave-shape profile (Nelson and Fink, 1980). In addition, the sweep zone, or volume of active sediment that is mobile over the course of a year, is unknown for these beaches. Nelson (1979) concluded that the beaches in southern Maine are slowly retreating landward as a result of sea-level rise and record storms, but human influences have stabilized many of these beaches. Aside from Nelson's work, no one has studied the effects of seawalls on southern Maine beaches.

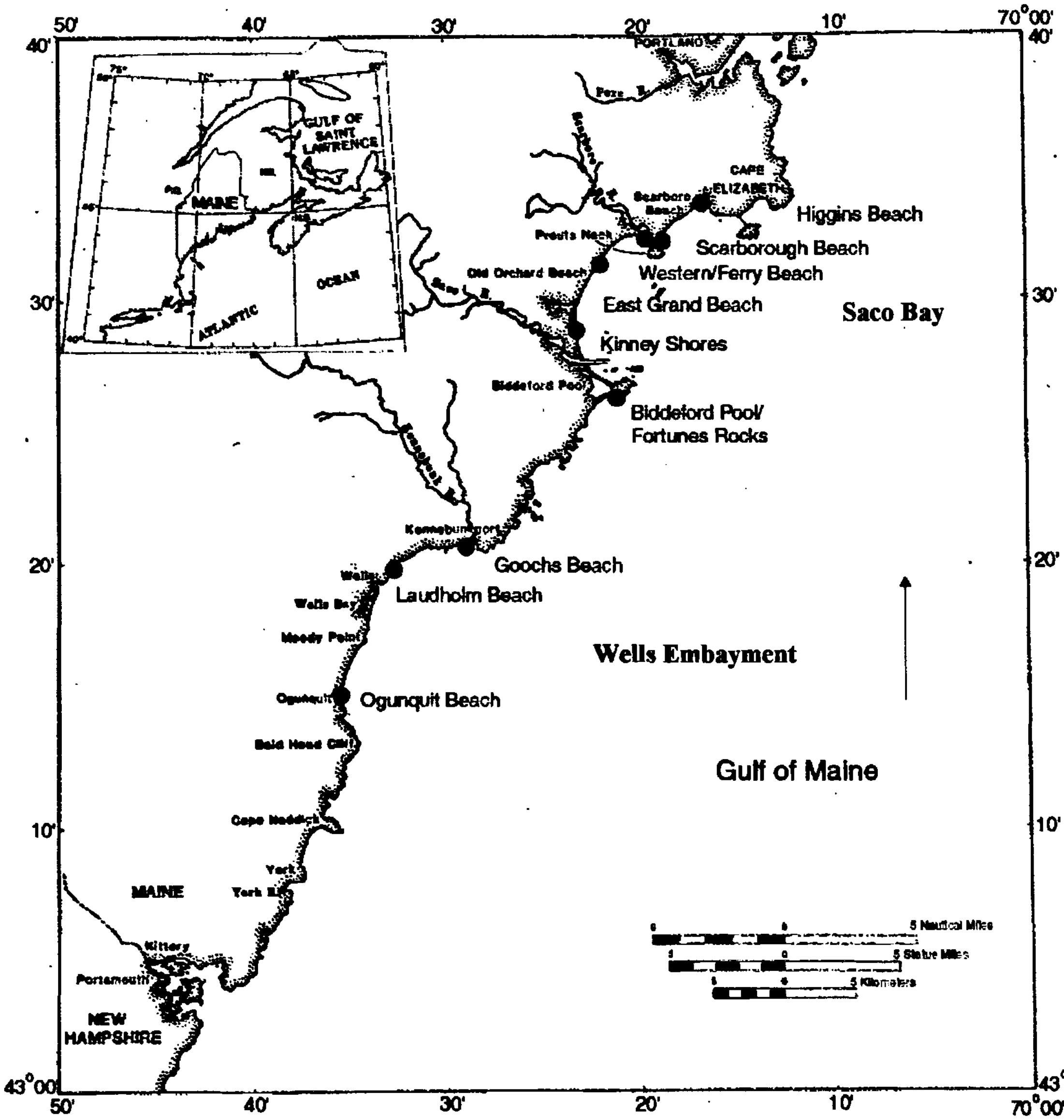


Figure 1.1 Location map of beaches in the study, southern Maine. Detailed aerial photos of individual beaches in Appendix A. (Map taken from Kelley *et al.*, 1989a).

The beaches involved in the study are significantly different with respect to physiography, incident wave and current energy and direction, available sediment supply, and extent of development. One or more of these characteristics may contribute to the changes that the beaches are experiencing. This study explores the beach characteristics independently and collectively.

The beaches are located within Wells Embayment and Saco Bay (Figure 1.1). These two embayments have a similar physiography, but different exposure level to waves, winds and storms. Two bedrock headlands frame Saco Bay, leaving it less exposed to waves and wind than the open orientation of Wells Embayment. Wave refraction is more significant in Saco Bay than Wells Embayment. In addition, the barriers in Saco Bay contain more shoreface sand per length of beach than the barriers in Wells Embayment, and the Saco River still contributes sediment to the Saco Bay barriers (Kelley *et al.*, 2001). The importance of the location of the beaches within these embayments has not previously been studied.

The beaches in Wells Embayment include Ogunquit Beach, Laudholm Beach and Goochs Beach (Figure 1.1). The beaches in Saco Bay include Kinney Shores, East Grand Beach, Western Beach, and Scarborough Beach (Figure 1.1). Because of their physiographic location and the antecedent geology, the study groups Biddeford Pool with the barriers in Wells Embayment, and Higgins Beach with the Saco Bay barriers. This study focuses on the beaches as two distinct systems (Wells Embayment and Saco Bay), as well as analyzing each barrier separately.

Storm events (Dolan and Davis, 1992) and the volume of available sediment (Schwab *et al.*, 2000) are two important factors that influence the behavior of beaches.

This study couples the topographic data of the beach profiles with offshore data collected by current meters to determine the response of beaches to changing oceanographic conditions, particularly storm events. The relationship between storm processes and sediment dynamics is poorly understood. There is a popular conception that New England winter storms usually result in widespread beach erosion and severe coastal property damage (Kelley *et al.*, 1989b). Although storms do impact the coast in this way, they can also be responsible for reworking sediment onto the beach and rebuilding it (Dickson, 1999). This project presents the first work in Maine that directly relates beach response to measured storm events by current meters.

A series of ground penetrating radar transects taken along the beaches helps define the volume of sediment contained in Maine's barrier systems. This study combines the calculated barrier volumes with offshore volumes to determine the amount of sediment available to each beach. Several of the beaches have a natural sediment supply and large amounts of sand, onshore and offshore, that can be reworked into the system, while others contain little sediment and are recycling the sand that already exists. The topographic profile changes may correlate directly to the available sediment.

In summary, the overall goal of this project is to determine how individual beaches respond to a variety of meteorological changes depending on their level of development and the volume of sand contained in, or available to, each beach. This study also places the profiles into the framework of a process-response model for barrier evolution. The database created will be useful to future studies of barrier systems and will provide a framework for studying the sand beaches in southern Maine. In addition, the results will help coastal managers when they make decisions regarding development and beach nourishment.

HYPOTHESES

Four primary hypotheses are proposed for the sand beaches in southern Maine based on previous work in the area, as well as along other barrier systems in New England:

1. The beaches will show seasonal fluctuations with accretion and a significant berm buildup during the summer, followed by erosion and a concave upward profile during the winter.

2. The net volume change of active sediment over the course of one year will be close to 0. The number of storms taking sediment from the beach will be balanced by the number of storms and long periods of fair-weather swells responsible for bringing sediment closer to shore.

3. Developed and undeveloped beaches will show responses similar to one another (if seawalls do not enhance changes that occur along the beach). Undeveloped beaches will experience the greatest change over a year.

4. Beaches within Saco Bay and Wells Embayment will not respond similarly to one another because of their level of exposure.

PREVIOUS WORK

Short-term Variations in Beach Morphology

Weather patterns are one of the primary controls on the short-term changes that are observed along beaches. The seasonal influence of winter-storm activity and summer-calm conditions are shown in the growth cycles of the berm on undeveloped beaches (Dubois, 1988; Larson and Kraus, 1994; Lacey and Peck, 1998), as described below. It is important to point out that the terms "winter" and "summer" do not imply that storm activity is strictly confined to the winter season.

Bottom sediment movement is greatest in the fall and winter, due to an increase in strong meteorological events (Gadd *et al.*, 1978). On the Atlantic Coast, Northeast storms produce downwelling that results in offshore-directed sediment transport, while upwelling created by southwest storms results in onshore-directed sediment transport (Gadd *et al.*, 1978; Niedoroda *et al.*, 1984; Wright *et al.*, 1994; Dickson, 1999). Upwelling occurs twice as often as downwelling on the Maine coast (Dickson, 1999).

In addition to storms, tidal currents and swells produce combined flow during times of weak winds, which is still sufficient for sediment transport in southwest Maine (Dickson, 1999). The strongest bottom currents capable of transporting sand occur during storms with a sustained wind speed >7 m/s. The threshold velocity for fine sand entrainment is 12 cm/sec on the southern coast of Maine (Dickson, 1999).

Seasonal profiles

During the summer, low-energy wave conditions produce a constructional profile, also referred to as a summer or berm profile (Nelson and Fink, 1980). Long-period swells return sand from offshore to the exposed beach, forming a steep berm and, thus, a reflective profile. The longer time between wave crests allows water to percolate into the sediment on the upwash so it cannot be remobilized and carried away during the backwash (Wright and Short, 1983). Wind may redistribute this sand into the dunes. Features that characterize constructional profiles include: 1) a broad berm platform, 2) berm crest, 3) steep berm slope, 4) ridge and runnel system on low-tide terrace, and 5) break-point bars (Wright and Short, 1983) (Figure 1.2a).

A storm profile, also referred to as a winter, erosional, or bar profile, is a response to steep, high-energy wave conditions (Nelson and Fink, 1980). As steep waves break, they increase the turbulence at the base of the wave, which enhances sand entrainment into flow. The waves then transfer berm sand offshore, creating a more dissipative profile (Wright and Short, 1983). In doing so, the berm's morphology is flattened. Features that characterize storm profiles include: 1) a frontal dune scarp, 2) concave upward beachface, 3) low-tide terrace with a coarse lag surface, 4) offshore bars, and 5) storm wave breaches of the frontal dune ridge (Wright and Short, 1983) (Figure 1.2b).

Beaches with seawalls

The seasonal cycles of beaches with seawalls are more ambiguous than those of undeveloped beaches. Structures are usually built where erosion is already a problem, and it is therefore unclear whether the structures enhance the erosion or whether the changes occur independently of the wall (Weggel, 1988). Some beaches with seawalls show seasonal variation similar to those without seawalls, as long as a significant

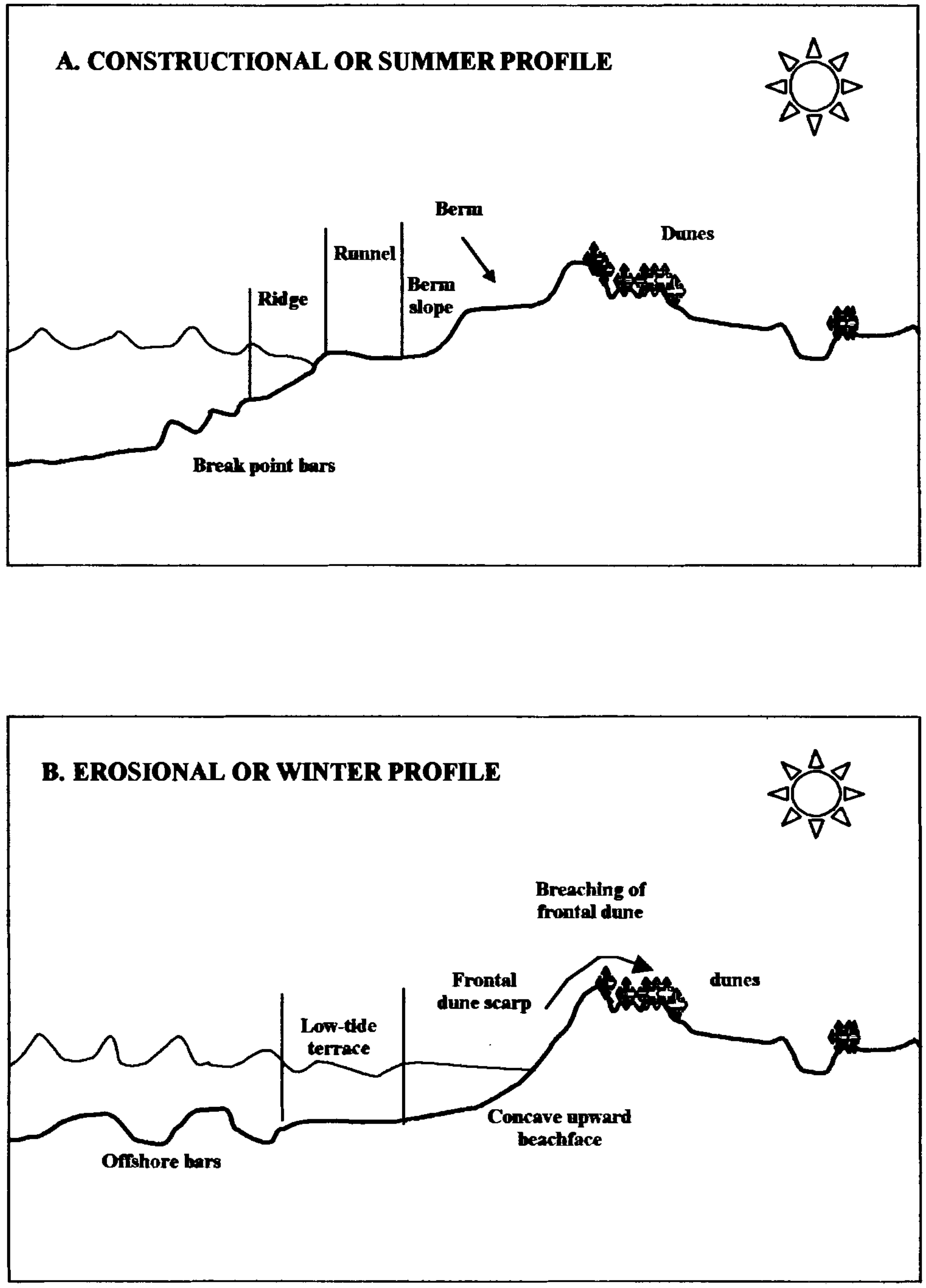


Figure 1.2. Schematic diagram showing seasonal beach profiles:
a. constructional or summer profile and b. erosional or winter profile (modified from Shephard, 1973 and Nelson and Fink, 1980). No vertical or horizontal scale implied.

sediment supply exists (Kraus, 1988). However, along many beaches, seawalls cause a narrowing of the beach due to scour (Pilkey and Wright, 1988).

A study along the California coast demonstrated that during the fall/winter, the berm retreated sooner in front of seawalls, particularly along walls located closer to the shoreline, resulting in a flatter profile (Griggs and Tait, 1988). The berm then began to rebuild in May/June through August, at a similar rate on both developed and undeveloped beaches. The accretionary phase was not influenced by the presence of the seawall and therefore considered independent of the structure (Griggs and Tait, 1988).

Seawalls have also been found to significantly alter sediment suspension and transport (Miles *et al.*, 2001). A study along the South Devon shoreline (United Kingdom) found that a beach with a seawall resulted in a mean sediment concentration up to three times larger and a stronger longshore current than observed on a nearby natural beach (Miles *et al.*, 2001). A combination of an increased sediment load and enhanced longshore currents led to longshore sediment transport rates an order of magnitude greater in front of the wall than on the natural beach (Miles *et al.*, 2001).

The response of a beach with seawalls to changing conditions is usually site-specific and dependent on a number of factors (Kraus and McDougal, 1996; Kraus, 1988). These factors include the location of the seawall relative to the active shoreface, the length of the seawall, the shape of the seawall, and the long-term behavior of the beach (Weggel, 1988).

Short-term profiling efforts in Maine documented the seasonal weather patterns on both undeveloped (Jones, 2000) and developed (Belknap, 1973) beaches. Erosion phases, primarily in the winter, were driven by northeast winds and the sediment was moved offshore, while accretion phases, primarily in summer, were driven by southeast winds. Both events required significant wind and wave energy to mobilize sediment. The profile responses from local weather patterns also varied along transect, which Jones (2000) attributed to localized longshore transport during erosion-dominant periods.

Active sand volume

A certain percentage of the total volume of sand within a beach system is mobile. This active volume of sediment is referred to as the sweep zone, and is usually greater in undeveloped, rather than developed beaches (Clarke and Eliot, 1988). In a stable system, the volume of sand may be high in the summer when sand accretes to form the berm, and low in the winter when the sand moves offshore to form bars (Dubois, 1988; Larson and Kraus, 1994; Lacey and Peck, 1998). The net volume change over one year, in an ideal, stable system, is close to zero (Figure 1.3) (Haines *et al.*, 1999). The sediment is simply redistributed in a cross-shore manner, although the migration process may be slow. There appears to be a strong correlation between the offshore region and the shore-zone with the offshore leading the response by 1.25 years (Haines *et al.*, 1999). A persistant increase in the volume often results from an increase in the available sediment over time (Haines *et al.*, 1999).

Long-term Variations in Beach Morphology

Using a series of aerial photographs dating back to 1940, Nelson (1979) first focused attention on the decadal shoreline changes of the large sand beaches in southern Maine. He studied behavior of 49 km of shoreline and concluded: 31 percent of total

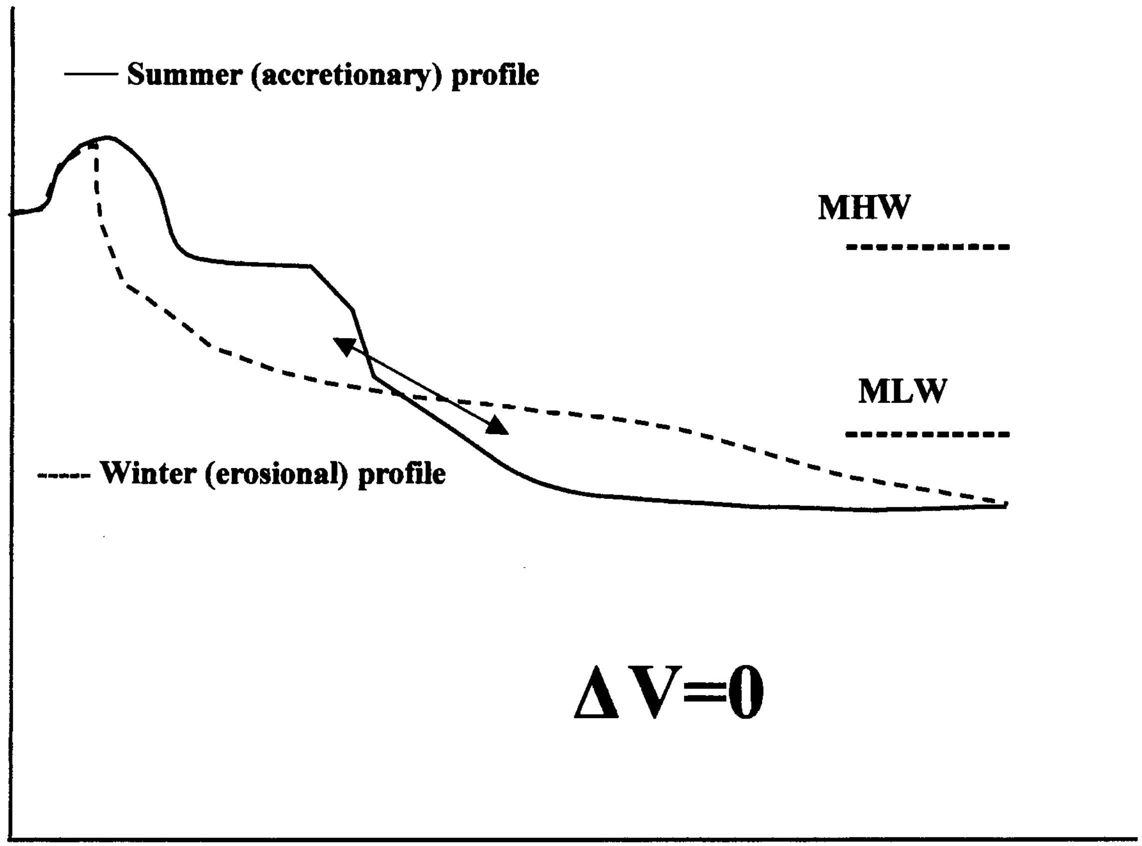


Figure 1.3. Schematic diagram depicting generalized seasonal topographic profiles.

beach length showed net retreat; 31 percent was stabilized by exposed seawalls; 10.5 percent accreted as a result of jetties and sand nourishment; 14.5 percent accreted naturally; and 12 percent showed no net change (Nelson, 1979).

If human influences are excluded, 62 to 72 percent of the shoreline shows a natural tendency to retreat. This was determined by summing the 31% of the beaches that retreated naturally with the 31% that were stabilized by seawalls. The stabilized beaches were showing natural retreat before the emplacement of the structure. If we assume that the 10.5% of shorelines that accreted due to jetties and sand nourishment would have otherwise retreated, this increases the value to 72%.

Of the total shoreline studied, five beaches, or 9.3%, were chosen as representatives of the long-term historical retreat rate of Maine's sandy coastal beaches. The beaches were chosen based on the following criteria: 1) long, straight beaches without influence from seawalls, jetties and beach nourishment 2) distance from naturally variable features such as spits and cuspate forelands, and 3) steady rather than discontinuous retreat histories. These beaches showed an average retreat rate of 33 cm/yr.

The major agents of shoreline retreat are sea-level rise and large storms. Nelson (1979) believed that storms account for the unexpectedly high historical retreat rate (33 cm/yr) observed on long straight and long concave-seaward beaches of his study. Winter storms in 1952-1953 were responsible for major retreat and overwash on southern Maine beaches. Record storms of 1978 caused retreat that exceeded the previous 38 years of recession on two southern Maine beaches (Nelson, 1979).

A 33-year database, the longest documented record of beach profiling, from the coast of Rhode Island shows a similar retreat rate of 0.5 m/yr from 1962-1995, and also depicts a decline in sediment volume following the 1978 storm (Lacey and Peck, 1998). The annual variability was attributed to cross-shore sediment transport associated with seasonal variations in storm frequency and intensity. On a short time scale (1.5-5 years), the profiling stations were out of phase due to longshore transport. But longer-period cycles (>9 years) showed similar patterns among the profiles. Lacey and Peck (1998) attributed the similar results to variation in longshore sediment transport, sea level, wind and wave climate.

In contrast to the two previous studies, four years of profiling at five different locations along Old Orchard Beach (Figure 1.1) revealed that there was little seaward growth or landward erosion of the barrier (Farrell, 1972). The profile stations did show variation by changing directly with respect to the wave regimes caused by offshore wave refraction.

Impact of large storms

Large storms have a significant impact on shoreline changes; they have the ability to rapidly redistribute large volumes of sediment, accelerate rates of erosion or accretion, and control short-term shoreline movement (Morton *et al.*, 1995). Studies along the Outer Banks of North Carolina demonstrated that regardless of the level of development, in general, a beach will erode vertically during a storm until a downward limit is reached, at which point the maximum change becomes horizontal (Fucella and Dolan, 1996). However, beaches with wide berms in Massachusetts exhibited less overall change than sand beaches backed by seawalls following a 1991 Halloween Eve storm, as measured by topographic profiles (FitzGerald *et al*, 1994). Wave height, wave steepness, and pre-storm configuration determine the extent of vertical erosion on the beach (Fucella and Dolan, 1996).

Erosion and structural damage are dependent upon a number of factors, including pre-storm beach and dune morphology, geological conditions, exposure to waves and wind, storm duration, fetch, wind speed and wave energy, and presence or absence of coastal structures (Dolan *et al.*, 1990; Zhang *et al.*, 2001). Although the height of storm waves determine the destructive potential of a storm, the storm tide determines the elevation that storm waves will damage beaches and dunes (Zhang *et al.*, 2001). The storm tide is the sum of the astronomical tide and storm surge (the observed water-level value minus the predicted water-level value). During high tides, storm waves can reach and attack higher up on the beach profile (Zhang *et al.*, 2001). This is especially critical when a storm coincides with spring high tides. Storm duration determines the amount of time available for storm waves to erode the beach.

<u>Northeast storms</u>

The most severe and greatest number of extratropical storms that affect the Gulf of Maine are usually associated with cyclonic (low-pressure) disturbances and originate in the middle-latitude westerly wind belt between the months of December and April (Dolan *et al.*, 1988). These Northeasters, as they are referred to in New England, have lower wind speeds and less pressure drops than hurricanes, the second type of low-pressure system to affect the Atlantic Coast, but they often have a greater impact on the coastline (Zhang *et al.*, 2001). Although Northeasters have smaller wind speeds, these storms occur more frequently and are much larger in size (Zhang *et al.*, 2001). They also can persist for several days.

Northeast storms can significantly alter the coast. The Halloween Eve Storm of 1991 caused extensive erosion and structural damage along many beaches in northern New England (FitzGerald *et al.*, 1994). A storm in March 1989 generated >1.5 m waves for 115 hours, resulting in millions of dollars of damage along the mid-Atlantic Coast (Dolan *et al.*, 1990). A northeast storm in January, 1978 caused severe structural damage, killed four people and resulted in up to six meters of erosion along one beach.

Beach recovery

There have been few studies of long-term impacts of major storms and whether beaches and dunes eventually recover to their pre-storm position (Morton *et al.*, 1994). Following the 1978 storm, Nelson and Fink (1980) stated that extreme storms do not cause a permanent shoreline and frontal dune ridge retreat, but rather the retreat is a short-term equilibrium event. Within the next several years, the frontal dune ridge will be reconstructed, only slightly landward of its pre-storm location. One storm of record every 50 to 100 years allow sufficient time for beaches and dunes to recover sediment that was lost in the storm. Their conclusions were based on observations (specifically measurements of washover deposits) before and after the 1978 storm.

Post-storm beach recovery can be evaluated in terms of losses and gains in sand volume, or in terms of pre- and post-storm positions of morphological features (Morton *et* *al.*, 1994). Kraus (1988) showed that sediment volumes eroded by storms at beaches with and without seawalls are comparable, as are post-storm recovery rates.

Measurements of eight topographic beach profiles along the Rhode Island coast before and after the 1978 storm showed that the storm caused a decline in sand volume of all of the profiles (Lacey and Peck, 1998). Following the storm, six out of eight stations showed an increase in volume equal to approximately 20% of their original volume within the next year. This was followed by a slowing in the rate of increase. Along many of the profiles, the beach reached its pre-storm volume within five years.

Over a one-year time period, the seasonal changes in beach topography and beach volume along the Delaware coast varied with changes in the wave climatic regimes, which are in phase with storms (Dubois, 1988). Following the storms, the waves rebuilt the beach in two stages, from March through August. In the first stage, the beach accreted vertically (aggraded) and in the second stage, it accreted laterally (prograded).

In contrast, in a 10-year beach profiling study along the Texas coast Morton *et al.* (1994) showed that beach recovery occurred in four time-dependent stages following a category 3 hurricane. Undeveloped beaches experienced all four stages. In addition, forebeach recovery in developed and undeveloped beaches was similar, but houses on developed beaches impeded recovery of the backbeach and dune (Morton *et al.*, 1994). Post-storm recovery lasted four to five years, at which point the maximum cumulative recovery (67%) was accounted for. After this point, the profiles began to respond to local events that caused changes in the profile volumes. Only two of the seven profiles completely recovered the sand that they had lost (Morton *et al.*, 1994). The remainder of the sand was transported downdrift or stored in the shoreface.

Chapter 2

STUDY AREA

GEOLOGICAL SETTING

Coastal Geology

Barriers are most common along continental margins where micro-mesotidal ranges are dominant (Hayes, 1979). Relative sea-level change and sediment supply govern the formation of barriers. In addition to these two factors, the wave and wind climate and the regional geology maintain the changing systems and are responsible for the barrier's physiographic characteristics (FitzGerald and VanHeteren, 1999). The glaciated New England coast incorporates more numerous barrier systems than the mid-Atlantic region, but the total barrier length is less and their distribution is more sporadic. Forbes and Syvitski (1994) defined paraglacial coasts as "those on or adjacent to formerly ice-covered terrain, where glacially excavated land-forms or glaciogenic sediments have a recognizable influence on the character and evolution of the coast and nearshore deposits." The coast of Maine falls into this category, and it contains over 200 small barrier systems (Duffy *et al.*, 1989).

Four coastal compartments, based on bedrock structure and geomorphology, comprise the coastline of Maine (Figure 2.1) (Kelley, 1987). Arcuate embayments with intervening headlands characterize the southwest compartment, which extends from the Piscataqua River, New Hampshire to Cape Elizabeth, Maine. The embayed coast is a result of differential weathering of rocks, underlying structural trends, and the glacial processes that dominated the area in the past. Because of abundant sand supply and process-response mechanisms, the southwest coastal compartment contains a variety of

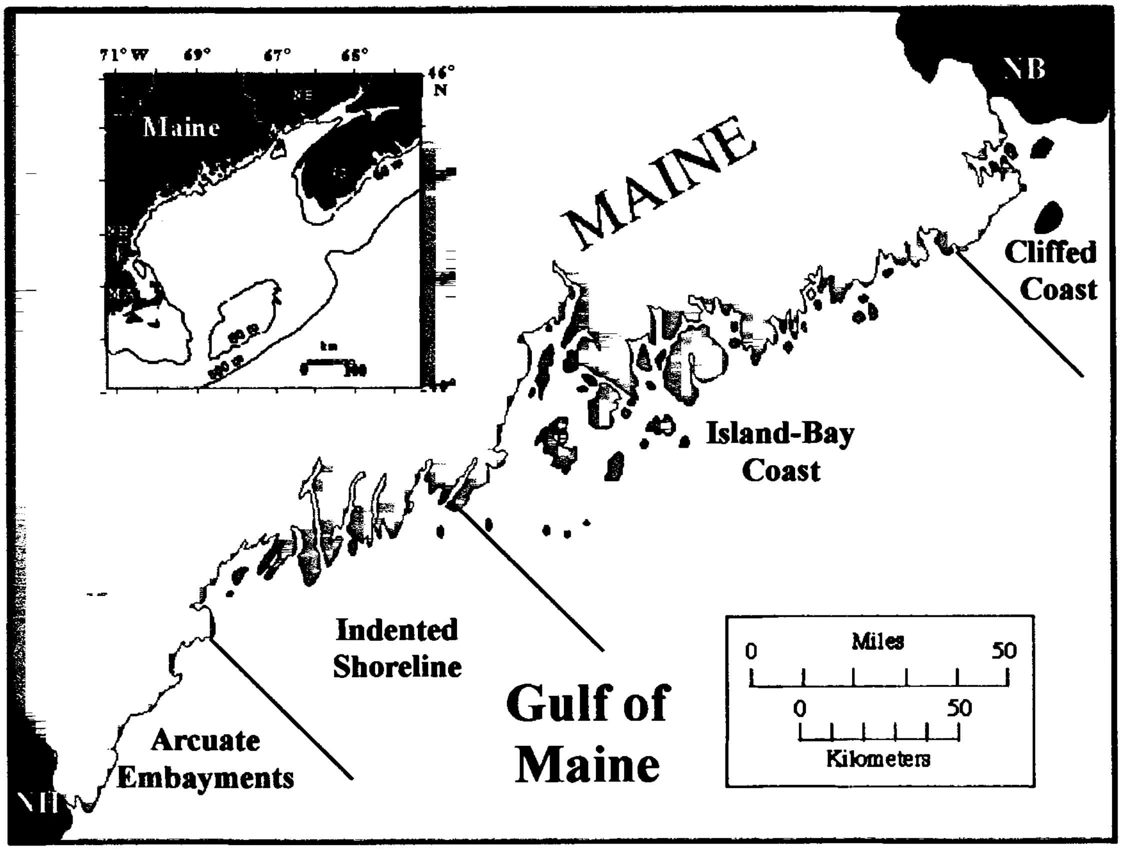


Figure 2.1. Maine coastal compartments (Kelley, 1987)

barrier systems. Salt-marsh is the dominant morphologic feature in the coastal compartment, but the sandy barrier beaches distinguish this part of the coastline from other areas (Ward, 1999). Ninety percent of the beaches are sandy. The remainder are pebble to cobble beaches.

Bedrock Geology

A complex terrain of meta-sedimentary, intrusive and metavolcanic rocks, ranging in age from Precambrian to Mesozoic, underlies the coastal area and inner shelf of southwest Maine (Osberg *et al.*, 1985). Paleozoic intrusive and meta-sedimentary rocks commonly crop out on islands and shoals throughout the region. The crystalline bedrock units are foliated, jointed, and fractured, causing them to have variable resistance to glacial and fluvial processes.

Bedrock exerts a primary control on the morphology of the shoreline (Kelley, 1987; Belknap *et al.*, 1987b). Differential erosion of the less-resistant rocks in the Kittery, Berwick, and Cape Elizabeth Formations has led to the geometry of Saco Bay and Wells Embayments. The headlands left behind formed the pinning points for moraines and for beaches at earlier stages in the transgression. In addition, much of the inner shelf in Saco Bay (30%) (Figure 2.2) and Wells Embayment (50%) (Figure 2.3) is mapped as bedrock (Kelley *et al.*, 2001). Bedrock outcrops frame shelf valleys, compartmentalize sediment transport (Kelley *et al.*, 1995a), and lead to wave refraction (Farrell, 1972).

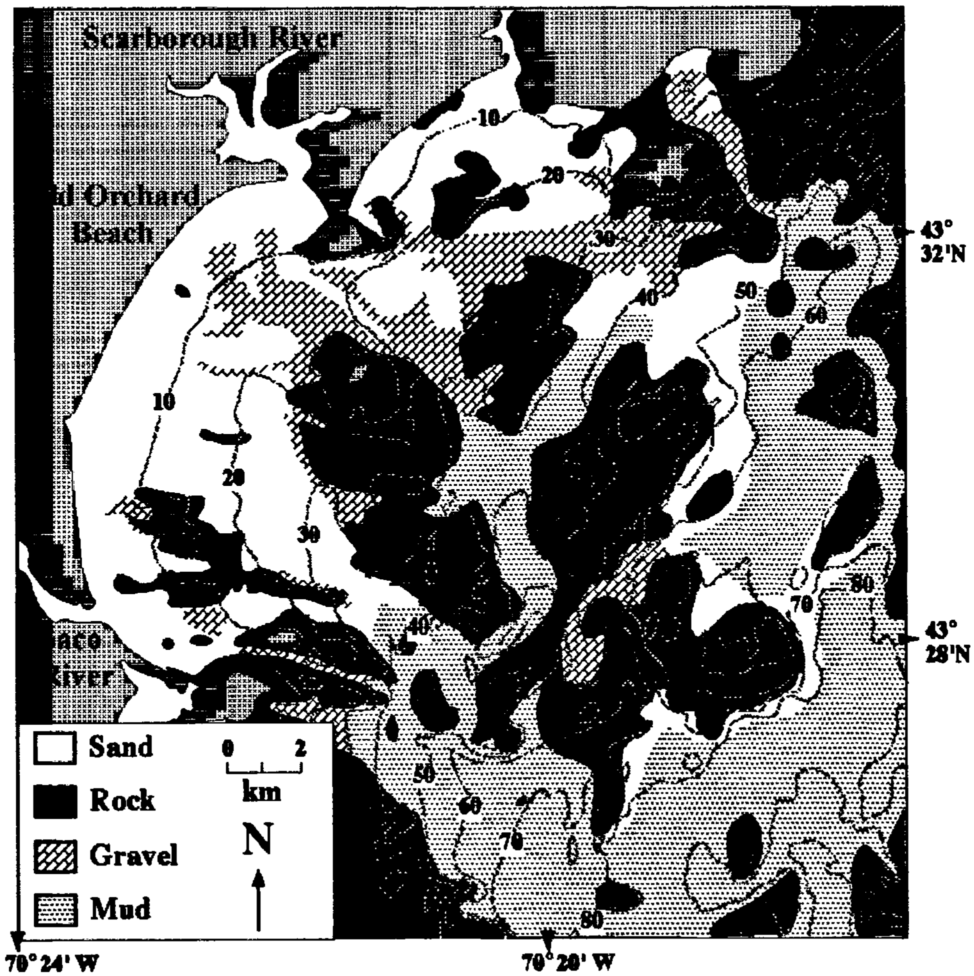


Figure 2.2. Surficial sediments in Saco Bay (Kelley *et al.,* 2001).

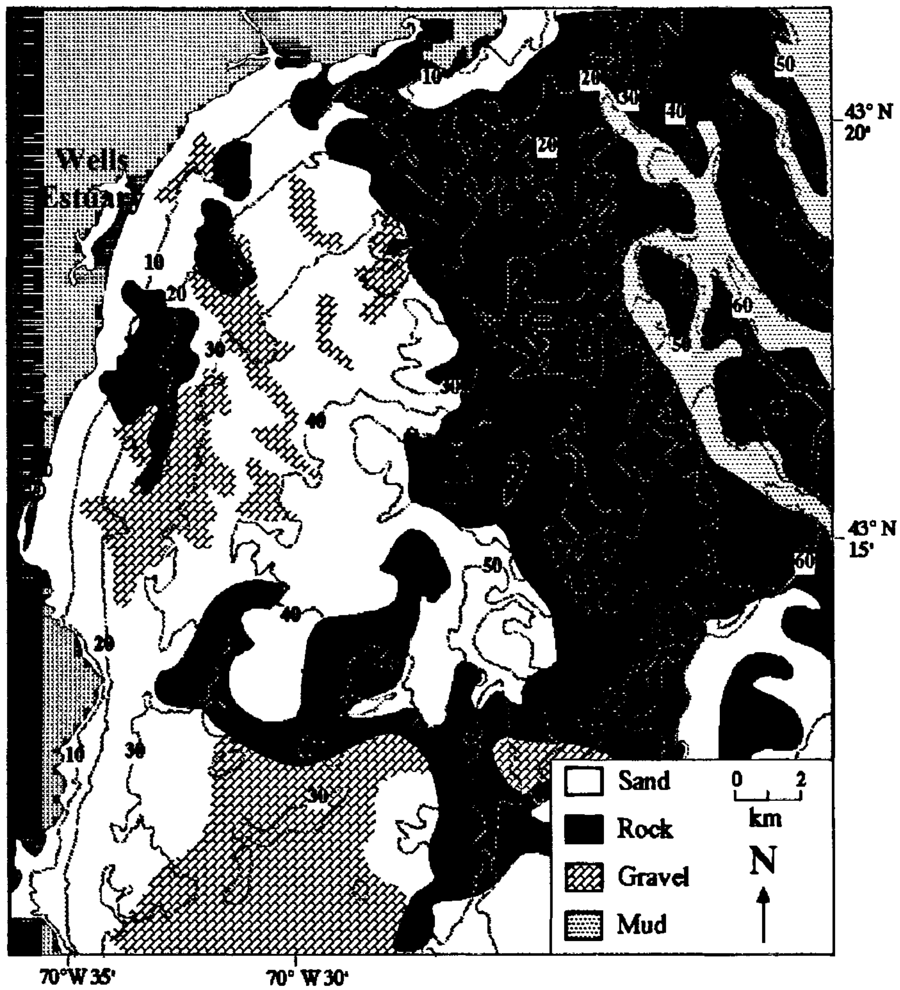


Figure 2.3. Surficial sediments in Wells Embayment (Kelley *et al.*, 2001).

Glacial and Sea Level History

Chronology of deglaciation in southwestern Maine

The Late Wisconsian Laurentide Ice Sheet reached its terminal position at the north end of Georges Bank approximately 19 ka (all dates are ^{14}C uncalibrated) (Smith, 1982; 1985; Hughes *et al.*, 1985). Withdrawal of the ice began between 18 and 17 ka, and the ice margin retreated to the present coast by 14 ka (Smith, 1985; Smith and Hunter, 1989, Dorion *et al.*, 2001). During this time, glaciers deposited thin tills, sand and gravel outwash plains, scattered moraines and ice-contact stratified drift in southern Maine (Smith, 1985; Hunter *et al.*, 1996). These deposits can be seen on the state surficial map (Thompson and Borns, 1985).

Sea-level fluctuations

Glacial activity caused isostatic depression of the crust of northern New England below sea level. Thus, a transgression accompanied deglaciation (Belknap *et al.*, 1987a; Kelley *et al.*, 1989a; 1992), allowing deposition of the fine-grained glaciomarine sediment of the Presumpscot Formation. The most widespread Quaternary unit in southwestern Maine (Bloom, 1960; 1963; Thompson and Borns, 1985), the Presumpscot Formation ranges in texture from predominantly mud to layers of sand. This glaciomarine mud, glacial outwash sand and gravel, and till in the form of moraines (Figures 2.2 and 2.3), were the primary sources of sediment during barrier formation and Holocene sea-level rise (Belknap *et al.*, 1986; 1989; Kelley *et al.*, 1989a).

As a result of the isostatically depressed land and the globally rising ocean level, the sea reached a highstand 60-130 m above present between 12.5 and 13 ka (Belknap *et al.*, 1987a; Smith, 1985; Stuvier and Borns, 1975; Thompson and Borns, 1985). As the rate of isostatic rebound increased, the sea rapidly retreated across the coastal lowlands, reaching a lowstand between –55 and –60 m around 11-10 ka (Barnhardt *et al.*, 1995). At this time the ice had completely retreated, land rebound was slowing and relative sea level was at a maximum lowstand on the continental shelf.

Radiocarbon dates on intertidal shells, wood in delta and estuarine sediments, and numerous peats from salt-marsh cores reveal that the rate of sea-level rise during the Holocene transgression was highly variable (Belknap *et al.*, 1989; Barnhardt *et al.*, 1995; Kelley *et al.*, 1995c; Gehrels *et al.*, 1996). Sea level rose rapidly following the marine lowstand. It slowed and leveled off near –20 m around 9 ka, but accelerated again from 7-5 ka. The rate of relative sea-level rise slowed during the late Holocene. The mean-tide level rose at a rate of 0.7-2.1 mm/yr between 5.7 and 3.5 ka and at a rate of 0.0-0.6 mm/yr since then (Gehrels *et al.*, 1996). Tide gauge records, however, show an increase in the rate of sea-level rise to 2-3 mm/yr during at least the past 60 years (Belknap *et al.*, 1989).

Many sea-level curves for Maine have been published in an attempt to reconstruct sea-level history (Bloom, 1960; Schnitker, 1974; Stuvier and Borns, 1975; Belknap *et al.*, 1987a; 1989; Kelley *et al.*, 1992). Barnhardt *et al.* (1995) constructed the most recent and complete sea-level curve (Figure 2.4).

Physiographic Zones

Shipp (1989), Belknap and Shipp (1991), and Kelley *et al.* (1989a; 1990; 1998) conducted extensive studies of the southwestern part of the Gulf of Maine using high-resolution seismic reflection profiles, side-scan sonar, and submersible observations. Combining these findings with the results from bottom samples, Kelley *et al.* (1989a)

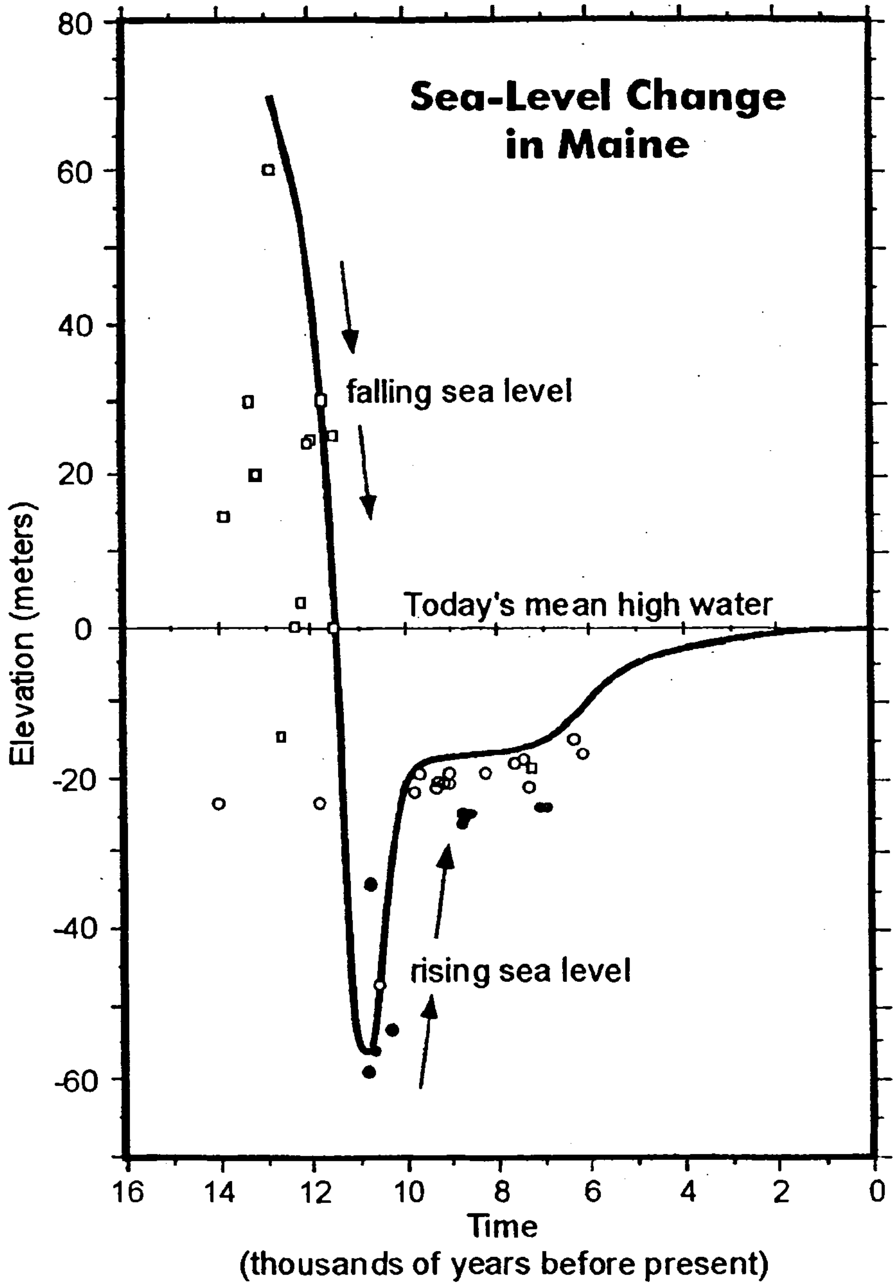


Figure 2.4. Sea-level curve for coastal Maine over the past 14,000 years (Barnhardt *et al.*, 1995). The dots represent coordinates of radiocarbon dates and elevations/depths from shells of marine animals with a known relationship to sea level and wood fragments.

divided the continental shelf, the nearshore region to a depth of 100 m, into five zones based on surficial sediment texture and composition, geometry of sedimentary deposits, and late Quaternary geological history (Figure 2.5).

Nearshore Ramps define the first physiographic zone. These are gently sloping regions that extend from beaches to the 30 m isobath. They possess coast-parallel contours, and are also found adjacent to high bedrock cliffs. Nearshore Basins are mud-filled troughs seaward of coastal areas lacking a significant river input. They border much of the indented shoreline compartment, but do not exist in this study area. The Rocky Zone extends beyond the 30 m isobath and is the most abundant feature in the region. Relief changes abruptly in this zone; the area contains steep bedrock cliffs, and many large boulders. Shelf Valleys cut through the Rocky Zone and generally widen in a seaward direction. Steep bedrock walls border the valleys and bedrock crops out occasionally. The Shelf Valleys end in the Outer Basins, which slope gently until 60 m where there is an abrupt break, often interpreted as a shoreline from a lowstand sea level (Shipp *et al.*, 1991). The seafloor continues into water deeper than 100 m. Bedrock borders the Outer Basin and occasionally crops out, interrupting the flat, muddy seafloor.

Sand Sources

Sand in Saco Bay and Wells Embayment is found in three geomorphic settings (Figure 2.6 and 2.7): 1) near lowstand positions of sea level (50-65 m) (Shipp *et al.*, 1991), 2) in mid shelf positions, and 3) along the modern shoreface (Kelley *et al.*, in press). The shoreface in both regions consists of a wedge-shaped sand deposit that varies

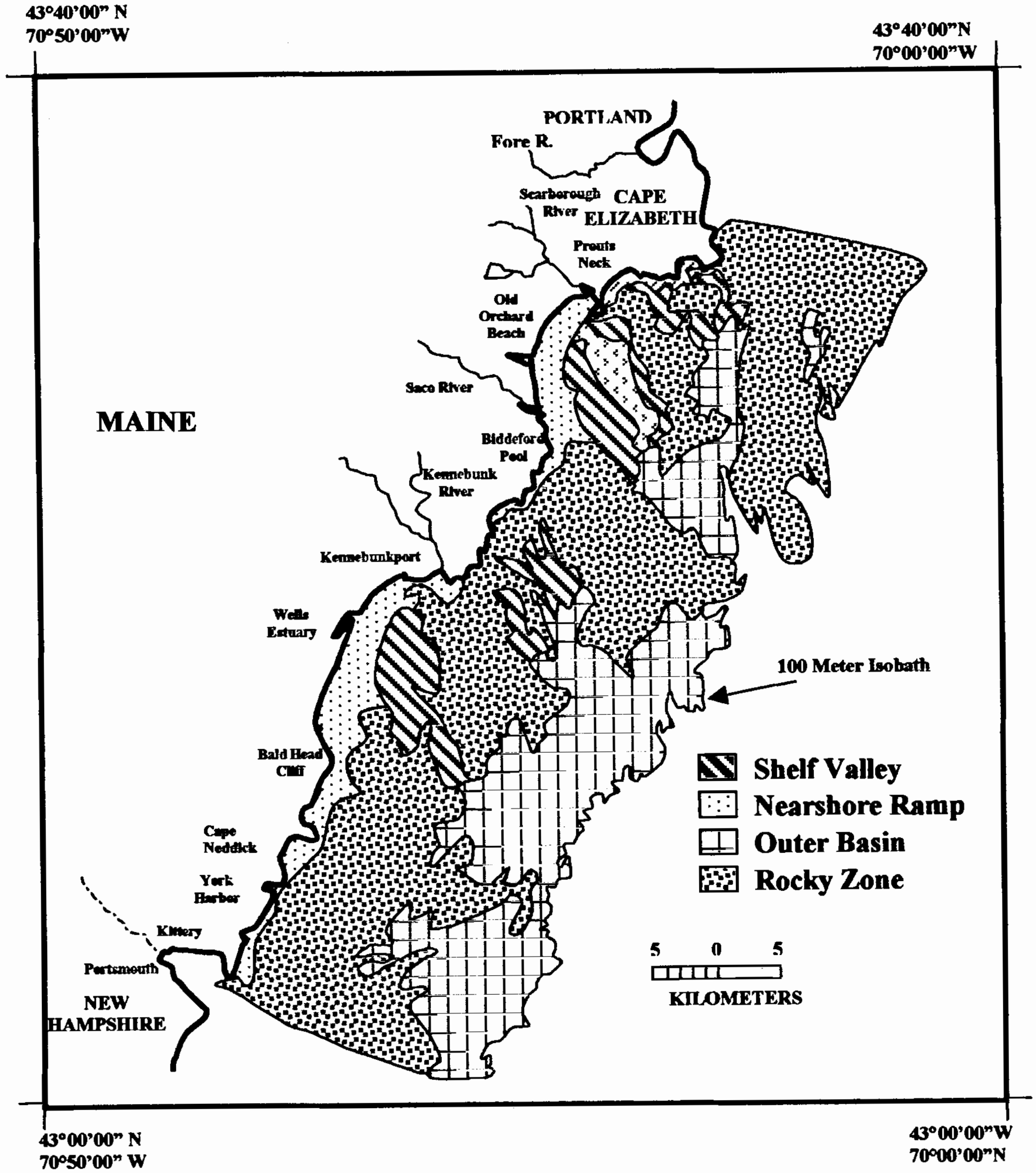


Figure 2.5. Physiographic zones (modified from Kelley *et al.*, 1989a).

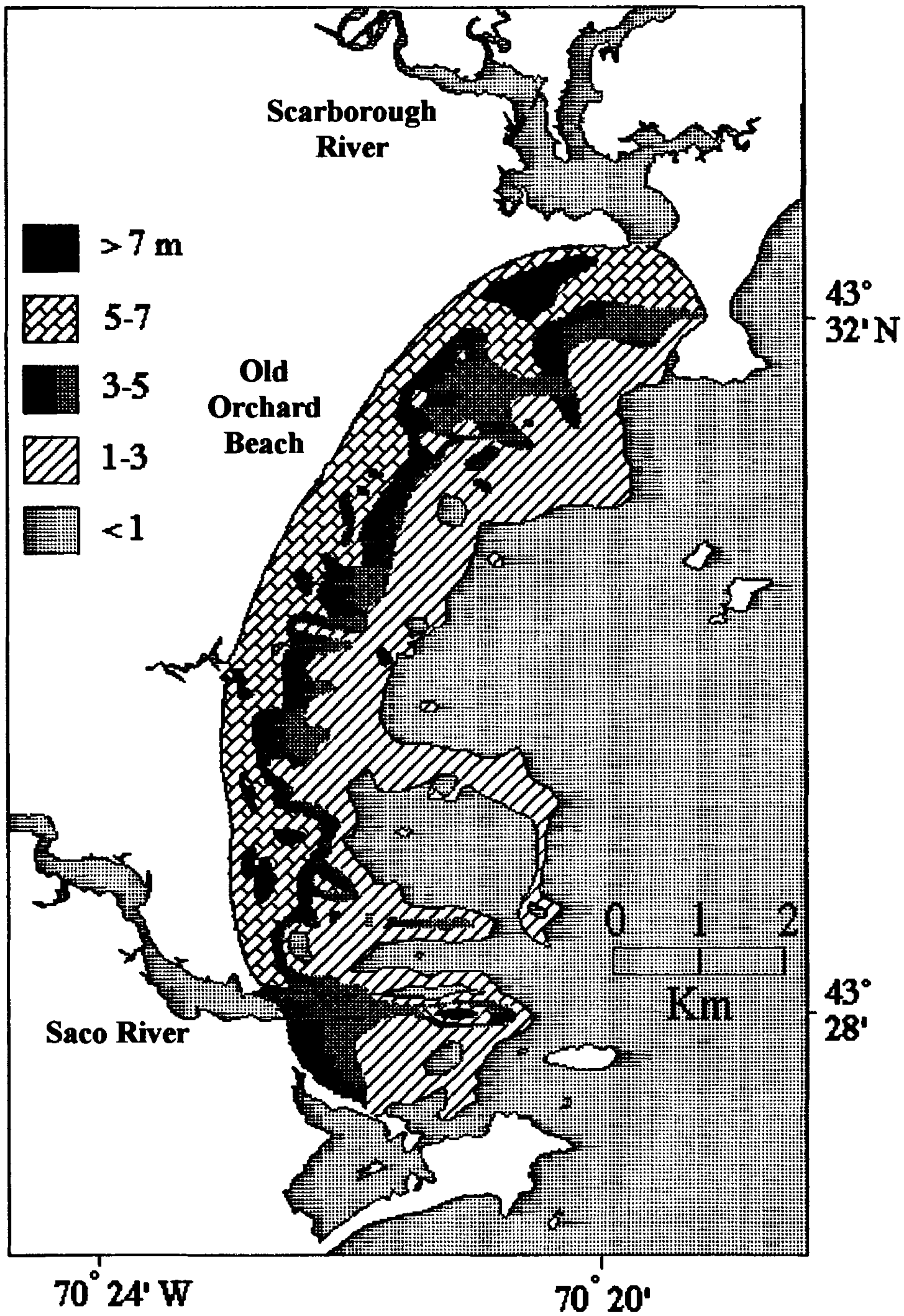


Figure 2.6. Sand distribution in Saco Bay (Kelley *et al.*, 2001, from Barber, 1995).

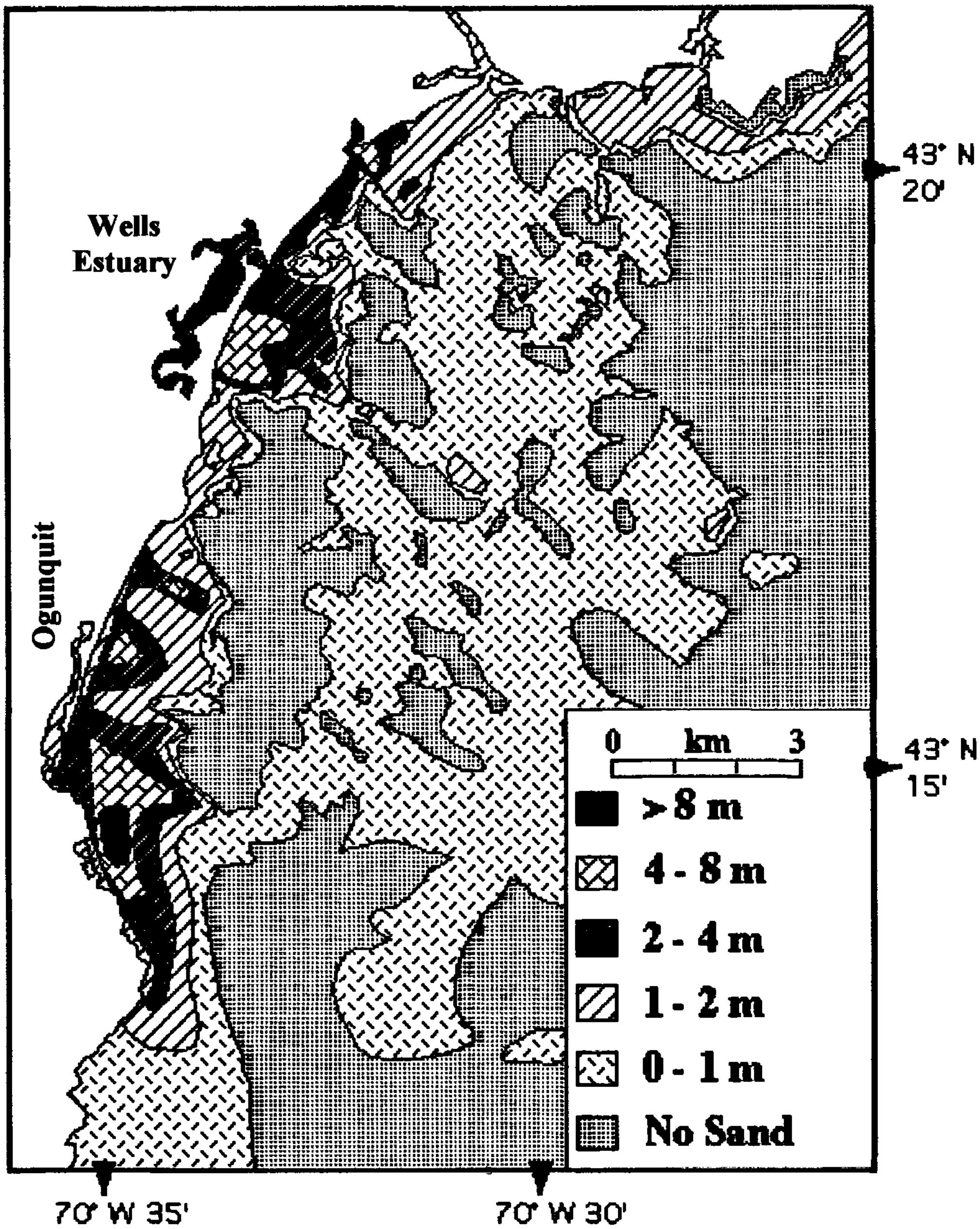


Figure 2.7. Sand distribution in Wells Embayment (Kelley *et al.*, 2001, from Miller, 1998).

in length and width (Barber, 1995; Miller, 1998). The barriers in Saco Bay contain more shoreface sand per length of beach than the barriers in Wells Embayment (Table 2.1).

	Saco Bay	Wells Embayment
Shoreface Sand Volume (10^6 m^3)	56 x 10^6 m^3	41 x 10^6 m^3
Sand Beach Length (10^3 m)	12.7 x 10^3 m	12.7 x 10^3 m
Shoreface Vol./Beach Len. (m^3/m)	4.4 x 10^3 m^3/m	3.1 x 10^3 m^3/m

Table 2.1. Beach length and shoreface sand volume (Kelley *et al.*, 2001).

Sand in Saco Bay is derived primarily from the Saco River, which continues to introduce sediment to the system (Kelley *et al.*, 1995a). The annual discharge of the river is 3.1 x 10^9 m^3 (Barber, 1995), with an estimated sediment yield of 10,000 to 16,000 m^3/yr of sand, which mostly travels to the north by longshore transport (Kelley *et al.*, 1995a).

In comparison to Saco Bay, Wells Embayment lacks a significant fluvial input, and the barriers are recycling older material. The sand in this region probably came from glacial sources, especially from reworking of local moraines (Hussey, 1970; Duffy *et al.*, 1989; Shipp, 1989; Miller, 1998). Other possible sources include sand deposits offshore, interpreted as regressive fluvial systems deposited during the Holocene lowstand (Kelley *et al.*, 1986, 1987; Shipp, 1989; Montello, 1992).

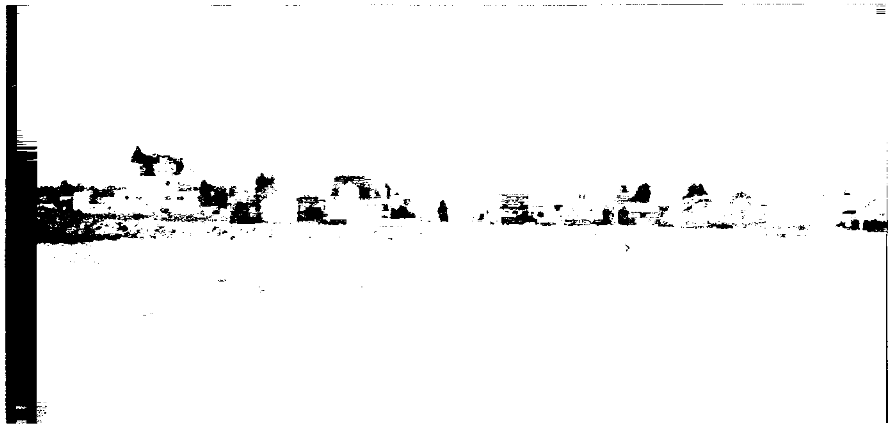
PHYSICAL SETTING

The beaches in this study have different levels of development, and are defined here as highly developed, moderately developed and undeveloped (Table 2.2). Highly developed beaches have seawalls and waves commonly reach the structure at high tide (Figure 2.8a). Moderately developed beaches may have a seawall as well, but the seawall is no longer active, such as along East Grand Beach where a significant dune has developed in front of the structure (Figure 2.8b). Undeveloped beaches are those in a natural state with no development or engineering structures (Figure 2.8c). Several of the undeveloped beaches are adjacent to developed beaches however. The following section describes the beaches individually within Saco Bay and Wells Embayment, starting with the northern most beach and moving south.

Beach Name	Seawall Status[1]	Erosional Status[2]	Replenishment History
Higgins/Higgins spit	Active/None	Moderate	None
Scarborough	None	Low	None
Western/Ferry	None	Low	None
East Grand	Inactive	Low	None
Kinney Shores	Inactive	Low	None
Biddeford Pool/ Fortunes Rocks	Inactive/Active	Low/high	None
Goochs/ Middle Beach	Active	High	1985
Laudholm	None	Moderate	None
Ogunquit	None	Moderate	Dune restoration 1974-1975

[1] Seawall status indicates whether a seawall exists. An active seawall is defined if the high tide reaches the seawall.
[2] The erosion status is relative and beaches are defined with respect to one another

Table 2.2. Characteristics of beaches involved in profiling project.



a.

b.

c.

Figure 2.8. Examples of beaches defined by development status: a. Highly developed beach (Higgins), b. Moderately developed beach (East Grand), and c. Undeveloped beach (Scarborough)

Saco Bay

Location

Located 20 km south of Portland, in Cumberland and York counties, Saco Bay is a cresent-shaped arcuate embayment that opens into the Gulf of Maine to the east (Figure 1.1 and 2.9). The shoreline has a log-spiral, crenulate shape with straighter pocket beaches. Two bedrock headlands, Prouts Neck to the north and Biddeford Pool to the south, frame the bay, making the system self-contained and less influenced by outside meteorological activity (Barber, 1995; Farrell, 1972; Kelley *et al.*, 1989c). The barrier system consists of a series of spits and barriers, stretching from the Scarborough Estuary in the north to the Saco River in the south. A majority of the barriers front extensive salt marsh systems, which make up 93% of the intertidal estuarine environment (Kelley *et al.*, 1986). Goosefare Inlet interrupts the shoreline, just south of Old Orchard Beach. There are several islands and bedrock shoals within the bay, which play an important role in the refraction of incoming waves (Farrell, 1972).

Geological history

A regression followed the general retreat of ice from the coast of Maine and subsequent isostatic rebound of the land (Belknap *et al.*, 1987a). During this time, the Saco River deposited sand and gravel outwash over the Presumpscot Formation. As sea level continued to fall and the land gradient increased, the Saco and other local rivers started cutting down into till, glaciomarine mud, and regressive sands in the valley (Kelley *et al.*, 1989c). Rivers deposited this material in deep water until the sea level lowstand, around 10.8 ka (Barnhardt *et al.*, 1995).

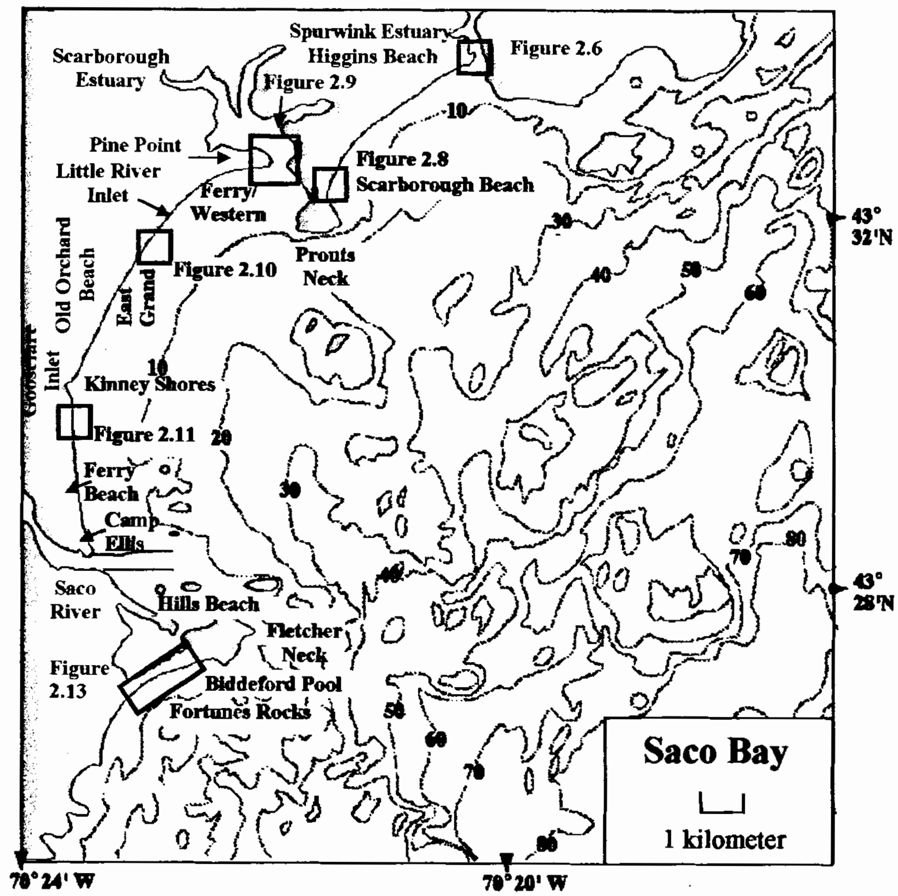


Figure 2.9. Location map, Saco Bay, Maine. Boxes correspond to subsequent figures. Isobaths are in meters.

Following the low stand, sea level rose, transforming the Saco, Scarborough and Spurwink Rivers into relatively broad estuaries by 6 ka (Kelley *et al.*, 1989c). Although the Saco River continued to supply sediment, mainland beaches, which were probably the most common feature at the time, received sediment from bluff erosion and possibly an offshore glacial deposit (Kelley *et al.*, 1995a). The shoreline continued to move landward until 3 ka , when sea level slowed its rate of rise (Belknap *et al.*, 1989). Barrier spits began to grow laterally and vertically (vanHeteren *et al.*, 1996).

During the past 7,000 years, an abundant sediment supply and the protected embayment were sufficient to maintain the barriers as sea level rose. Although a transgression occurred, the barrier beaches grew seaward since the rate of sea-level rise slowed (Kelley *et al.*, 1995a; vanHeteren *et al.*, 1996). The Saco River still supplies most of the sediment to the barrier, annually contributing an average of at least 16,000 m^3/yr of sand (Kelley *et al.*, 1995a). Although some of the barriers continue to prograde today, there are a few beaches, such as Camp Ellis, that are eroding. This is a result of the contemporary rapid sea-level rise, as well as human interference (Kelley and Anderson, 2001).

Human interference

The shallow tidal delta at the mouth of the Saco River made it difficult for boats to enter the estuary in the mid-1800's. Because of the demand for improved river navigation, the U.S. Army Corps of Engineers (USACOE) built jetties on the north and south banks of the river mouth, in 1866 and 1890, respectively (Kelley and Anderson, 2001). The USACOE believed eroding glacial deposits in the bay supplied the beach with sediment. They inferred that the sand moved landward to Old Orchard Beach and then traveled north and south (Kelley *et al.*, 1995a). Based on this assumption, which was later disproved (Kelley *et al.*, 1995a), the USACOE extended the jetties in length and height several times to keep sand out of the navigation channel (Kelley and Anderson, 2001). The construction of the jetties eliminated the large ebb-tidal delta of the river (Farrell, 1972).

Industrial activities and commercial fishing were extremely important to Saco Bay in the past, and estuaries within the bay provided ports for these activities (Farrell, 1972). The Little River inlet closed in 1875 due to human influence in (Farrell, 1972). Jetties and seawalls have affected the patterns of sand movement within the bay, often enhancing erosion. Sand eroded adjacent to the Saco River north jetty traveled north to Pine Point. As a result of this sand transfer, the Scarborough River required dredging for navigation in 1955, and a jetty was constructed at the southern side of the Scarborough River entrance (Kelley *et al.*, 1995a). Most of the erosion within Saco Bay, however, results from wave refraction and interrupted delivery of Saco River sand to the beaches by the jetties located north and south of the Saco River mouth.

Higgins Beach

Location

The northeast-southwest trending Higgins Beach is an 850 m long spit (Nelson, 1979), located at the mouth of the Spurwink River Estuary in Cumberland County (Figure 2.10). To the southwest, bedrock borders Higgins Beach, while the Spurwink River tidal inlet limits the extent of the beach at its northeastern end. An extensive

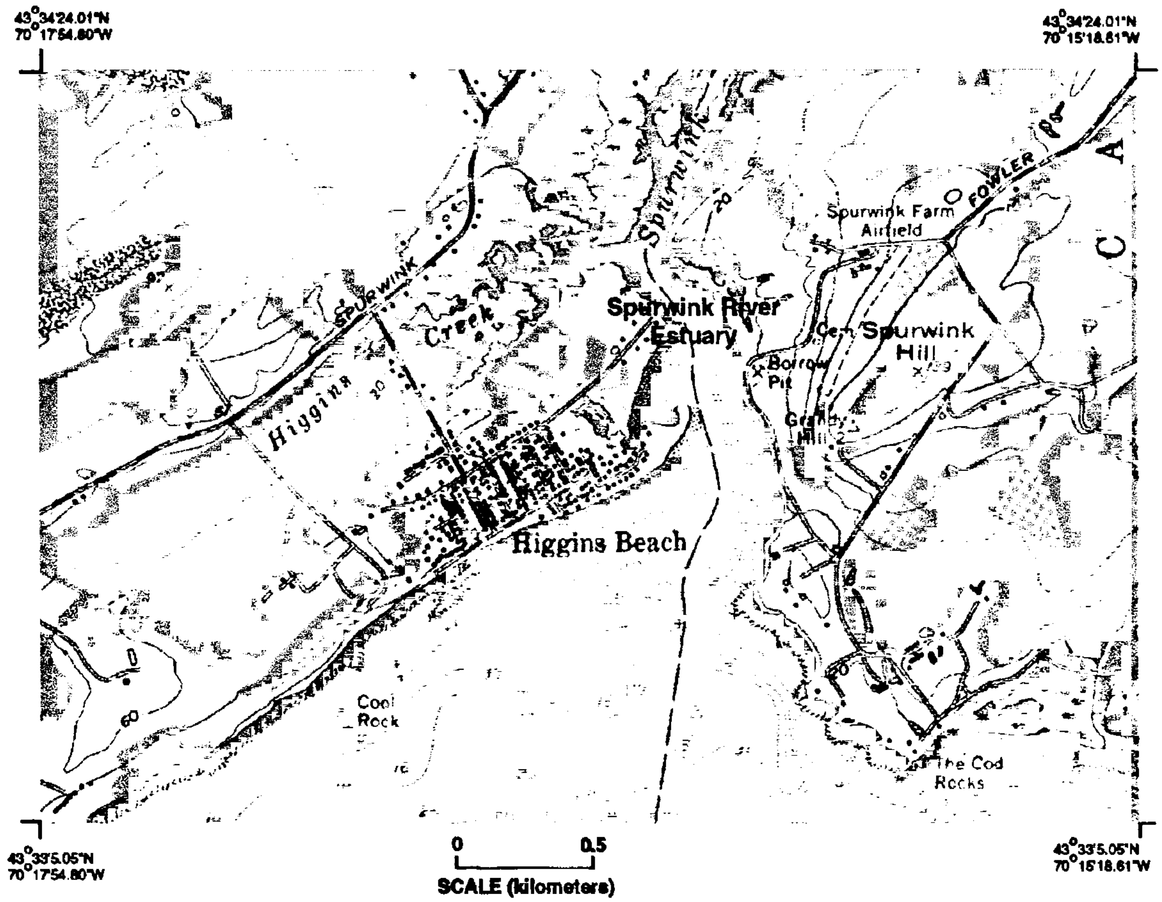


Figure 2.10. Location map of Higgins Beach. Modified from the USGS 7.5' topographic map of the Prouts Neck quadrangle (Maptech Inc. software, 1997).

intertidal sand flat fronts the area. This tidal flat acts as both the low-tide terrace of the beach and the ebb-tidal delta of the Spurwink River. A salt marsh and tidal flat exist to the east, while bedrock uplands back the region.

Geological history

The Higgins Beach system originated as part of the Saco Bay system of beaches over 3,000 years ago, but was cut off from the beaches in Saco Bay as sea level rose. From historical photos, it appears the shoreline retreated 40-50 m between 1851-1953 (Nelson, 1979). The sand in the system has moved to the northeast, resulting in elongation of the recurved spit system on the northeast end and a narrowing of the beach along its exposed southwestern side (Figure 2.11). Presently Higgins Beach is a closed system with no new sand being added from outside sources (Higgins Beach Public Improvements Ad-Hoc Committee, 1998).

Development status

Higgins Beach is densely developed with many types of seawalls fronting the roads and houses. The seaward position of development in the dunes limits the extent of the dry beach at high tide. A pair of massive Northeast storms in 1978 (Nelson and Fink, 1980) resulted in extensive property damage (Kelley *et al.*, 1989b). Because of the damage, and in an effort to maintain the quality of the area, the local community is actively working to create a plan to manage the beach (Higgins Beach Public Improvements Ad-Hoc Committee, 1998). Sand dunes on the eastern end are the only remaining undeveloped areas of the beach.

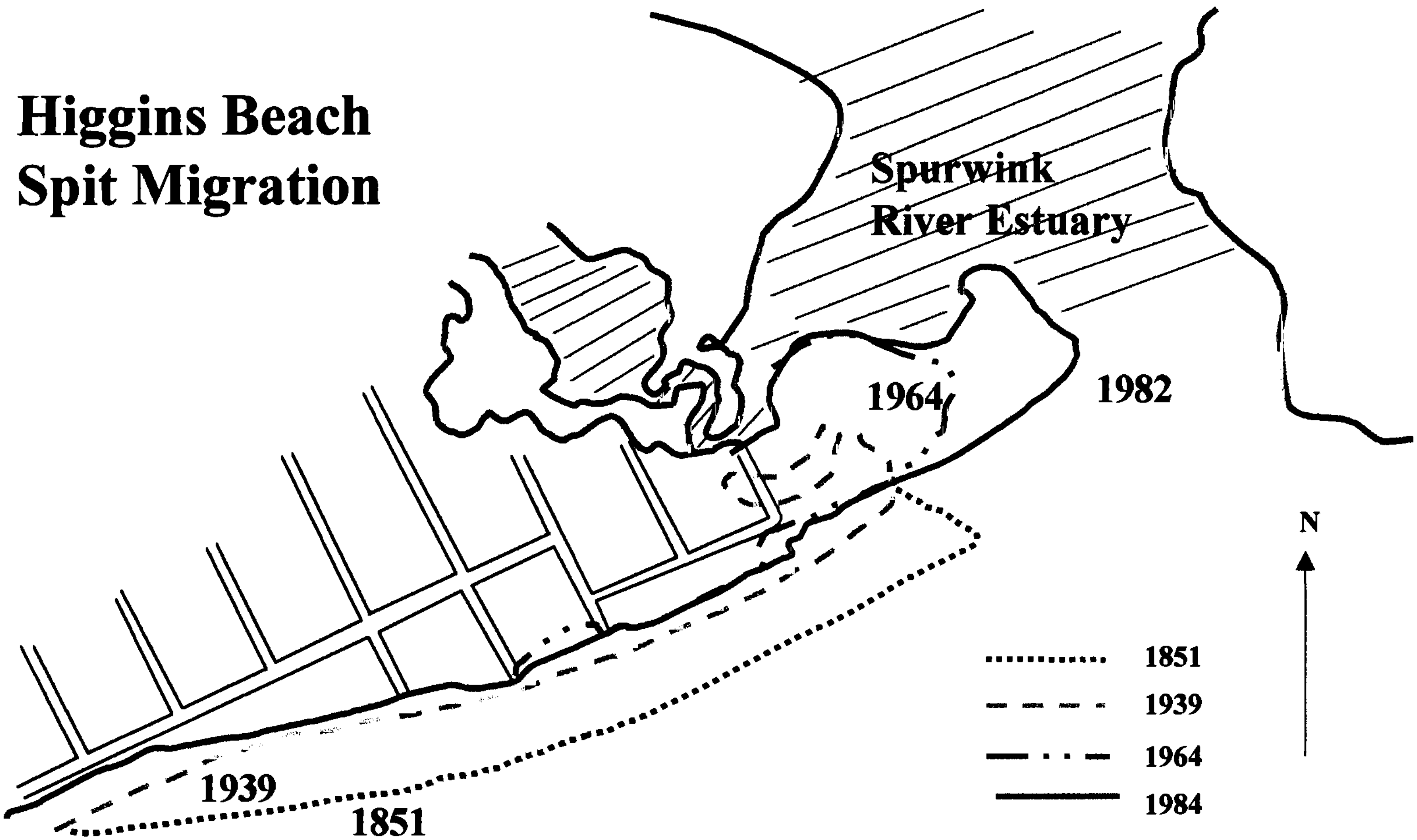


Figure 2.11. Sketch map depicting past positions of Higgins Beach spit (modified from Kelley *et al.*, 1989b)

Scarborough Beach

Location

Scarborough Beach is a 2.1 km (Nelson, 1979) fringing beach forming the eastern shore of Prouts Neck (Figure 2.12). The beach is anchored by bedrock at both ends, and no relict spits exist. A difference in grain size divides the beach into two provinces. Shooting Rock, an offshore shoal, shelters part of the beach from waves, producing a cuspate foreland, or seaward-projecting bulge in the beach. North of the cuspate foreland, the beach is entirely sandy. Sand, gravel and cobbles comprise the beach south of the foreland. Massacre Pond, a freshwater pond that was formerly a salt-water tidal lagoon, backs the beach and has a broad, cattail-dominated fringe (Nelson, 1979). To the north, the marsh narrows and leads into an elongate alder swamp.

Geological history

Historically, Scarborough Beach is relatively stable, or only slowly eroding. A salt marsh peat exposure, found behind the beach, indicates that the beach was once an open barrier with a back-barrier lagoon and salt marsh (Nelson and Fink, 1980). The fact that Massacre Pond is freshwater now indicates that the beach grew seaward in the past and converted the salt pond to freshwater (Duffy *et al.*, 1989). The reverse is occurring now as sea level is rising more rapidly. The dunes have retreated up and over the old salt marsh, along the beachface. The southern 500 m of the dune field fringes on long-stabilized Holocene dune sand of Prouts Neck. The northern 650 m fringes on upland glacial deposits (Nelson, 1979).

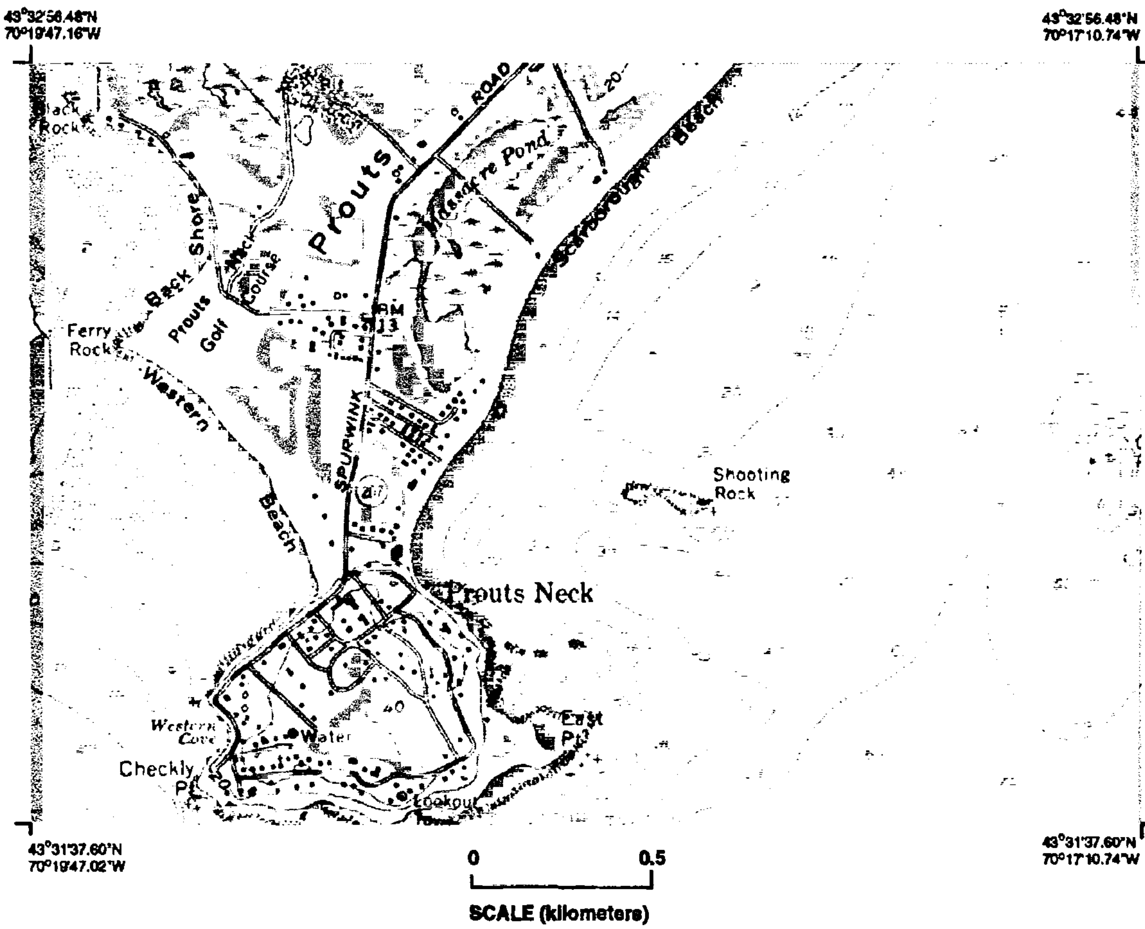


Figure 2.12. Location map of Scarborough Beach. Modified from the USGS 7.5' topographic map of the Prouts Neck quadrangle (Maptech Inc. software, 1997).

Development status

Part of Scarborough Beach is a state park that remains undeveloped. A maritime forest exists behind the dunes, along most of the beach (Kelley *et al.*, 1989b). The beach is publicly accessible through the state park entrance, but an entrance fee is required to enter the park from the road. Dune fences and signs along the beach front keep pedestrians from trampling the fragile grass. A wooden walkway cuts through the dunes and allows tourists access to the beach. The southern end of Scarborough Beach is developed, and there are a few houses on the northern end, as well. This low level of development qualifies Scarborough Beach as part of the federal and state Coastal Barrier Resources System (Maine Geological Survey, 2001; National Fish and Wildlife Service, 2001).

Western and Ferry Beach

Location

Western Beach is a 980 m (Nelson, 1979) straight, fringing, pocket beach, oriented northwest-southeast (Figure 2.13). It forms the western shore of Prouts Neck and extends to Ferry Rock. Western Beach contains many acres of rippled intertidal flats (Trefethen and Dow, 1960). Ferry Beach (Back Shore on 7.5' topographic map) curves almost circularly from Ferry Rock to Black Rock, another bedrock outcrop to the north. The beach is 840 m long (Nelson, 1979), but a broad relict spit extends 240 m farther north-northeast into the adjacent marsh. Ferry Beach is partly a pocket fringing beach and partly a pocket barrier beach. Both beaches are located at the mouth of the

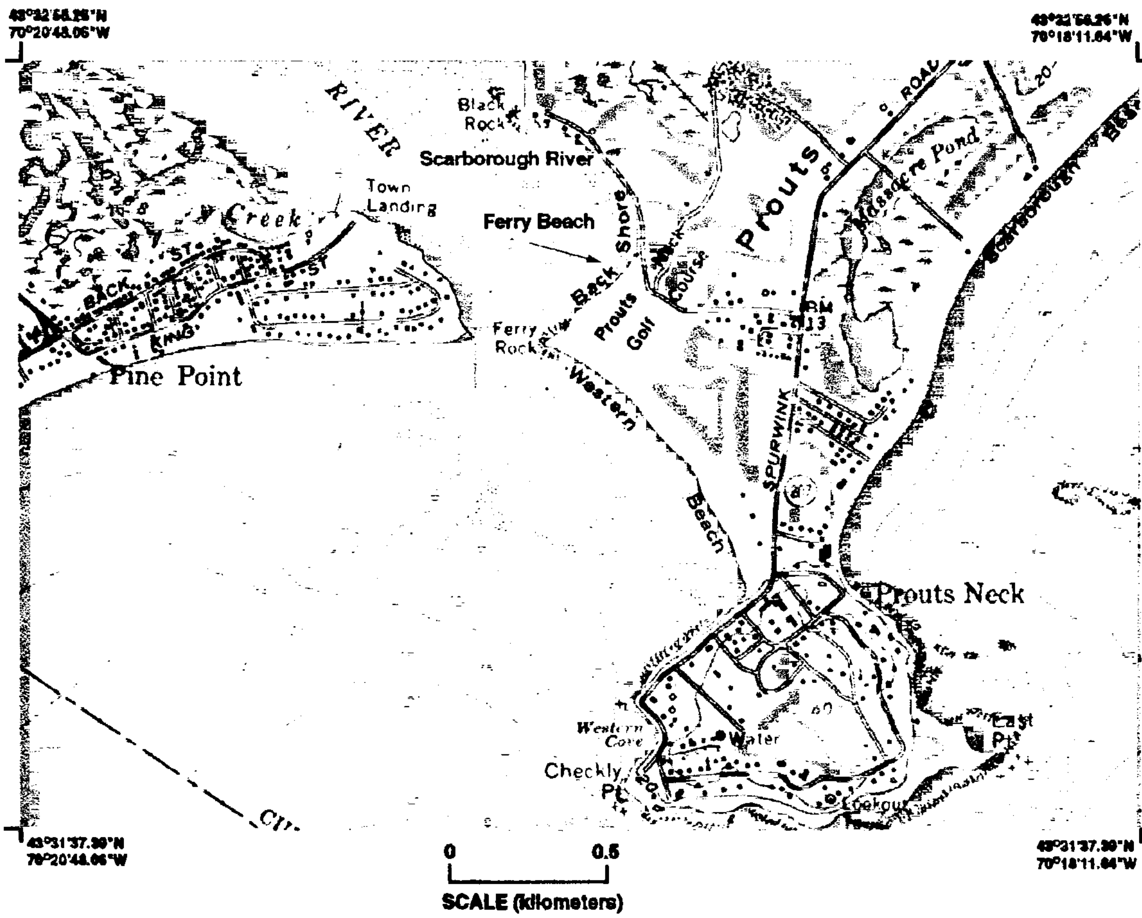


Figure 2.13. Location map of Ferry and Western Beaches. Modified from the USGS 7.5' topographic map of the Prouts Neck quadrangle (Maptech Inc. software, 1997).

Scarborough River, and the low-tide terrace is also part of the ebb-tidal delta of the river. A forest and a golf course are found behind Western and Ferry Beaches.

Geological history

Historically, the shorelines of both Ferry Beach and Western Beach were stable (Nelson and Fink, 1980). However, numerous paleo-dune ridges, cross-cutting one another, and relict erosional scarps suggest a complex history of episodic erosion and accretion at Western Beach. Air photos indicate accretion along the beach since 1953 (Nelson, 1979). Pine Point on the opposite side of the Scarbrough River, is a possible sand source for the accreting beach (Farrell, 1972).

A relict spit of Ferry Beach indicates the meander activity of the Scarborough River, as well as the past location of the beach (Farrell, 1972), although the beach remained stable from 1940 to 1976 (Nelson, 1979). The Scarborough River inlet has changed very little in the past 17 years, indicating that most of the sediment in the inlet is recirculated (FitzGerald *et al.*, 1989). The presence of landward migrating swash bars suggests that sand is exchanged between the ebb delta and adjacent beaches (FitzGerald *et al.*, 1989). On Western Beach, flood tide currents are generally stronger than ebb tide currents, as shown by the asymmetric patterns of ripples (Trefethen and Dow, 1960).

Development status

Western Beach and Ferry Beach remain undeveloped (Kelley *et al.*, 1989b). The golf course behind Western Beach represents a minimal developmental impact on the beach and Ferry Beach is a town park owned by Scarborough. As long as sediment is available, it appears that Pine Point will continue to contribute material to the beaches on the eastern shore of the Scarborough tidal inlet. A single jetty built in 1962 along the western side of the Scarborough River inlet altered accretion patterns along the adjacent Pine Point (Nelson, 1979) and has influenced inlet processes (FitzGerald *et al.*, 1989).

East Grand Beach

Location

East Grand Beach is the northern extension of Old Orchard Beach, a 7.3 km long barrier complex that extends, unbroken, from Goosefare Brook to the Scarborough River inlet (Nelson, 1979) (Figure 1.1 and 2.14). The barrier is divided politically into two sections: East Grand Beach is located in the northern section, in Cumberland County while Surfside Beach comprises the southern section in York County. Grand Beach generally trends northeast-southwest. An extensive salt marsh, connecting to the Scarborough River inlet and its tributaries, backs much of Grand Beach. A small section of Old Orchard abuts a sandy glacial upland.

Geological history

The Old Orchard Beach ridge was not always the smooth, curved crescent shape that it now is. The coast was slightly irregular with rocky promontories, small stream inlets and a more open Scarborough Estuary (Farrell, 1972). Before 1859-1868, the Little River Inlet, a tidal reentrant, formed the Old Orchard Beach-Scarborough town line, as well as the York-Cumberland County boundary (Figure 2.14). When the Little River tidal reentrant was contiguous with marshland that drained into the Scarborough

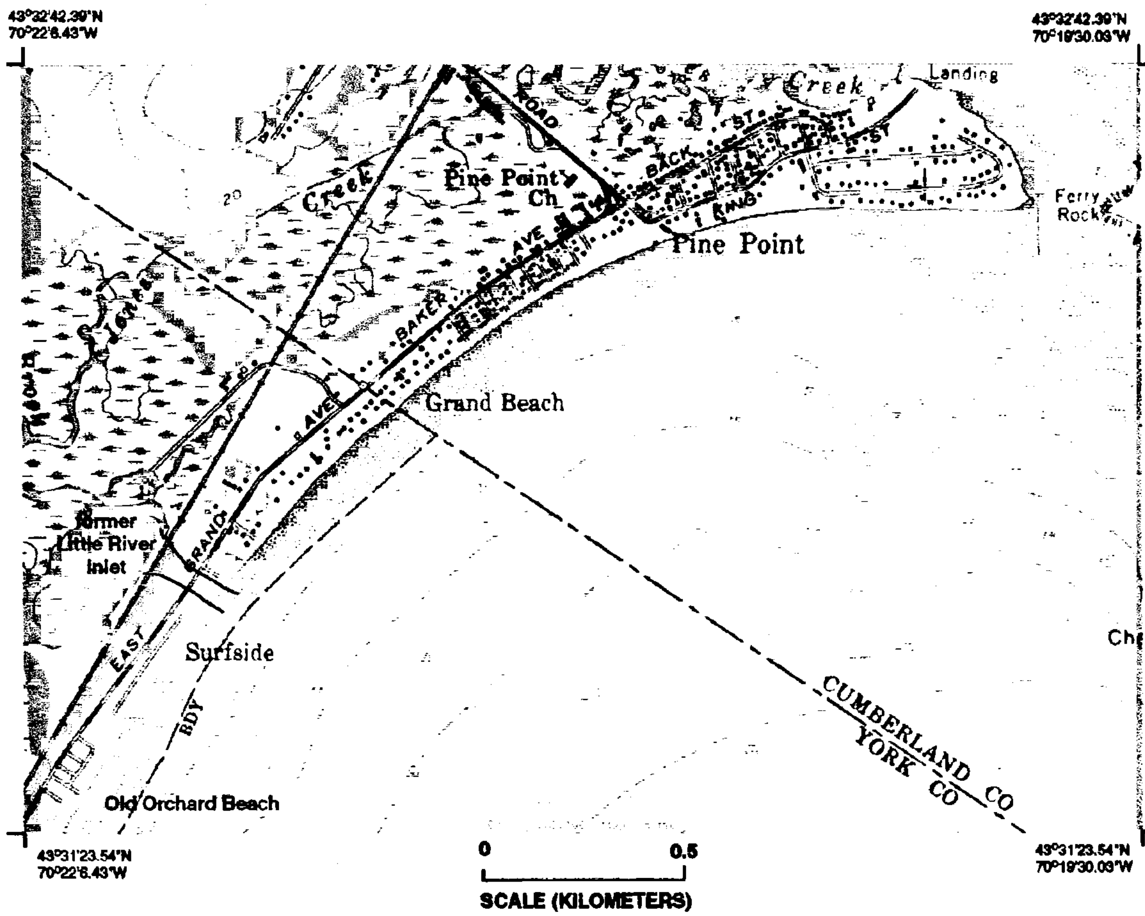


Figure 2.14. Location map of East Grand Beach. Modified from the USGS 7.5' topographic map of the Prouts Neck quadrangle (Maptech Inc. software, 1997).

River, Pine Point was a barrier island. It was possibly the only true barrier island in Maine (Nelson, 1979). The inlet closed shortly after a railroad causeway was constructed. The Saco River is the main source of sand to the beach, which travels north from the river mouth. Old Orchard beach currently appears relatively stable (Farrell, 1972), although shoreline retreat is likely as sea level continues to rise (Kelley *et al.*, 1995a).

Development status

Humans have greatly modified the natural environment of East Grand Beach. Houses, condominiums, motels and restaurants line the shore from Old Orchard to Grand Beach. These buildings sit on top of large volumes of buried sand that are remnants of ancient frontal dunes (Kelley *et al.*, 1989b). Five million cubic meters of sand, eroded from Camp Ellis, was added to Pine Point between 1867 and 1955 by longshore drift (Barber, 1995; Kelley *et al.*, 1995a; Kelley and Anderson, 2001).

Kinney Shores

Location

Kinney Shores, in York County, is a 1 km north-south trending barrier spit that terminates in the north at Goosefare Brook (Figure 2.15). Ferry Beach and the heavily eroding Camp Ellis Beach make up the remaining extent of the barrier to the south (Figure 1.1). Goosefare Brook has broad high-marsh meadows with extensive salt pannes. Lows in the glaciomarine sediment, which are ultimately controlled by bedrock,

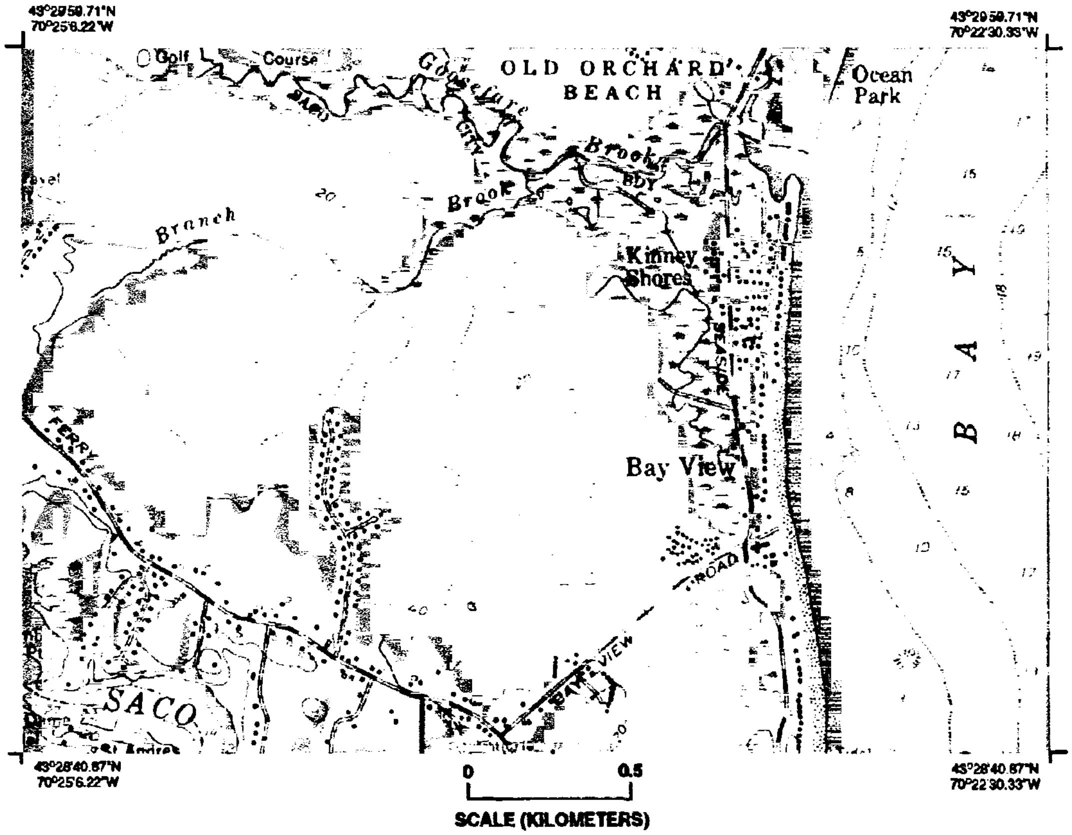


Figure 2.15. Location map of Kinney Shores. Modified from the USGS 7.5' topographic map of the Biddeford quadrangle (Maptech Inc. software, 1997).

stabilize the brook. Dunes and a pitch pine forest back the area to the west side of Route 9, covering a substantial barrier spit formed several thousand years ago.

Geological history

Relict spits in the Goosefare Brook marsh (Farrell, 1972; Kelley *et al.*, 1989c; 1995; vanHeteren *et al.*, 1996; Millette, 1997), represent sequential shoreline positions and a seaward progradation of the shoreline (Figure 2.16). Progradation requires input of sediment during the late Holocene. Aerial photos from 1970 show that the inlet was once located farther south (Farrell, 1972). In addition, seismic reflection profiles demonstrate inlet scars offshore of the present inlet that are preserved below a ravinement surface (Barber, 1995). The dynamic Goosefare Inlet is highly unstable and humans have greatly altered the area in recent years. The brook was the dumping spot for Old Orchard's treated sewage outfall until an offshore pipe was put under the beach in the 1990's. In addition, a bulkhead stabilized the inlet on its north end when a railroad trestle was built for easy access to the other side of the brook (Kelley *et al.*, 1989b).

Development status

Kinney Shores is heavily developed and the natural state of the area has been altered as a result of seawalls and houses. Residential development exists along the frontal dunes of the beach, eliminating the natural sand migration of the beach-dune system (Kelley *et al.*, 1989b). A 1978 storm caused extensive damage to the area, despite the seawalls intended to protect property (Kelley *et al.*, 1995c). The northern end, near Goosefare Brook, is the only area remaining undeveloped.

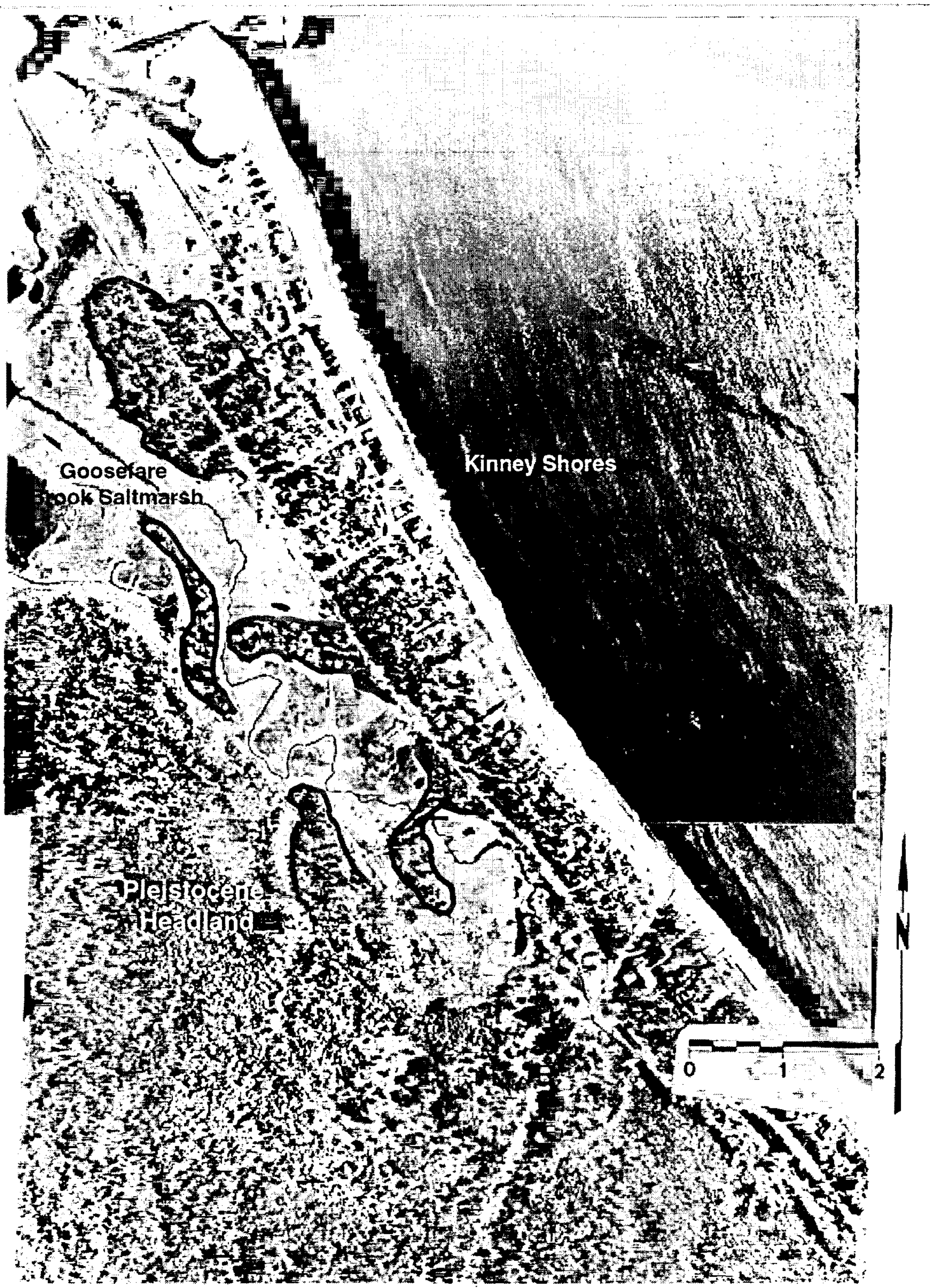


Figure 2.16. Paleospits in the Goosefare salt marsh, landward of the present Kinney Shores Beach (1966 aerial photograph from Farrell, 1972).

Biddeford Pool

Location

Biddeford Pool, Biddeford, consists of two transgressive barriers, over 10 km in length, connecting two bedrock headlands to the mainland (Figure 2.17). Hills Beach to the north and Fletcher Neck to the south, comprise the pair of supratidal tombolos that protect the embayment, or "The Pool", from the open ocean. The beaches along Biddeford Pool are generally rocky at the head of the system, while sandy beaches comprise the length of the two barriers. A sandy-muddy tidal flat, incised by a dendritic tidal creek system, creates the backbarrier environment (FitzGerald *et al.*, 1989; Hulmes, 1981).

Geological history

Hulmes (1981) concluded that Biddeford Pool was never an open-water environment. She interpreted its formation by the slow landward migration of barrier beaches. Flooding tides transported muds and sands through the inlet and washover deposits carried material across the barrier. The Saco River and glacial bluffs were sources of sediment to the region. Biddeford Pool has a fairly stable geomorphic configuration, although processes such as washover and the potential of inlet switching may cause changes to the shoreline (Kelley *et al.*, 1989b). Hulmes (1981) found Fletcher Neck was transgressive and estimated a shoreline retreat rate of 18 cm/yr based on the age of peat outcrops on the beachface. Hills Beach receives its sand from the Saco River, and very little, if any, is carried south around the point to Fletcher Neck.

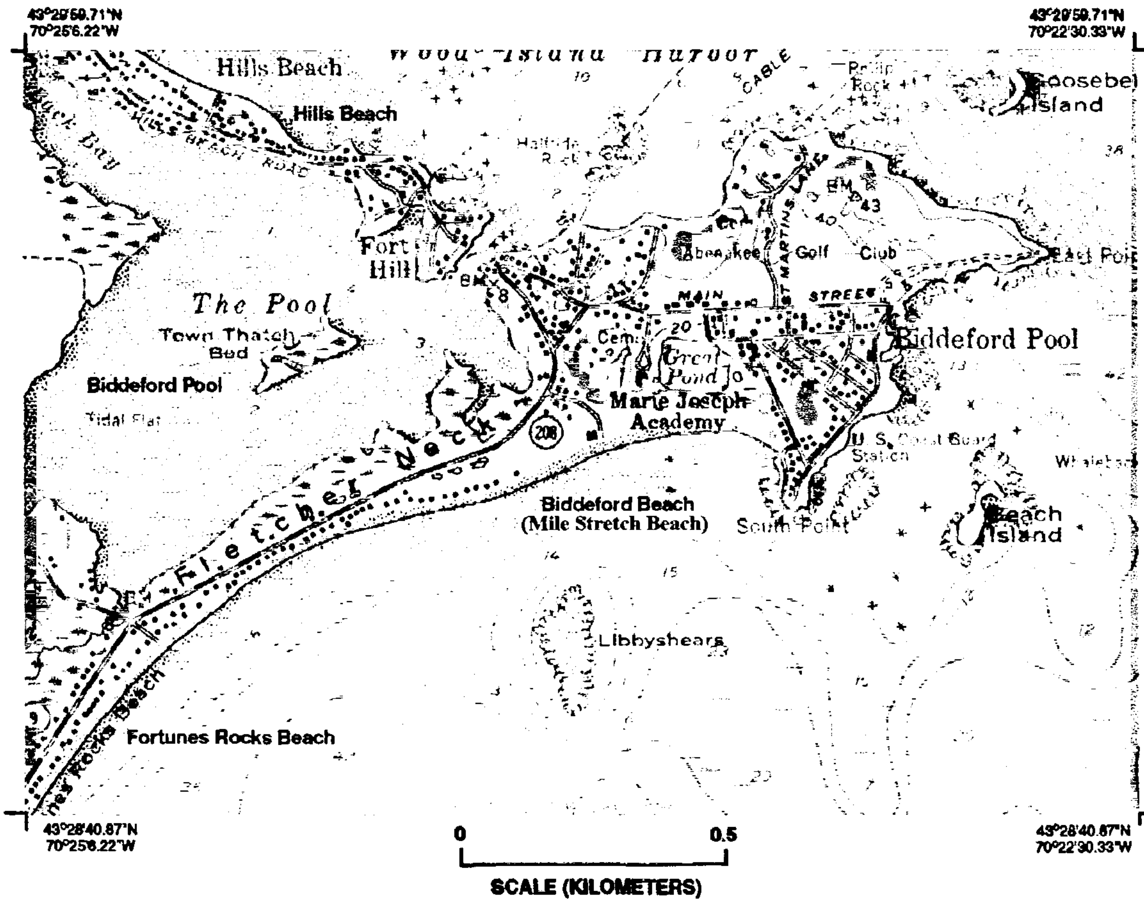


Figure 2.17. Location map of Biddeford Pool. Modified from the USGS 7.5' topographic map of the Biddeford Pool quadrangle (Maptech Inc. software, 1997).

Development status

Much of Biddeford Pool is highly developed. Houses line the frontal dune ridge along the western part of Fletcher Neck and Fortunes Rocks Beach. A seawall extends along most of the beach length to protect homes and property. Biddeford Beach (Mile Stretch Beach), at the eastern end of Fletcher Neck, is the only publicly accessible beach in the area, via a wooden bulkhead that cuts off the natural supply of sand to the dunes in this region (Kelley *et al.*, 1989b). There is a large amount of development along Hills Beach, too, although the southern Saco River jetty provides some protection from storm waves.

Wells Embayment

Location

Wells Embayment is the first major arcuate barrier/headland system north of New Hampshire (Figure 1.1 and 2.18). It is 50 km south of Portland in York County. Cape Arundel to the north, and Bald Head Cliff to the south, form the boundaries of Wells Embayment. The shoreline is less embayed than Saco, leaving it more exposed to incoming waves and storms than Saco Bay (Kelley *et al.*, 1993). The system consists of a series of barriers fronting extensive salt marshes and tidal creeks. Most of the barriers are pinned to bedrock outcrops and glacial deposits. Tidal inlets interrupt the series of barriers and spits that compose the Embayment. Exposures of bedrock, glacial drift, marine clay and cobble/boulder lag deposits commonly occur along the beaches.

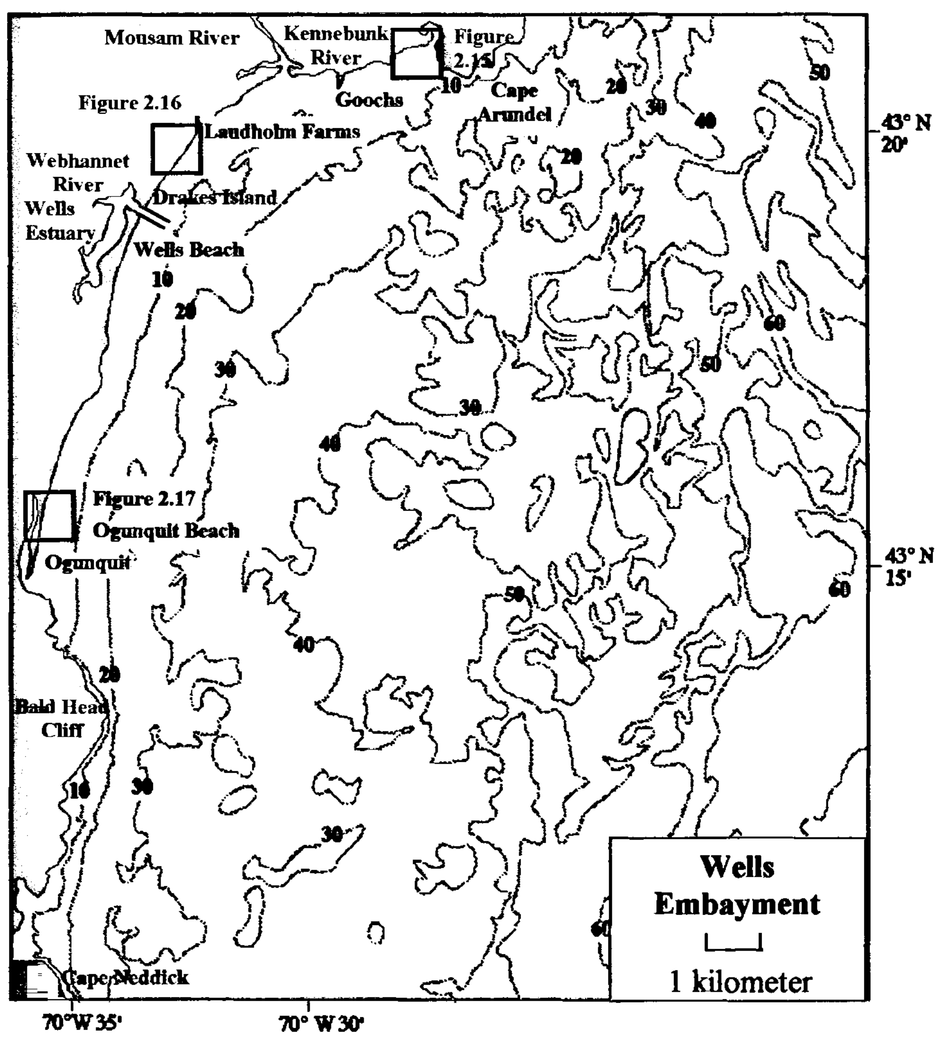


Figure 2.18. Location map, Wells Embayment, Maine. Boxes correspond to subsequent figures. Isobaths are in meters.

Geological history

Hussey (1970) developed the first model of the evolution of the Wells Barriers. Although the model was a reasonable evolutionary account for the beaches in the area, Hussey used a sea-level curve from Boston because a complete curve from Maine did not exist. As a result of the differences between the sea-level histories from the two regions, there are problems with his model. Montello *et al.* (1992a; 1992b) have since proposed a new model for Wells using a newer sea-level curve. Kelley *et al.* (1995c) and Gehrels *et al.* (1996) used radiocarbon dates from salt marsh plants to reconstruct the history of sea-level rise and marsh formation at Wells.

Following deposition of the glacial-marine Presumpscot Formation and isostatic rebound of the land as the ice retreated, a sea-level lowstand resulted in the deposition of regressive shorelines and littoral sediments (Shipp *et al.*, 1991; Kelley *et al.*, 1995c). The Webhannet and Little Rivers cut into Pleistocene material and deposited sediment on top of the Presumpscot Formation as base level fell. Because the rivers in Wells Embayment had small drainages and could not support large amounts of sediment, eroding glacial headlands were the primary source of sediment to barriers (Kelley *et al.*, 1995c). The eroded remnants of these barriers remain on the inner continental shelf (Miller, 1998). The barriers shifted landward as the glacigenic sources were depleted.

As sea level rose, the barriers migrated landward, mixing with reworked glacial sediment. The landward moving barriers incorporated the glacial deposits, and were periodically pinned to bedrock highs. Radiocarbon dates show that the barriers reached near the present day location between 5 and 4 ka (Hussey, 1959). The Webhannet Estuary was colonized by high marsh, higher high marsh and/or freshwater marshes around 5 ka (Belknap *et al.*, 1989). By about 3 ka, marsh/tidal flats transformed the backbarrier environment and the barriers migrated a short distance onshore to their present location. Eroding glacigenic deposits provided material for the colonization of low marsh (Kelley *et al.*, 1995c).

Human interference

Wells Embayment also hosts one of the largest sand beach and marsh systems in northern New England (Kelley *et al.*, 1989a). The area is an important popular summer resort; beaches provide job opportunities and local businesses depend on tourism (Montello *et a*l., 1992a). Many segments along Wells Embayment are developed. Seawalls and riprap protect private homes and businesses, and sewer and water lines run through the town dunes.

Coastal engineering structures also contribute to changing barrier dynamics. Historically, the Wells estuary was important to the local community as a harbor, in addition to being a source for salt hay, shellfish, fish and waterfowl (Kelley and Anderson, 2001). Prior to World War II, there was little industrial development along the coast. Soon after the war, however, it became apparent to many citizens that the harbor needed to be expanded and navigation through the inlet improved. It was important for large fishing boats to be able to anchor safely and travel efficiently through the inlet. In 1961, the USACOE began building jetties at the mouth of the Webhannet River to prevent sand from moving into the navigation channel (Kelley and Anderson, 2001). Although the USACOE dredged the harbor while building the jetties, shoaling remained a problem.

The USACOE continued to dredge the harbor and extend the jetties in an attempt to keep the harbor open and free from significant amounts of sand. The jetties block the free transport of sediment along the beach, however, and the sand has accumulated on both sides of the structures (Kelley and Anderson, 2001). Because of the shadow effect of the jetties, waves coming from different approach directions cannot transport sand back to the end of the beaches. A recent proposal allowed the USACOE to dredge part of the harbor again in the fall of 2000 (Kelley and Anderson, 2001). They placed dredged sand on the adjacent beaches that were losing sediment. Topographic profiles show that this sediment is presently being eroded from the beach (Dickson and Marvinney, 2001).

Goochs Beach

Location

The east-west trending Goochs Beach is a 1300 m long barrier (Nelson and Fink, 1980), located at the mouth of the Kennebunk River in Kennebunk (Figure 2.19). Oakes Neck, a bedrock headland, forms the western boundary, while the spit terminates at Old Fort Point, a second headland. An extensive marsh system and tidal flat create the back barrier environment of Goochs Beach.

Geological history

During the summer of 1956, tree stumps were found on nearby Kennebunk Beach. Radiocarbon dating of these stumps indicated that a lower sea level prevailed prior to approximately 3 ka (Hussey, 1959). Basal peats are commonly exposed on the beachface, especially during times of low tide following a storm (Mills, 1997). This

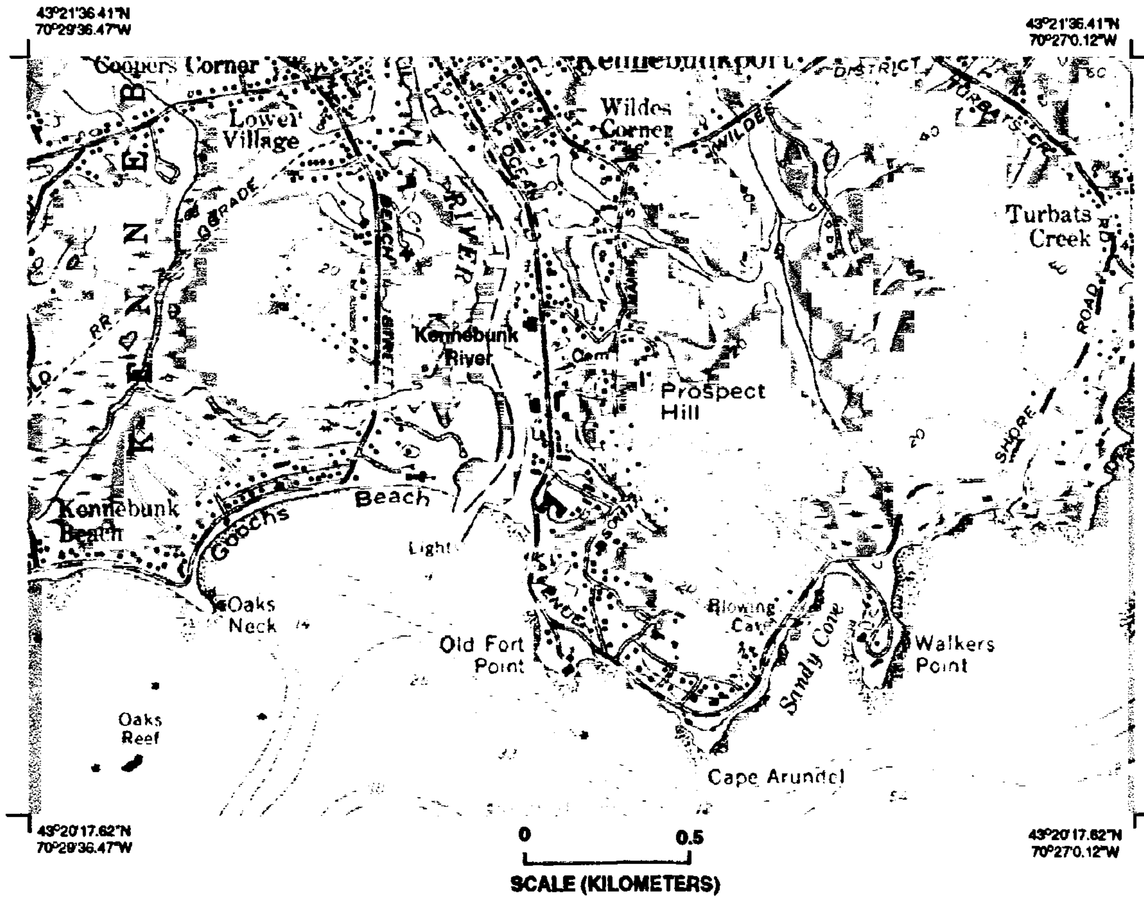


Figure 2.19. Location map of Goochs Beach. Modified from the USGS 7.5' topographic map of the Kennebunkport quadrangle (Maptech Inc. software, 1997).

indicates that the barrier has transgressed over an ancient marsh. Peat deposits are lacking along the beachface and at depth near the Kennebunk River. This suggests that 1) the barrier has not rolled over itself completely at this point, or 2) the Kennebunk River has historically eroded its banks to an extent that it removed barrier sands and peat deposits (Mills, 1997). The Kennebunk River Inlet had a distinct ebb-tidal delta before elimination by the construction of a 400 m jetty. Goochs Beach experienced accretion following jetty construction, although it is probable that some of the accretion is attributable to erosion of the ebb delta (FitzGerald *et al.*, 1989).

Development status

The western two-thirds of Goochs Beach is more heavily developed than the eastern one-third. A 10-foot high seawall runs along the length of the beach, protecting the road and houses. The seawall has failed repeatedly in the past, making the landward areas dangerous during extreme storms. Because parts of the beach are somewhat rocky, artificial nourishment may be the only solution to return sand to the area (Kelley *et al.*, 1989b).

Laudholm Beach

Location

The 2 km Laudholm Beach/Drakes Island barrier complex (Nelson, 1979) in Wells, extends northeast from the Webhannet River to the Little River (Figure 1.1 and 2.20). Laudholm Beach is the undeveloped northeast extension of Drakes Island. The beach terminates in the Laudholm spit, which forms a double spit with Crescent Surf on

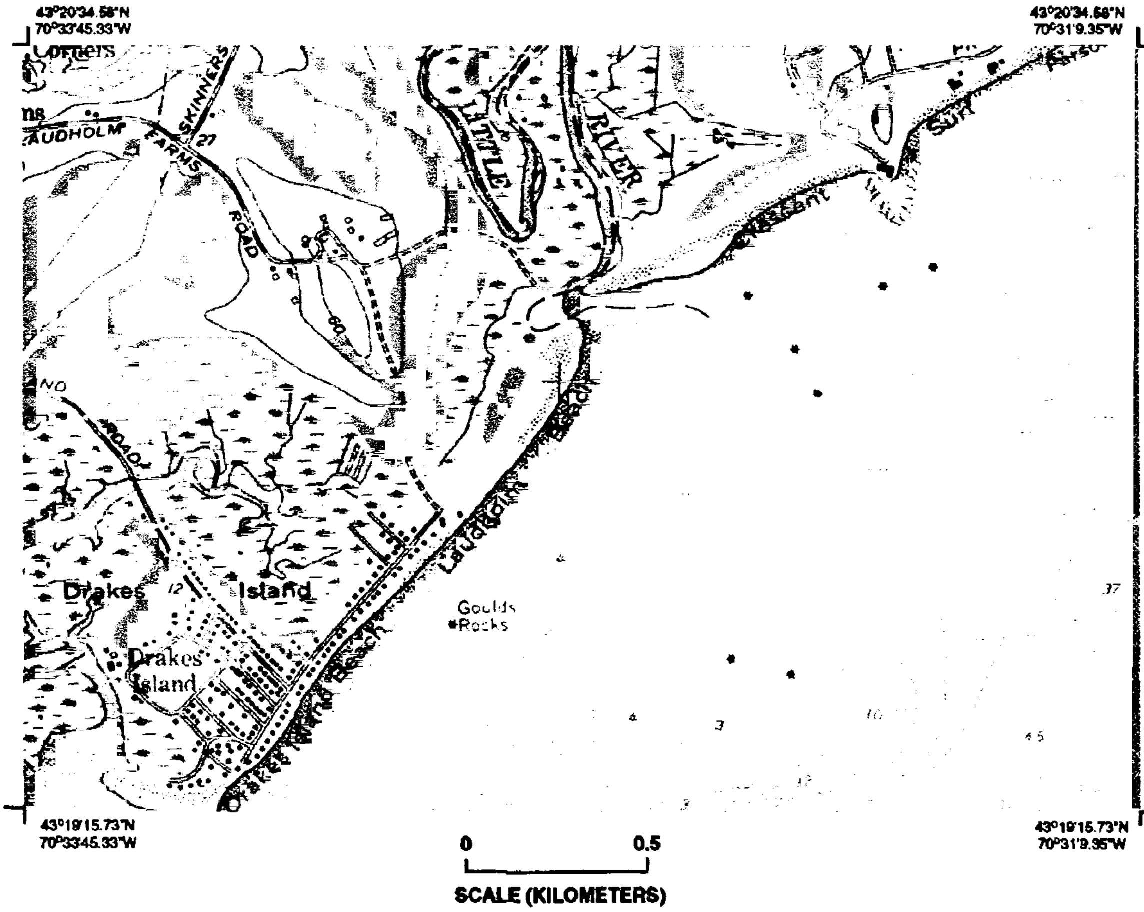


Figure 2.20. Location map of Laudholm Beach. Modified from the USGS 7.5' topographic map of the Wells quadrangle (Maptech Inc software, 1997).

the north side of the Little River. The Little River is a tidal reentrant with an extensive back-barrier salt marsh. It is one of the few barrier complexes in Maine remaining in a natural state (Nelson and Fink, 1980), because Laudholm Trust, the Rachael Carson National Wildlife Refuge, and the State of Maine protect the beach.

Geological history

Patches of gravel, cobble, and boulders on the low-tide terrace of Laudholm Beach are remains of small till mounds, deposited about 13 ka (Kelley *et al.*, 1995b). Peat exposed on the shoreface during the winter indicates that the beach has migrated landward over time, as a result of the rising level of the sea (Hussey, 1959). Relict frontal dune ridges are visible behind the present shoreline, indicating that the spit end is historically unstable. The spit is possibly extending into the Little River as a result of longshore sediment transport.

Development status

Although Drakes Island is highly developed, Laudholm Beach is still in a natural state. The area is well vegetated with species such as American beach grass, beach pea, beach heather and a climax pitch pine forest (Nelson, 1979). A typical beach profile from this area shows distinct geomorphic features. Different grain sizes distinctly define a berm, beachface and low-tide terrace. Overwash is a natural process that occurs on Laudholm Beach, as evidenced by gravel, wood, flotsam and debris, on top of and behind the dunes. The Maine Department of Conservation and the Wells National Estuarine Reserve manage the beach and its low level of development qualify it as part of the

Crescent Surf Coastal Barrier Resources System (Maine Geological Survey, 2001; National Fish and Wildlife Services, 2001).

Ogunquit Beach

Location

Ogunquit Beach, located in York County, is a 2,300 m long (Nelson, 1979) barrier oriented north-south (Figure 2.21). Moody Beach to the north and Ogunquit Beach comprise one of the longest continuous barrier spits in Maine. The spit terminates in the Ogunquit River Inlet, which abuts a bedrock headland. The ebb-tidal delta of the inlet is poorly developed, while the flood delta has multiple subdivisions and is well developed (FitzGerald *et al.*, 1989). Wide meandering tidal channels, a flood tidal delta and intertidal reentrant sands occupy the back-barrier environment (Figure 2.18). There is also an extensive salt marsh system. Seaward of the beach lies a 12 million m^3 deposit of sand off Bald Head Cliff (Miller, 1998; Kelley *et al.*, 2001).

Geological history

The Ogunquit spit most likely formed with transgression of the sea over a coastal lowland of glacial moraines (Nelson and Fink, 1980). The spit prograded into the inlet as a result of a net southerly longshore transport of sand. In its present location, sand that reaches the inlet, circulates in a counterclockwise gyre, and is deposited both in the ebb and flood-tidal deltas (Figure 2.22) (FitzGerald *et al.*, 1989; 1983; Lincoln and FitzGerald, 1988). In 1974 the flood tidal delta was mined of its sand, which was used for construction of an artificial dune to protect a sewage treatment plant. One year later,

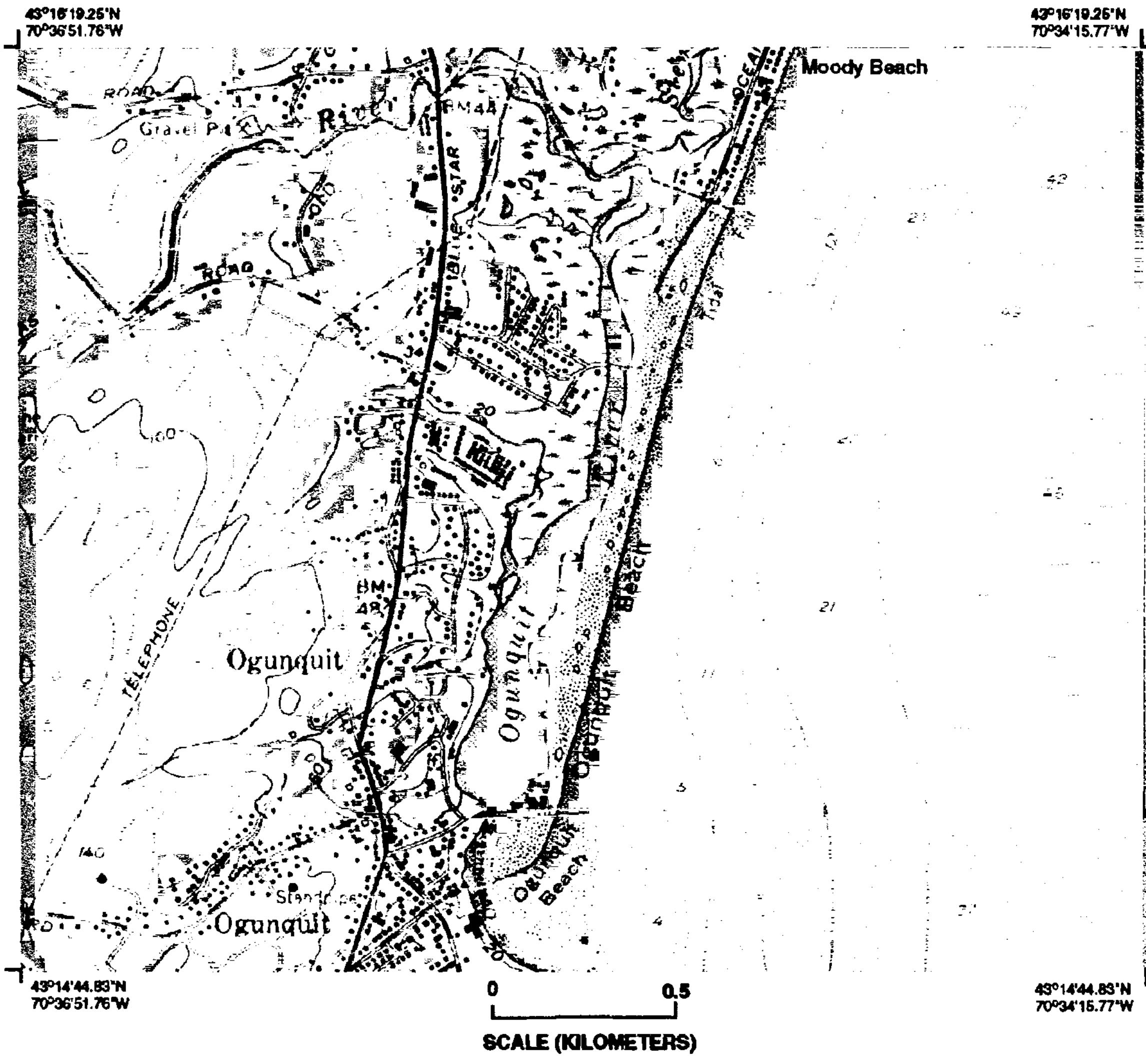


Figure 2.21. Location map of Ogunquit Beach. Modified from the USGS 7.5' topographic map of the Wells and York Beach quadrangles (Maptech Inc. software, 1997).

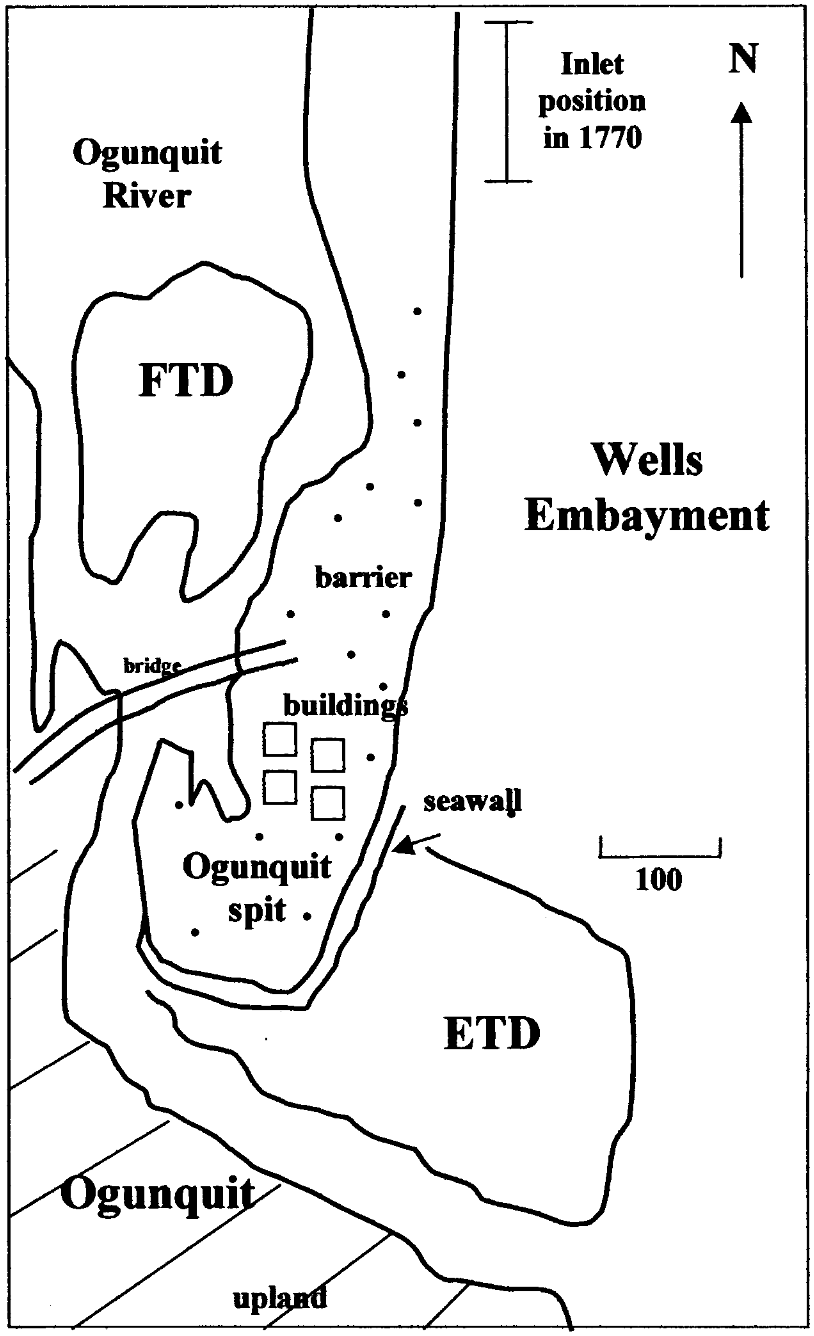


Figure 2.22. Sketch map of the Ogunquit barrier spit. FTD represents the flood-tidal delta. ETD represents the ebb-tidal delta.

the delta had reformed to its original shape and size, indicating that landward transport of sediment was dominant (FitzGerald *et al.*, 1989). The Ogunquit River Inlet naturally shifted to a new location in the past 200 years; an old inlet existed north of the present inlet on a 1785 British map (Figure 2.22).

Development status

Although Ogunquit Beach's dune was built to protect the sewage plant at its north, the dunes do not offer long term stability and protection for the plant. Between the sewage plant and the Norseman Motel to the south, the beach is extensively vegetated. A riprap revetment and a seawall protecting a parking lot stabilize the spit end. Property located near the Norseman is armored, and therefore, less impacted by storms than the sand dunes. Nelson and Fink (1980) cite Ogunquit Beach as a classic example of a beach with a distinct summer vs. winter profile.

MODERN PROCESSES

Coastal Oceanography

Significant sediment transport occurs in the shoreface as a result of an interplay between various oceanographic forces, including winds, waves, tides and storm surge. During coastal storms, waves and currents generally remove sand from the beach and surf zone and transport it seaward, depositing it on the upper shoreface, while fair-weather wave processes return the material to the surf zone and beach during non-storm intervals (Niedoroda and Swift, 1981; Wright *et al.*, 1994). However, storms are also responsible for reworking sediment onto the beach and rebuilding it (Dickson, 1999). This section reviews coastal oceanography, with emphasis on components that are important to sediment transport and erosion/accretion cycles on the beach.

Annual Wave Climate

A southerly-southeasterly wave approach prevails in the Gulf of Maine, and there is a distinct seasonal difference in wave period and significant wave height (Belknap *et al.*, 1988; Jensen, 1983) (Figure 2.23). Using wind data to hindcast waves, Jensen (1983) determined a mean annual wave height of 0.3- 0.5 m for Cape Small, Maine. Belknap *et al* (1988) determined a value of 1.13 m from SSMO (Summary of Synoptic Meteorological Observations) observational data in the central Gulf of Maine. This latter value is closer to the mean annual wave height range of 0.6-1.2 m, determined from the NOAA Portland Buoy 44007 (NOAA, 2001). Average monthly wave heights are greatest during February, March, November, and December, and lowest in August

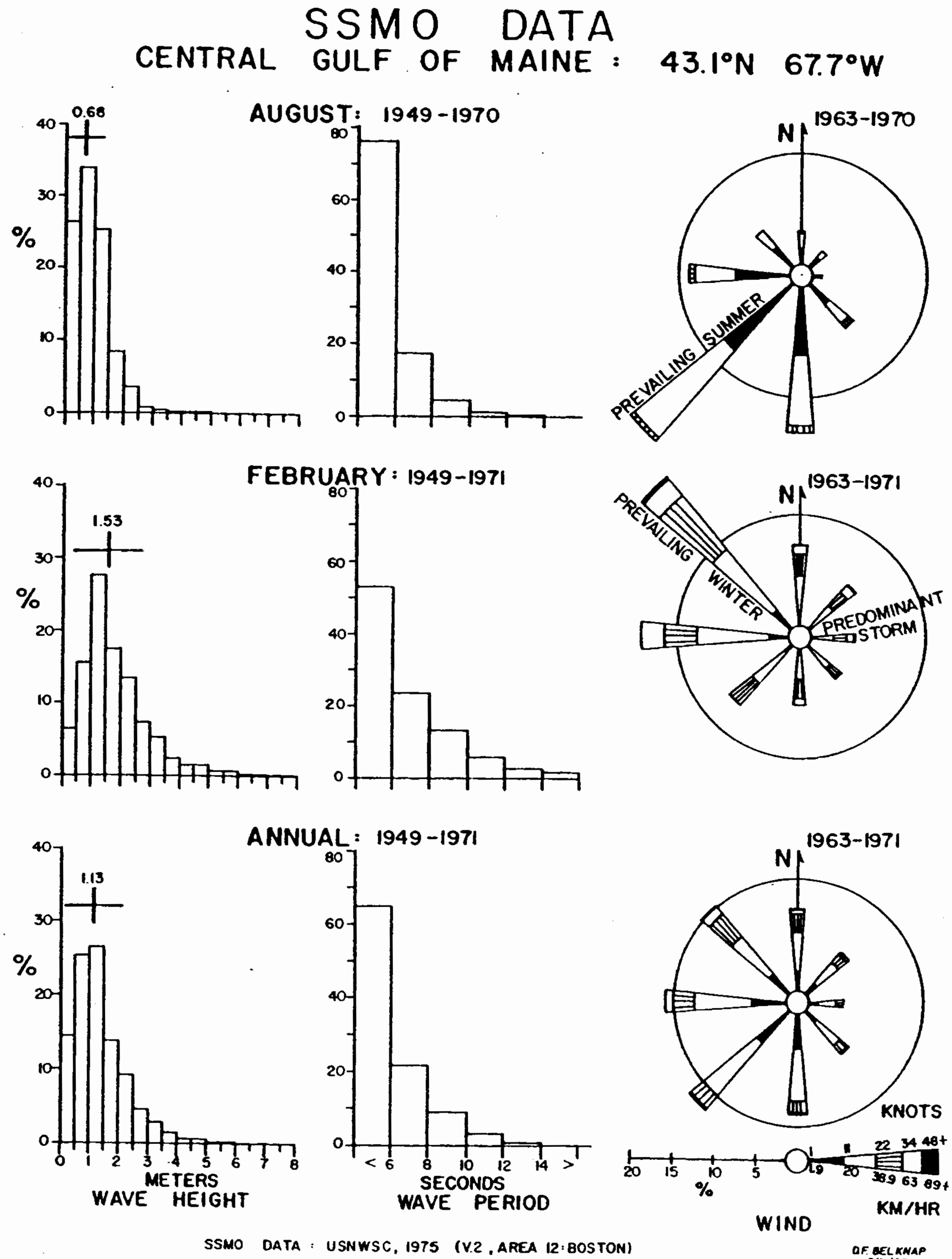


Figure 2.23. Rose diagrams of winds, histograms of wave heights and periods for central Gulf of Maine. Compiled from Summary of Synoptic Meteorological Observations (SSMO) data (from Belknap *et al.*, 1988).

(Jensen, 1983). Belknap *et al.* (1988) determined a 1.53 m average wave height during February and a 0.68 m wave height for August.

Waves are an important component of sediment transport. Swells often continue after storm winds have passed, transporting sediment for hours to days (Swift *et al.*, 1985). Swells also result from distant offshore storms, particularly in the summer when the waves combine with wind-driven upwelling to induce landward sand transport (Dickson, 1999).

Waves undergo a shoaling transformation as they approach the shoreface. The orbital paths near the bottom begin to develop an asymmetry, described by Stokes wave theory, which results in a forward stroke that is of shorter duration and faster velocity than the backward movement (Komar, 1998, p.169). Onshore sediment transport occurs until the shoreface steepens to a null point where gravity counteracts the upslope movement.

The abrupt change in grain sorting in 27 m (70 ft) water depth is indicative of the influence of shoaling waves on sediment texture in Saco Bay (Farrell, 1972). This change in grain size also demonstrates the effective wave base, or depth to which wave-generated bottom currents can move sediment. Waves from northeast storms with a 6-8 second period are capable of generating 30 cm/sec bottom currents at this depth. These bottom currents can entrain sand with a grain size of 3.4 phi (Farrell, 1972).

Wave Refraction

The orientation of many of Maine's barriers is a result of nearshore wave refraction. Once a wave enters intermediate to shallow water, the depth decrease slows the rate of advance of the wave, resulting in the rotation of the wave crests with respect to the depth contours (Komar, 1998). Wave refraction is proportional to the water depth and the wave length of Airy waves, where water depths are generally defined as:

Deep water	$h/L_{\infty} > 1/4$
Intermediate water	$1/4 > h/L_{\infty} > 1/20$
Shallow water	$h/L_{\infty} < 1/20$

where h is the water depth and L_{∞} is the deep-water wave length. Because of refraction, wave energy is dissipated in embayments, like Saco Bay, and concentrated on headlands, like Prouts Neck (Komar, 1998) (Figure 2.8).

Short, locally-generated waves do not usually undergo significant refraction, while long-period swells refract strongly, resulting in a perpendicular wave approach (Davies, 1973). Through wave refraction models of the Kennebec Paleodelta, Robbins (1992) found that as a wave approaches a bathymetric high, the wave height will increase. In addition, for a given wave height longer wave periods result in two general trends: 1) waves are influenced by the seafloor at greater depths and 2) elongated contour patterns of wave height become smaller and break up into numerous cells (regions of increasing and reduced wave height are smaller in area) (Robbins, 1992). This is true regardless of the wave approach direction.

Wave-ray paths in Saco Bay are very sensitive to refraction around bedrock headlands, offshore shoals, and islands (Figure 2.24) (Farrell, 1972). Waves of different

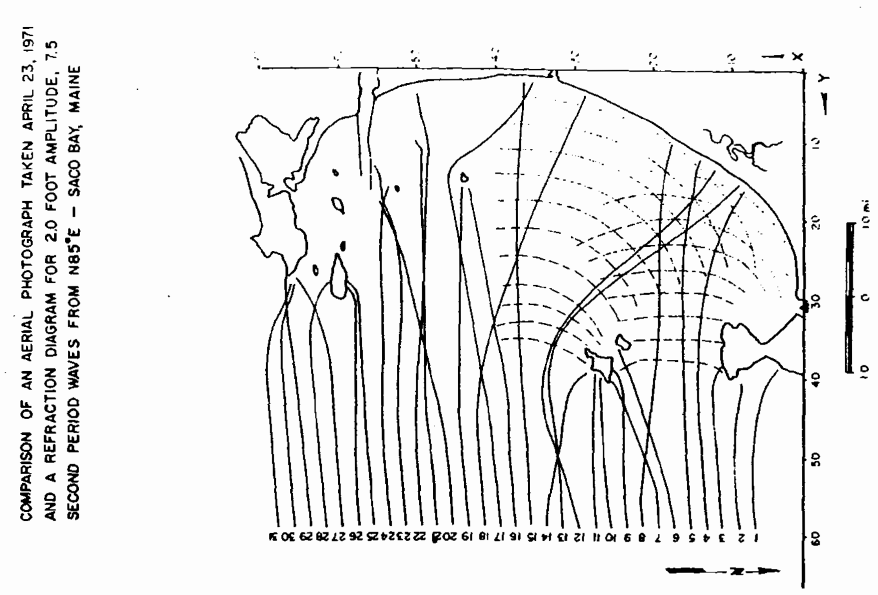


Figure 2.24. Aerial photograph and wave-refraction diagram for 2-foot, 7.5 second period waves from N 85° E, Saco Bay, Maine (Farrell, 1972).

periods and heights refract differently through the bay. Bottom topography and offshore islands influence long period waves and only a small percentage of waves (16%) directly strike the beach without undergoing a change in propagation direction. Most shoreface processes in Saco Bay result from 4-5 second period waves, which are more common, less refracted, and strike the beach more often than longer period waves (Farrell, 1972).

Wave refraction models in Wells Embayment have focused on the Wells Harbor entrance (Figure 2.25), rather than the entire embayment (Byrne and Zeigler, 1977). Predictions from the model and daily observations over a 10-month period showed that most large waves arrived within +/- 10° of the channel regardless of incident wave direction. In general, the wave approach at the harbor entrance was dominately from the south-southeast, or 45° to the south of the channel. In comparison, no waves with angles greater than 20° from the north (112.5°) arrive.

Swash vs. Drift Aligned Beaches

The plan view of a beach reflects the dominant wave-approach direction. Drift-aligned coasts are those affected by obliquely approaching waves that produce a predominant longshore drift (Figure 2.26a) (Davies, 1973). The beach is built parallel to the line of maximum drift, which is between 40 and 50 degrees to the direction of wave approach. If the angle of the approaching wave crest increases, there is less deposition and the alignment is restored. If the angle of approach decreases in obliquity, causing deposition, swash alignment occurs. In contrast to drift-aligned, swash-aligned beaches are built parallel to the crests of waves approaching perpendicular to the shore (Figure 2.26b). The beaches in the study area are both swash and drift-aligned.

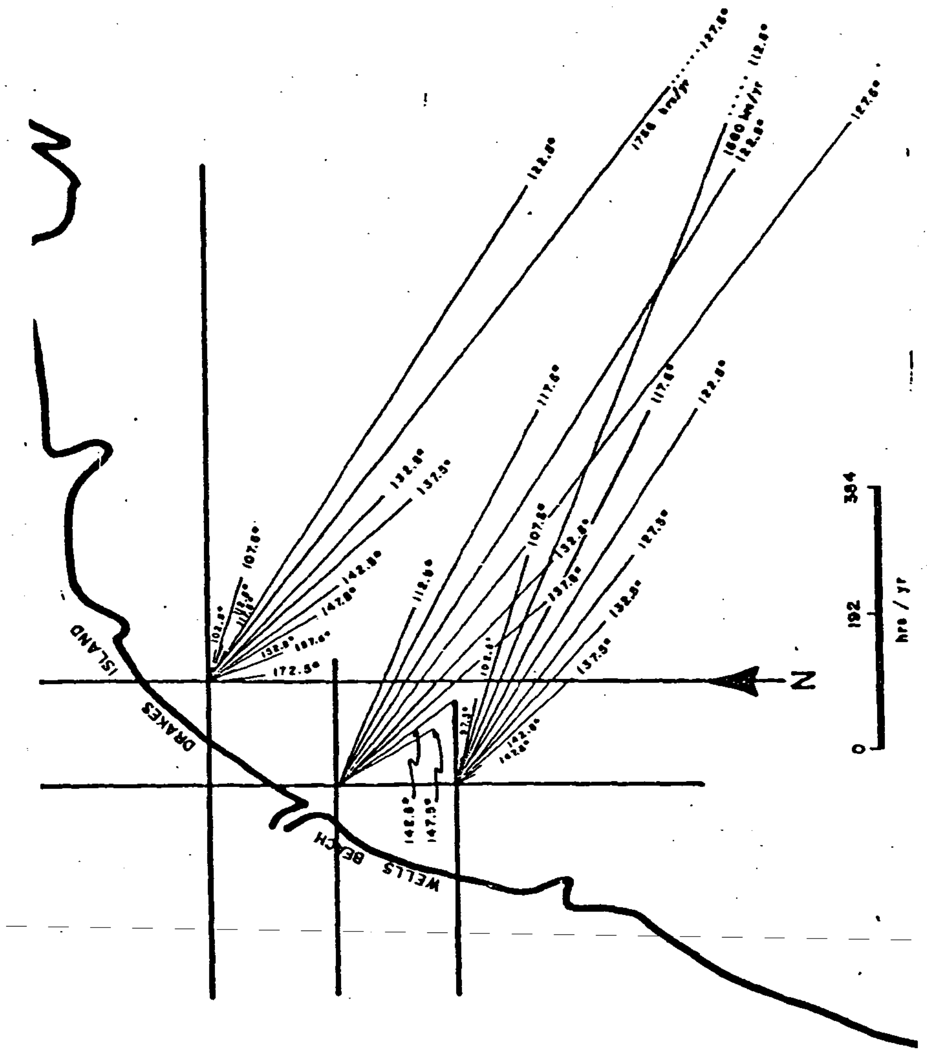


Figure 2.25. Duration of refracted waves greater than 2 feet as a function of angle of approach at the Wells Harbor, Wells, Maine (Byrne and Zeigler, 1977).

This results primarily from the orientation of incoming waves, in addition to refraction of these waves around headlands, islands and shoals in the area (Farrell, 1972; Byrne and Zeigler, 1977; Kelley *et al.*, 1995a), particularly in Saco Bay.

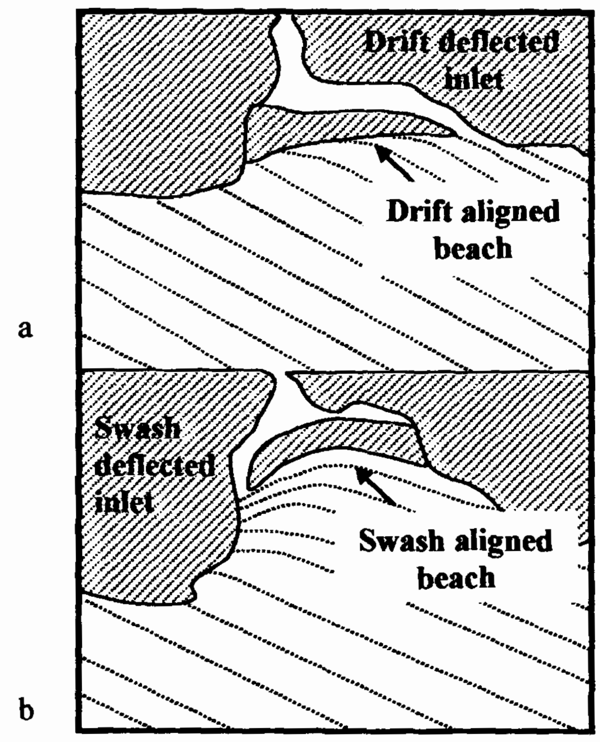


Figure 2.26. Comparison between drift and swash aligned beaches (Davies, 1973)
a. consistent wave approach direction on straight coast, b. strongly refracted waves in embayments.

The relationship between incoming waves and longshore currents results from the combination of the onshore directed radiation stress (S_{xx}) and the longshore directed radiation stress (S_{yy}) (Komar, 1998). These two stresses combine to yield:

$$S_{xy} = En \sin\alpha \cos\alpha \quad \text{(Komar, 1998, eq. 8.9a, p. 351)}$$

where E is the wave-energy density, n is the ratio of the wave group and phase velocities, and α is the angle the wave crests make with the shoreline. The maximum longshore currents occur when the wave ray approaches at a $45°$ or $135°$ angle.

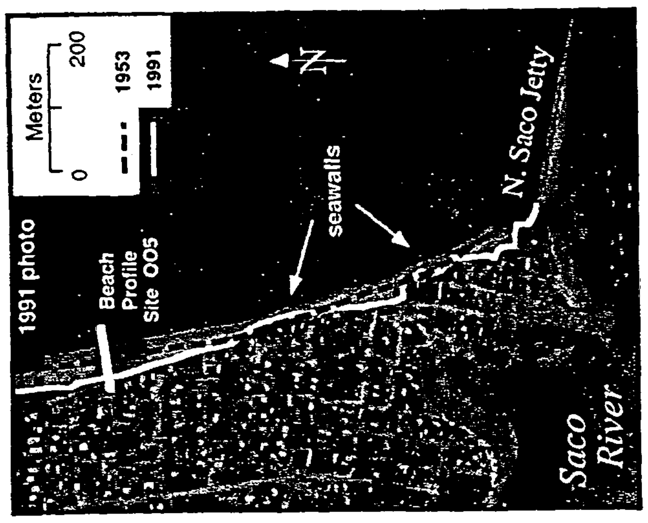
Longshore Sediment Transport in Saco Bay

There is significant evidence indicating that the sediment in Saco Bay is primarily transported alongshore to the north today. The clearest observation is that Pine Point, at the northern end of the bay, has been growing seaward and eastward into the Scarborough River inlet, while Camp Ellis at the southern end has been eroding (Figure 2.27) (Kelley *et al.*, 1995a). Local homeowners observed this longshore movement when dredged material from the Saco River harbor was placed on Camp Ellis and it moved north. In addition, historical air photos and beach profiles depict the erosion of Camp Ellis and concommittant growth of Pine Point.

Paleospits in the Goosefare salt marsh (Figure 2.16) also indicate transport to the north (Farrell, 1972; Kelley *et al*, 1995a; Millette, 1997). These paleospits show that sediment was derived from the Saco River. In addition, from 1871-1877, the Little River tidal inlet (Figure 2.8) may have closed because of a large volume of sediment introduced to the system. Additional indicators of transport direction include Saco River side-scan sonar images of bedforms and a fining of grain size down estuary, along the beach, and in the nearshore (Kelley *et al.*, 1995a).

Although the dominant transport is to the north, this direction can be reversed under the proper conditions. Spits at Camp Ellis and Goosefare imply some southerly

Camp Ellis



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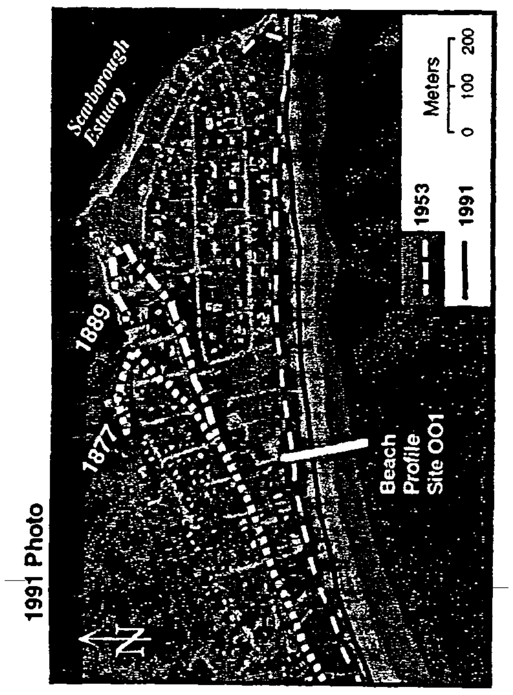
Pine Point



A

Figure 2.27. Changes in the shoreline positions of Pine Point and Camp Ellis (Kelley *et al.*, 1995a). See Figure 1.1 for locations.

directed transport. This southerly direction may result from the dominance of east-northeast storms in the winter that are responsible for significant sediment movement . In addition, refraction within the bay, around islands, shoals and tidal deltas, may result in a temporary reversal of flow direction.

Longshore Sediment Transport in Wells Embayment

The impoundment of sand on both sides of the Wells jetties shows that longshore transport moves sand to both the north and south within Wells Embayment (Figure 2.28) (Byrne and Zeigler, 1977). During the late spring to early fall, the northerly transport is slightly greater and is driven by southwest winds (Montello *et al.*, 1992a). During the late fall and winter, northeast winds produce a net southerly transport direction. Byrne and Zeigler (1977) estimated that impounded sand along the entrance to the harbor shows 27,000 to 42,000 m^3/yr of sand moves to the north, while 13,000 to 27,000 m^3/yr moves to the south. This yields a net northerly transport of approximately 14,000 m^3/yr in this region for the time period of jetty construction and inlet dredging (1962-1974).

Additional factors indicating longshore sediment transport within Wells Embayment include north and south prograding spits (Kelley *et al.*, 1993). For example, Lincoln and FitzGerald (1988) found evidence supporting a dominant net local southerly longshore transport along Ogunquit Beach. In addition, a 12 million m^3 sand deposit off Bald Head cliff (Miller, 1998) is possibly a result of southerly longshore transport. Nearshore lag deposits suggest that till at Moody Beach, Drakes Island and Great Hill supplied sediment to the longshore transport system (Hussey, 1970).

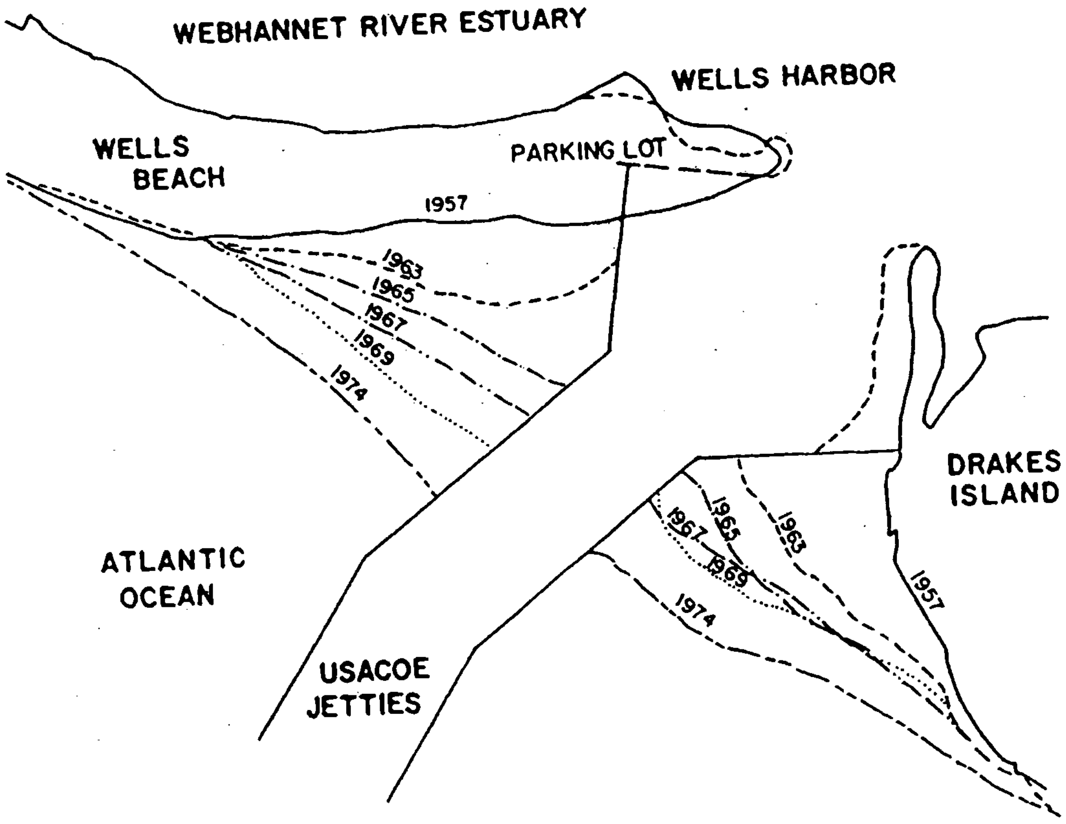


Figure 2.28. Shoreline changes at Wells Inlet (Kelley and Anderson, 2001)

Winds

The prevailing winds affecting the Gulf of Maine vary seasonally (Belknap *et al.*, 1988; Nelson and Fink, 1980) (Figure 2.23). South-southwest winds dominate in the summer, producing low-energy wave conditions and swells. These winds produce waves that can also induce longshore transport of sand (Nelson and Fink, 1980). In contrast, the beaches experience northwest winds during the fall and winter. Northwest winds blow offshore, flattening incoming waves and enhancing the onshore transport of sand (Dickson, 1999). The strongest winds produce winter storms, such as Northeasters, that create heavy surf conditions from the east and northeast. These storm winds are often responsible for significant erosional events (Nelson and Fink, 1980).

Cross-shore bottom flow often develops during coastal storms. Winds that have a dominant onshore component will produce a sea surface set-up against the shoreline and a horizontal pressure gradient force that opposes the surface currents. This pressure difference causes bottom currents to flow offshore, creating a circulation pattern referred to as downwelling (Figure 2.29) (Niedoroda *et al.*, 1985; Swift *et al.*, 1985). In contrast, winds that have a dominant offshore component produce a sea surface set-down and onshore flow at the bottom, or an upwelling circulation pattern (Niedoroda *et al.*, 1985; Swift *et al.*, 1985). Often, storms produce a shift in the wind direction as the storm center passes a coastal site, creating both upwelling and downwelling circulation patterns. The net sediment movement is dictated by the energy and duration of the circulation pattern, as well as the shoreface bathymetry (Figure 2.29) (Niedoroda *et al.*, 1984).

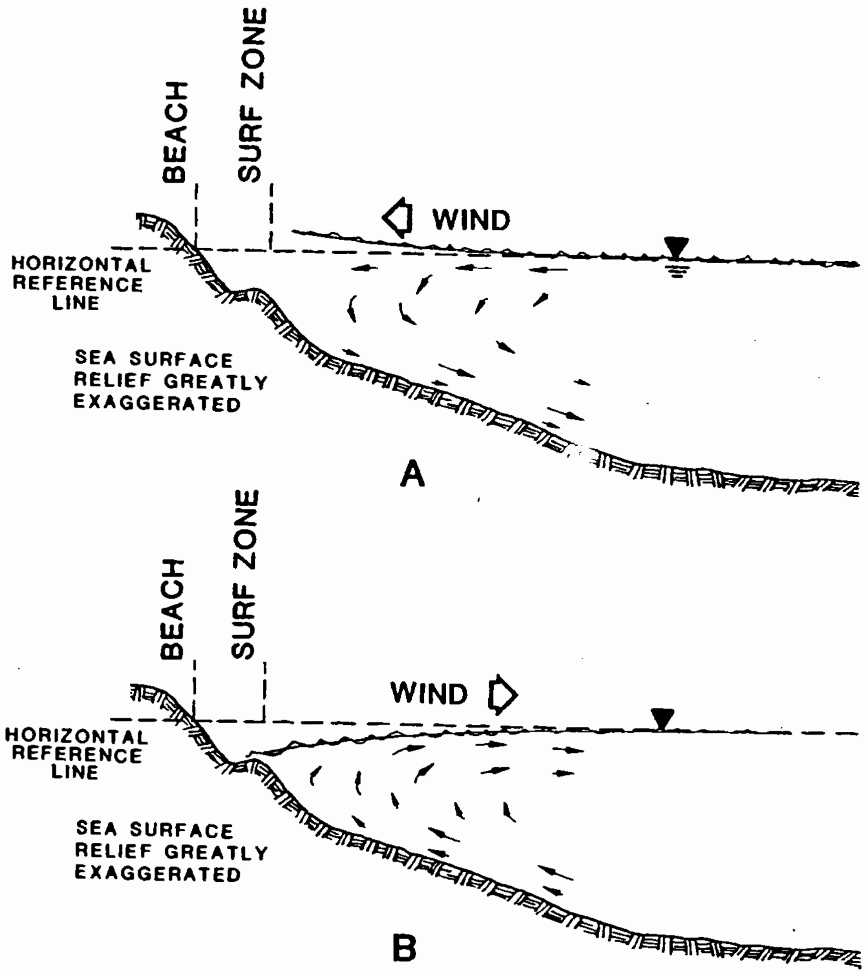


Figure 2.29. Shore-normal and vertical current components in the friction dominated zone. a. onshore winds create downwelling and sediment transport away from the shore and b. offshore winds create upwelling and sediment movement towards the shore. Sea level distortions have been greatly exaggerated (Niedoroda *et al.*, 1985).

Tides

Southern Maine has a mixed energy, tide-dominated shoreline (Figure 2.30) (Hayes, 1979). Tides in Maine are semidiurnal and increase along the coast from 2 m in the southwest to greater than 6.5 m in the northeast (NOS, 2001). The spring range is 3.1 m just north of the study area. If a coastal Maine storm persists for several days during periods of extreme astronomical high tides, it may cause severe coastal flooding and dune erosion. If the storm peaks during low tides and travels rapidly away from the region, beach erosion is minimal.

Tidal currents tend to vary over a tidal cycle in an elliptical pattern that is highly dependent upon the tidal phase and orientation relative to the coastline. Current meters located near the study area, offshore of Cape Porpoise (43°13.2'N, 70°16.8'W), recorded depth-averaged tidal currents of less than 6 cm/s (Brown, 1984). A counterclockwise rotary current ellipse constructed from the data had a major:minor axis ratio of 4:2, with the orientation of the major axis at 348° (Brown, 1984).

Tidal currents acting over the shoreface seldom have the speed to cause sediment transport without combining with other forces (Niedoroda, *et al.*, 1985). When they do have sufficient speed to cause movement, the net sediment transport is close to zero because of the symmetrical nature of the tides. Tidal currents in Maine cannot independently cause sand transport along the inner shelf (Dickson, 1999), except in areas of constricted flow near inlets.

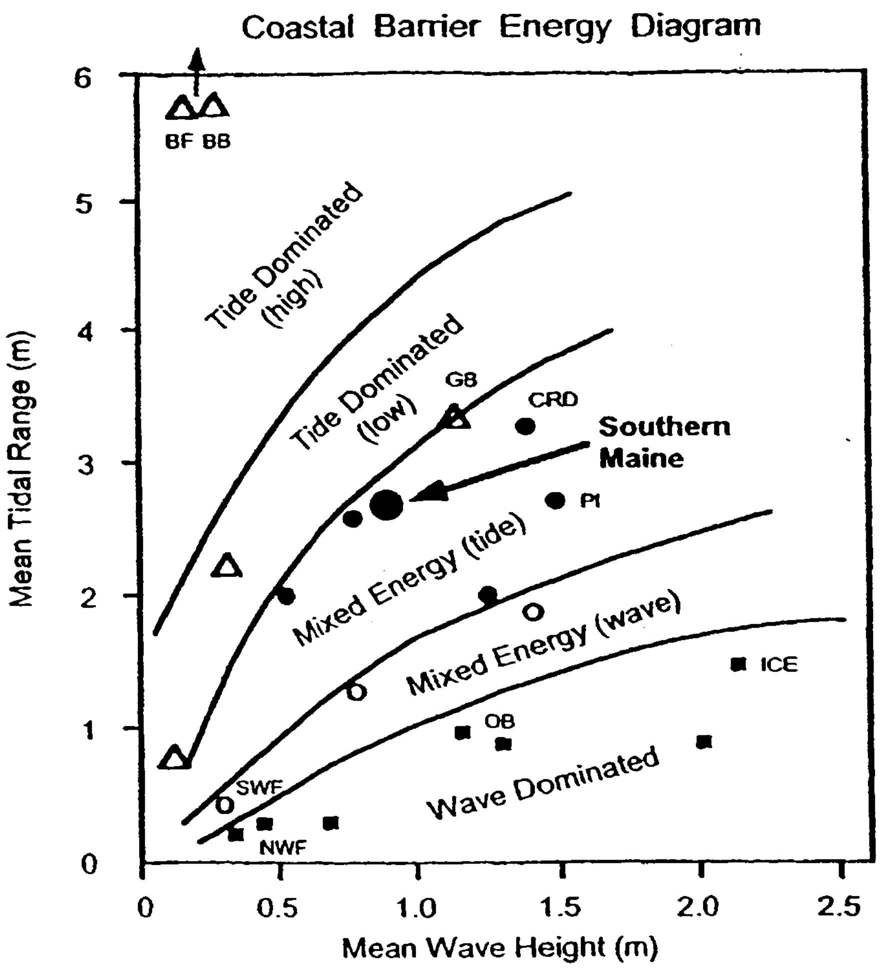


Figure 2.30. Coastal energy diagram showing a mixed energy setting for coastal Maine. Symbols are used to define energy boundaries. Examples from the Gulf of Maine include Plum Island, Massachusetts (PI), and the Bay of Fundy (BF) in Canada. The German Bight (GB) and Copper River Delta, Alaska (CRD) are mixed energy like the southern Maine coast. The Outer Banks of North Carolina (OB) and SW and NW Florida (SWF, NWF) are microtidal. Southeast Iceland (ICE) has the largest waves. Bristol Bay, Alaska (BB) is macrotidal (modified from Hayes, 1979 by Dickson, 1999)

Combined Flow

Combined flow refers to oceanographic currents that result from several forces acting together (Figure 2.31). Wave orbital currents, tidal currents and wind-driven currents have the greatest impact on combined flow and sediment transport on the shoreface, while other flow components are often too weak or do not last long enough to exceed the threshold needed for sediment motion (Swift *et al.*, 1985). In Maine, tidal currents and wind-driven currents are the primary components of combined flow, but during storms, the wind-driven circulation overwhelms the tidal current (Dickson, 1999).

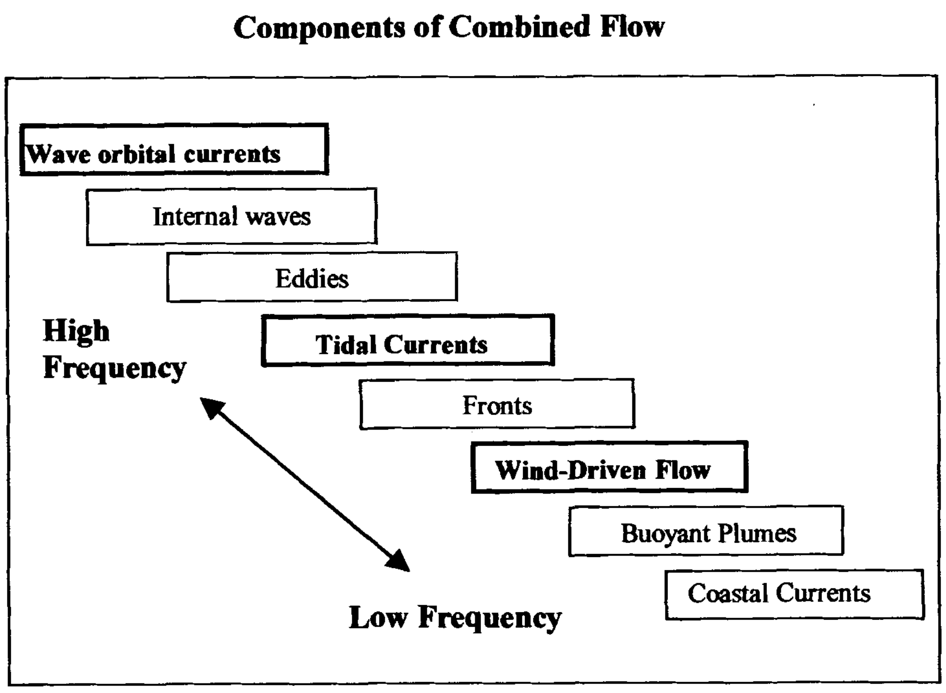


Figure 2.31. Components of combined flow. Illustration of sources of currents on the inner continental shelf and shoreface that are potentially involved in combined flow and sediment transport (Dickson, 1999, Figure 4.1).

Chapter 3

METHODS

Beach Profiling

Project initiation

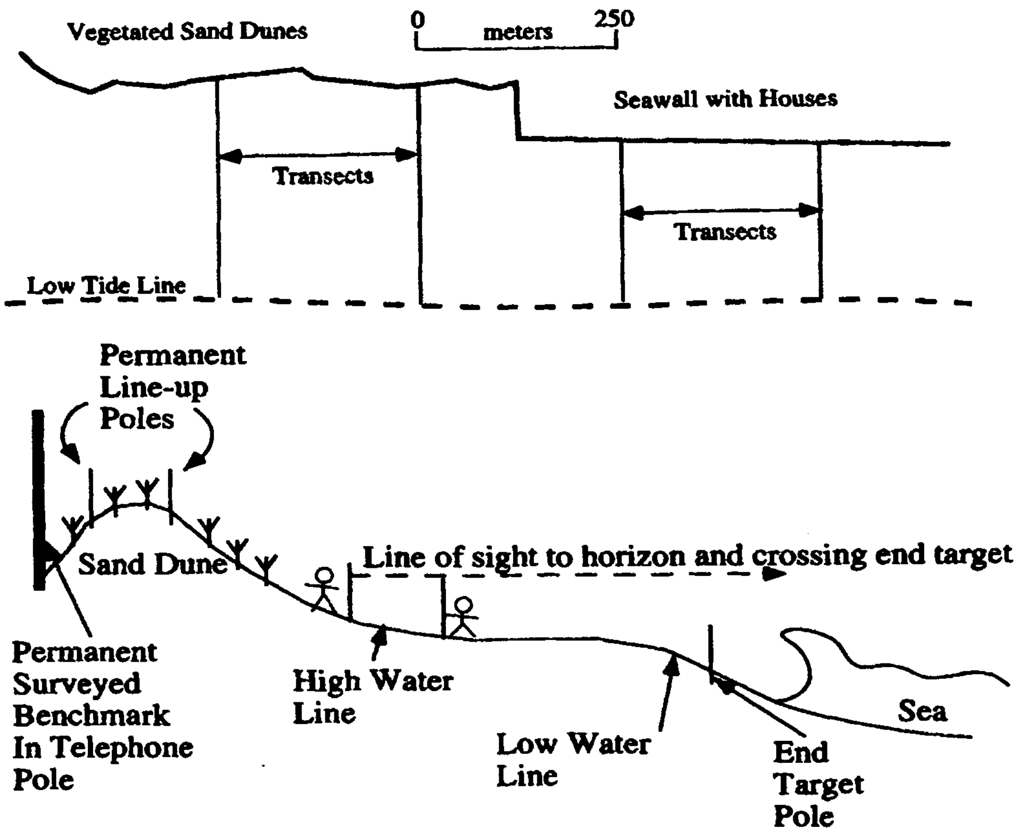
In June 1999, a press release from the Maine Sea Grant Communications Office and the Department of Conservation announced the need for volunteers to help study the beaches in southern Maine. More than 150 people responded, and collaborators from the University of Maine and the Maine Geological Survey held an organizational meeting to divide volunteers into teams based on their geographic location and interests. They established ten teams of between 4 and 15 people and trained them to monitor nine different beaches (Figure 1.1).

At each beach, the team members, along with state geologists, determined the location of two to four transects based on accessibility and interest (Appendix A). The transects were placed nominally 250 m apart and were perpendicular to the beach face (Figure 3.1a). There were two permanent poles, or reference stakes, at the beginning of the transect, one of which served as the starting point for the profile and was referred to as the front stake. The second stake, or back stake, was located about 20 m landward of the front stake and served as the replacement in the event that a storm removed the front stake.

Data collection

The volunteers used the Emery Method (Emery, 1961) of beach profiling to make monthly measurements at spring low tide (Figure 3.1b). This method utilizes a set of 1.5

a.



b.

Figure 3.1. Schematic diagram showing profiling methods: a. plan view of transect orientation and b. Emery Method of beach profiling along a cross-section.

m poles that are graduated to 1 cm intervals, and attached by a 3 m rope, using the ocean horizon as level. The rope slides on one pole to maintain a horizontal distance. The surveyors start by taking a vertical reading at the front stake, and continue making horizontal and vertical measurements along the length of the transect to the water's edge. The person holding the rod on the landward side sights to the horizon and records the elevation loss or gain. Measurements are taken every 3 m horizontally, or wherever a significant change in topography occurs. The transect orientation is maintained by visually aligning to the two permanent stakes, or to the front stake and a distant landmark.

Data collection began in June 1999 for one group, while other groups began taking measurements between July and October 1999. The volunteers continued taking measurements at least through June 2001, although profile monitoring may continue after this date. Each group collected data within a pre-determined three-day time span each month, usually corresponding to the spring low tide. The record from each transect consisted of a series of horizontal distances, vertical distances and appropriate annotations (end of dune grass, last high tide line, etc) where warranted (Figure 3.2). Volunteers also took photographs to document monthly changes.

There are several sources of error that may exist from the profile measurements, including but not limited to: 1) precision of horizon estimate, 2) misreading poles, 3) misalignment of the poles, 4) mistaking a positive for a negative value, or vice versa and 5) transcription errors. It is possible to assume that errors 1-3 average out along the profile. When the profile is plotted, an unusual jump may be evidence that the sign was switched. Transcription errors may be noted on the original sheets.

U. Maine/ Maine Geological Survey Emery Beach Profile Log Sheet

Profile Name ______ Date ______ Start Time ______ Page __ of _

Team Names ______ Visibility of Horizon ______

Back Stake Sand Elevation (if used)______ Front Stake Sand Elevation ______

General Condition of Beach and Dune ______

Vertical Units ______ Horizontal Units ______

Vertical	Horizontal
*	0.0

*Sand elevation at starting point (pin or stake). Minus (-) is pin above sand, plus (+) is sand above pin. Others: Minus is forward pole lower.

Vertical	Horizontal	Notes	Vertical	Horizontal	Notes

Field Sketch

Figure 3.2. Sample data sheet used by the volunteers to make monthly measurements.

Following data collection, the volunteers sent their data to the University of Maine, where I entered it into an Excel spreadsheet, plotted it linearly, and filed it for archives. The website (http://www.geology.um.maine.edu/beach) displayed the graphs, along with additional information and pictures of the beaches that were monitored. The graphs showed every month of profile data from the beginning of the project, and also documented a comparison between months with the greatest and least volumes of sand.

Data analysis

To evaluate monthly changes, a berm elevation was interpreted along each transect (Figure 3.3). The berm was determined geomorphically as "the nearly horizontal portion of the beach or backshore formed by the deposition of sediments by waves" (Komar, 1998). In the case where a distinct berm did not exist, generally along seawalled beaches, the berm was defined as the segment that showed the greatest elevation change near the head of the profile. An initial berm height and corresponding horizontal distance from the front stake was determined for the month of October 1999, along all transects. This horizontal distance was then used to find the monthly berm heights through March 2001. Averages were made along all beaches since they exhibited similar monthly trends.

Quantifying the volume of active sand, or the sweep zone, along each beach, was necessary to analyze yearly gains/losses of sediment. The horizontal distances of the individual profiles are not the same from month to month so a common length for every transect was determined. This required cutting some profiles short and extending others through linear extrapolation.

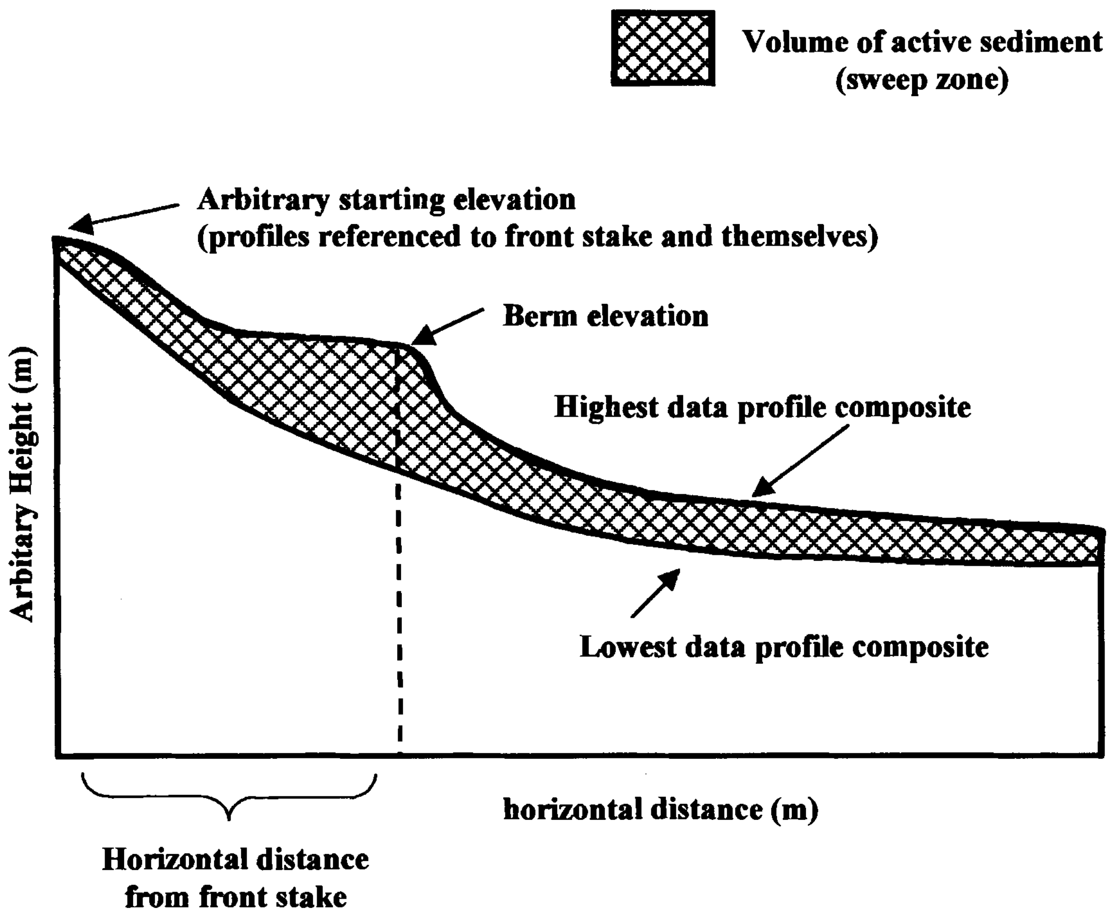


Figure 3.3. Illustration showing berm height and volume of active sediment.

The volume was found by multiplying the total area under the plotted profile (Figure 3.3), determined in a graphing program, by one meter to give the value a third dimension. From this data, an average monthly volume of sediment per meter of shoreline distance was found for each beach. The average was taken from the total number of transects on each beach. To determine the percentage of active sand that was gained or lost over one year, the difference between the volumes in October 1999 and October 2000 were divided by the total volume of active sediment over that year (Equation 3.1), or simply the difference between the minimum and maximum volumes measured from composite profiles (Figure 3.3). The volumes for March 2000 to March 2001 were also analyzed to look for seasonal variations.

Equation 3.1. absolute value (October 2000 vol. - October 1999 vol.)
absolute value (max. profile vol. - min. profile vol.

Meteorological Data

Portland Buoy

The National Data Buoy Center Station 44007 is 8 km southeast of Cape Elizabeth (43°31.88'N, 70°8.65'W, 18.9 m water depth), and sheltered by land from the N and NW directions. The 3 m discus buoy provided wind speed, wind direction, wave height, and dominant wave period on an hourly basis from June 1999-March 2001. Data exists on-line under NOAA archives (NCDC, 2001).

Wind speed and direction

An anemometer recorded hourly average wind speeds (m/s) and wind directions (degrees clockwise from N), over an eight-minute sampling period. Once entered into a spreadsheet, the wind-speed data showed monthly variation. Rose diagrams showed wind direction on a monthly basis. For specific storm events, intervals of data were extracted corresponding to times of the storm.

Wave height and dominant wave period

Accelerometers on board the buoy recorded hourly significant wave height (m) and dominant wave period (s) over a 20-minute sampling period. The significant wave height is defined as "the average heights of the highest one-third of the waves measured over a stated interval of time, usually 20 minutes " (Komar, 1998). The data sets were entered into spreadsheets and plotted to show monthly variation. For specific storm events, intervals of data were extracted corresponding to times of the storm.

Surface weather charts

Archived surface weather charts from NOAA's online National Climatic Data Center (NCDC, 2001) made it possible to follow storm tracks. These charts provided wind direction at the current meter sites during specific locations of the storms' meteorological centers. Coupling these data with buoy data allowed for a more complete record of storms during the study period. It was possible to reconstruct the storm event, wind direction, surface currents, and the resulting bottom- current directions.

Current Meters

Data collection

Two Falmouth Scientific 3D Acoustic Current Meters recorded bottom currents in shoreface locations of Saco Bay and Wells Embayment, Maine (Figure 3.4). The locations were chosen based on water depth (20 m) and the nature of the seafloor. Three deployments were made from the *R/V Gulf Challenger* out of Portsmouth, New Hampshire in February and November 2000, and January 2001 (Table 3.1). Instruments were placed in both embayments during each deployment, but due to programming errors, no data were collected in Saco Bay during the first deployment and in Wells Embayment during the third deployment. Pressure sensors, which record the passage of surface gravity waves, malfunctioned in all three deployments.

The instruments were attached 1 m above the seafloor to a taught-wire mooring with a separate surface tether (Figure 3.5). The mooring materials were found not to impart a magnetic field at a height of 1 m above the bottom (Dickson, 1999). The instruments internally collected bursts of data sampled at 1 Hz, but were averaged for 15 seconds to conserve memory resources (Table 3.1). The current meters recorded vector directions in magnetic north and times in Eastern Standard Time.

Sediment samples

During retrieval of the current meters, a small amount of sediment that remained on the concrete blocks, was bagged for analysis. Although the sediment may have been transported from a distance, it is probably an indicator of the sediment size at the current

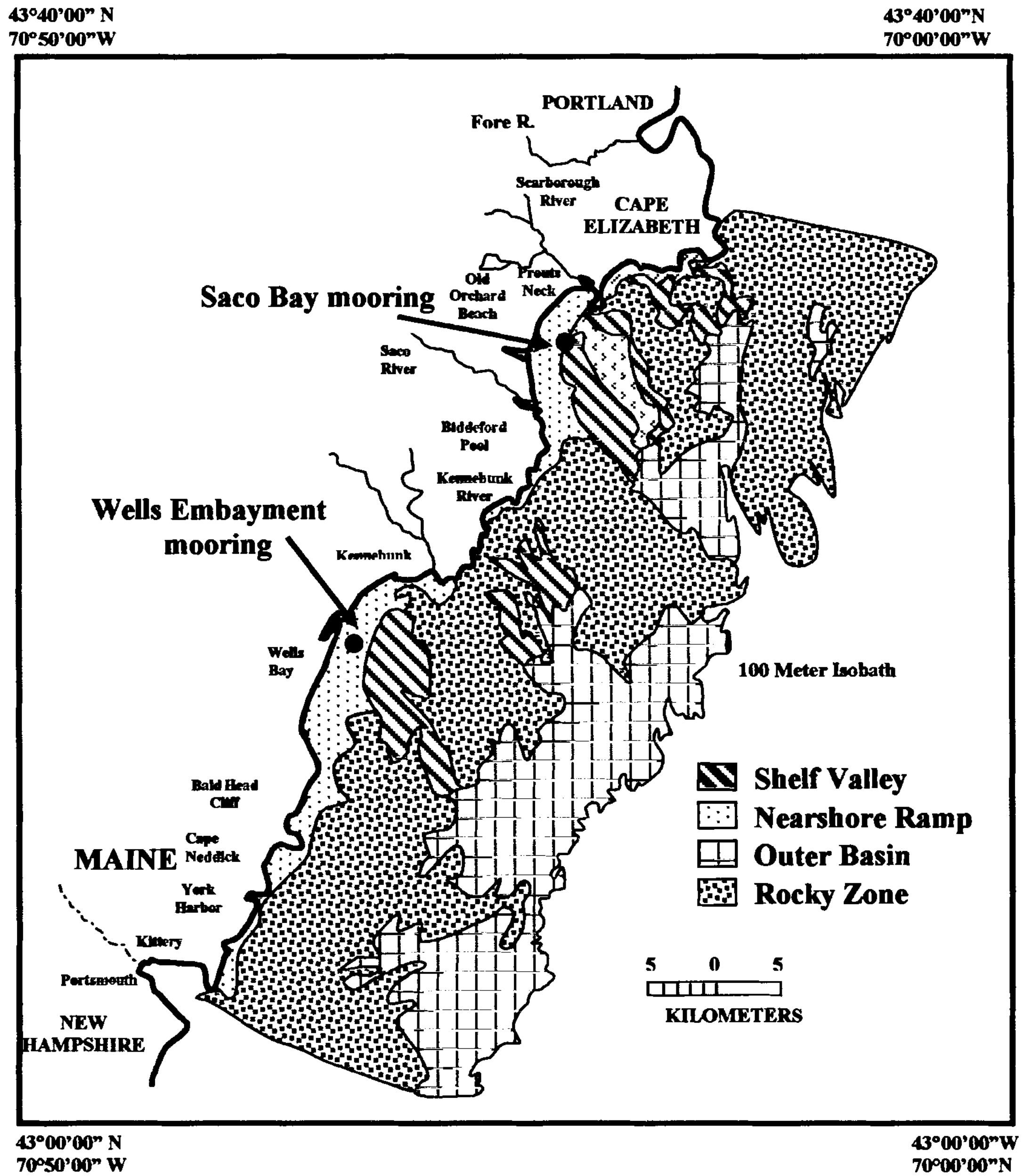


Figure 3.4. Location map of current meter moorings in relation to physiographic zones (Modified from Kelley *et al.*, 1989a).

Geographic Location Lat. Lon. (NAD83) Water Depth (m, MSL)	Instrument Type Serial Number Height above Seabed (m)	Collection Dates From-To Days of Record	Vector Type
Wells Shoreface 43°18.03'N 70°32.80'W 20.2	3D ACM 1601a 1	02/03/00, 12:00:10- 02/23/00, 00:02:54 21 days	1 Hz averaged over 15 seconds for 4 min. every 6 hours
Old Orchard Shoreface 43°29.83'N 70°20.29'W 20.8	3D ACM 1601a 1	11/28/00, 12:00:15- 01/10/01, 18:00:45 44 days	1 Hz burst data randomly sampled
Wells Shoreface 43°18.03'N 70°32.66'W 21.4	3D ACM 1600 1	11/28/00, 12:00:00- 01/17/01, 03:02:15 51 days	1 Hz averaged over 15 seconds for 4 min. every 1 hour
Old Orchard Shoreface 43°29.83'N 70°20.29'W 20.8	3D ACM 1601a 1	01/23/01, 12:00:15- 03/07/01, 20:01:00 44 days	1 Hz averaged over 15 seconds for 4 min. every 1 hour

Table 3.1. Current meter mooring characteristics.

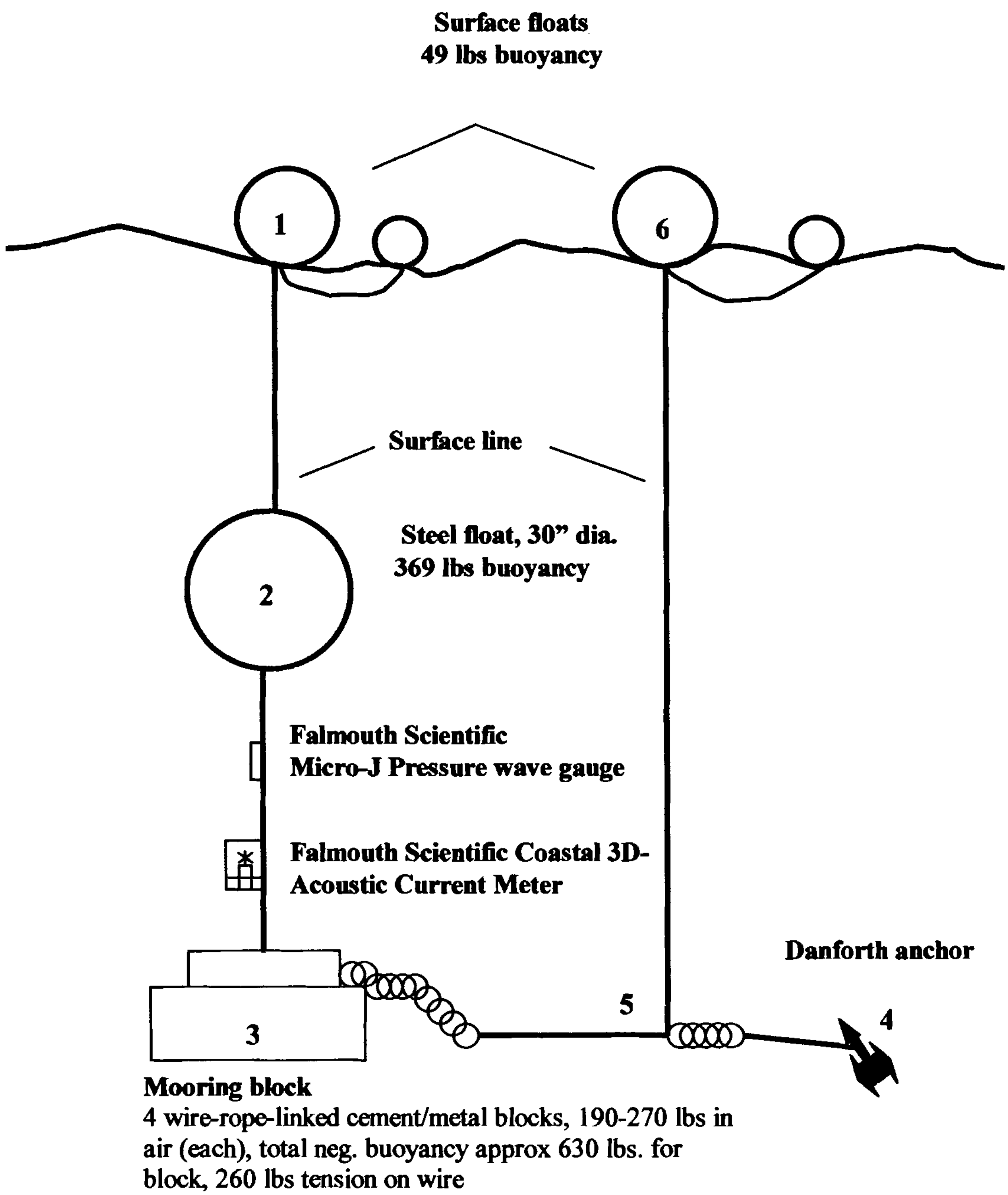


Figure 3.5. Mooring setup for wave-current measurements. Designed by Stephen M. Dickson, Maine Geological Survey. Mooring deployed in sequence indicated by numbers.

meter location, and was compared to previous sediment samples in the area (Barber, 1995).

Storm events

In this study, storm events were defined as having a significant wave height greater than 2 m and a horizontal scalar speed (cm/s) that was distinctly greater than the surrounding events. Combining these components with surface weather charts enabled a determination of the beginning and end of a storm; the storm was said to begin when the wind field surrounding the storm low was in contact with the current meters. The storm events are an arbitrary classification and may represent more or less "storms" than were reported by the National Weather Service during the sampling interval (NWS, 2001).

For each storm recorded by the current meters, the net direction of sediment movement was determined. This value was an average of all the currents that exceeded the threshold of sediment transport. In addition to looking at the storms recorded by the current meters, the number and types of storms that occurred from October 1999-March 2000 and October 2000-March 2001 were measured. A 2 m minimum wave height and surface weather charts were used to define storms.

Threshold velocity

The threshold of sediment movement occurs when the water exerts a force on the particles that is sufficient to cause them to move (Komar, 1976). To demonstrate the effects of storm circulation on sediment transport, a threshold velocity for each storm event was determined using the size of the sediment sample off the mooring blocks (3 phi) (125 microns), in addition to bottom grab samples previously collected from Saco Bay (Barber, 1995) and Wells Embayment (Miller, 1998). Each storm event was plotted on a curve for threshold orbital velocity devised by Komar and Miller (1976) (Figure 3.6).

Ground Penetrating Radar

Data collection

Twenty GPR records, two along each of the 10 beaches, were collected perpendicular to the shoreline over a three-day span during July 2000. The locations of the transects were chosen near the first and last topographic beach profile lines (Appendix A). A Sensors and Software Pulse EKKO 100 GPR was employed to gather the records while operating at a nominal frequency of 200 mHz. A high frequency like 200 mHz, provides only relatively shallow penetration but better resolution than 100 mHz or lower frequency. Travel velocity was originally set at 0.15 m/ns for dry sand, which is the manufacturer's recommended value. A vertical stacking of 16 was applied to reduce noise, and traces were taken every one-half meter. The number of records per transect corresponded to the length of the transect.

Two common mid point (CMP) transects were taken perpendicular to the GPR lines along Ogunquit and Western Beaches. CMP data test the time-depth relationships of the subsurface features so an accurate velocity is measured for the various materials. This method requires starting with the two antennae next to one another and moving them farther apart at measured intervals. The two-way travel time of a reflection increases as the transmitter and receiver are moved farther apart and the rate of increase directly

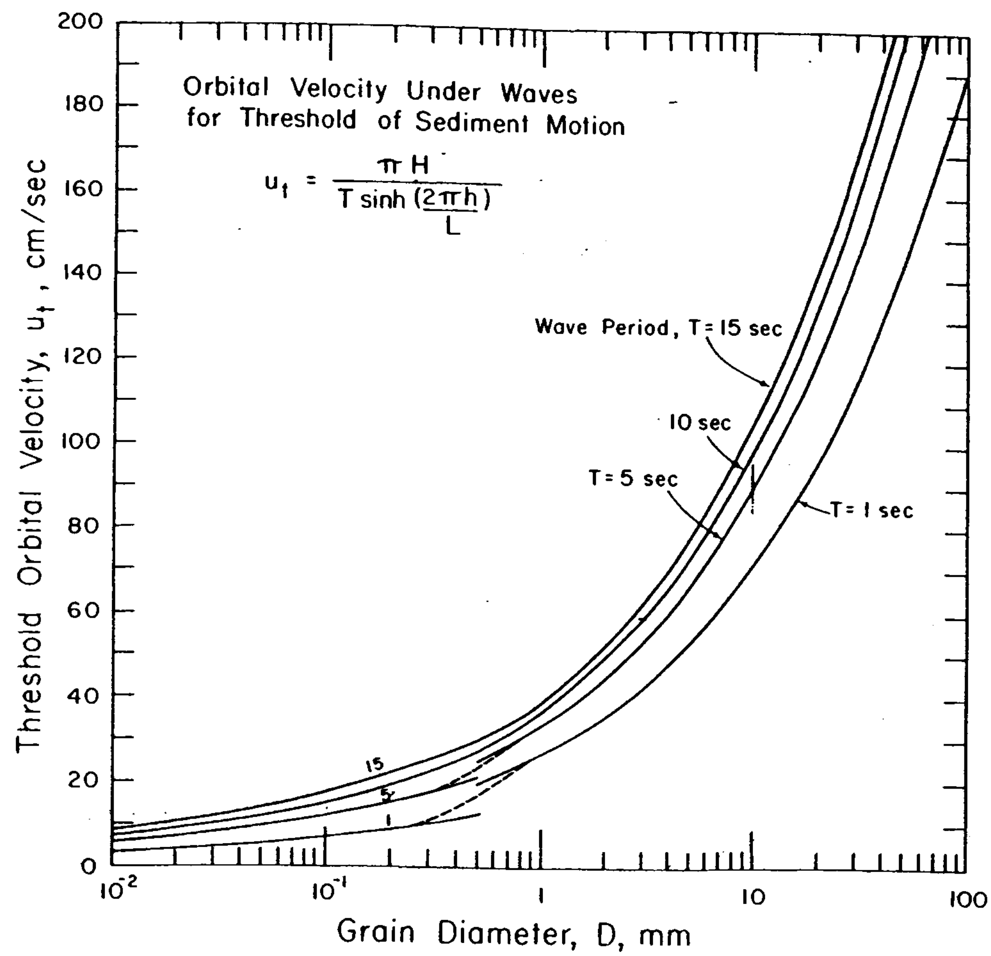


Figure 3.6. Curve for threshold orbital velocity. The wave period T and near-bottom orbital velocity u_t required for threshold of motion of sediment grain size D and density ρ_s = 2.65 g/cm^3 (quartz). The orbital velocity is in turn related to the wave height H and water depth h by the equation shown (Komar and Miller, 1976).

relates to the transmission velocity of the material. The result is a plot of time vs. distance with the velocity equating to the slope of the line.

Data processing

A topographic correction was applied to the raw data to show the relief and allow for accurate representation of the elevation of the underlying stratigraphy. Topographic surveys of the transects were made by selecting points along the transect with significant changes in relief and using a Sokkia Total Station to determine the elevations of these points with respect to one another. The IxeTerra Ground Penetrating Radar Data Management and Presentation Package software created a linear interpolation of the surface between the surveyed locations.

The software package was necessary to import the raw data, convert the profiles from time to depth, and correct the data for topography. The software also has the capability to change the original two-way travel time setting so different velocities are applied for various materials. From the CMP data, I calculated a velocity of 0.14-0.15 m/ns for both transects, and therefore kept the suggested value of 0.15 m/ns for data interpretation. The resulting graphs used in this thesis plot depth vs. horizontal distance based on 0.15 m/ns.

Sand volumes

For each beach except Higgins, which was divided into north and south because of differences in development, one record for interpretation and volume calculation was chosen. Interpretations for six of the nine beaches were based on previous work

(Hulmes, 1981; Montello *et al.*, 1992a; van Heteren *et al.*, 1996; Mills, 1997; Hunt, 1998). The remaining three interpretations depended on interpretation of known or recognized reflector patterns observed in the first six records. The coastal stratigraphic section includes bedrock, glacial marine sediment, marsh, and sand based on observations of nearby outcrops, cores, and offshore seismic reflection profiles. The GPR reflectors were interpreted in terms of these materials. Once the two-dimensional cross section of the sand facies was established, a Geographic Information System calculated the area of this unit. Multiplying this value by 1 m transferred the area with the sand unit into a volume.

Sediment Samples

Surface samples

Two to six surface samples were collected along GPR transects at every beach. Handful-size samples (100-200 gm) were taken where changes in geomorphology or vegetation occurred (ie. dune, berm, high-tide swash zone, low-tide terrace). This allowed for assessment of lateral changes in sediment composition along individual beaches.

Lab work

A Rapid Sediment Analyzer (Schlee, 1966) settling tube was used to determine the grain size distributions and the mean grain size for each sample. A subsample of 5-15 grams was used in the settling tube. The field samples did not have a uniform weight, so they were split into 1/16 of their original size to obtain a random sub-sample. The split portion was placed in deionized water to remove salt, and shaken for 15 minutes to cause the organic sediments to float to the surface. The samples were decanted after 10 minutes to remove excess rinse water and organics, and then placed in an oven to dry overnight. Once the sample was dried, it was split in half and one of these split halves was run through the settling tube.

Chapter 4

RESULTS

Beach Profiles

<u>Individual beach profile response</u>

The individual beach profiles demonstrated a wide variety of changes over the sampling interval (Appendix B), but the responses fit into four separate categories (Table 4.1): 1) profiles that exhibited most of the berm buildup during the summer months (June, July, August), 2) profiles that exhibited most of the berm buildup during the fall months (September, October, November), 3) profiles that showed no seasonal patterns, and 4) profiles that experienced minimal changes throughout the year.

Three out of four profiles along Scarborough, Laudholm, and Ogunquit Beaches demonstrated seasonal responses similar to one another (Table 4.1). The profiles along Scarborough showed a summer berm buildup, while the profiles along Laudholm and Ogunquit showed a fall berm buildup. The profiles along East Grand, Goochs, and Ferry/Western Beaches (with the exception of Ferry Profile 2) showed very little change during the sampling interval (Table 4.1). Measurements were not made at Ferry Beach Profile 2 starting in the fall of 2000, so the results are not directly comparable to the other three profiles along the beach.

Profiles along Higgins Beach that are within 200 m of one another (Figure 4.1) documented distinctly different responses (Figure 4.2). A direct comparison of the trends of the berm heights shows that the profiles were out of phase during the sampling interval (Figure 4.2). Higgins Beach Profile 1 showed an increase in the berm height during the summer of 1999 and 2000 (Figure 4.2), although the berm elevation was greater in 1999

Beach Profile	Summer berm buildup	Fall berm buildup	No pattern	Very little change
Higgins profile 1	X			
Higgins profile 2		X		
Higgins profile 3				X
Scarborough profile 1	X			
Scarborough profile 2	X			
Scarborough profile 3	X			
Scarborough profile 4		X		
Ferry profilel				X
Ferry profile 2		X		
Western profile 3				X
Western profile 4				X
East Grand profile 1				X
East Grand profile 2				X
East Grand profile 3				X
East Grand profile 4				X
Kinney Shores profile 1	X			
Kinney Shores profile 2			X	
Biddeford Pool profile 1		X		
Biddeford Pool profile 2		X		
Biddeford Pool profile 3		X		
Fortunes Rocks profile 4			X	
Goochs profile 1				X
Goochs profile 2				X
Goochs profile 3				X
Goochs profile 4				X
Laudholm profile 1		X		
Laudholm profile 2		X		
Laudholm profile 3			X	
Laudholm profile 4		X		
Ogunquit profile 1		X		
Ogunquit profile 2		X		
Ogunquit profile 3		X		
Ogunquit profile 4	X			

Table 4.1. Responses of individual beach profiles over 1.5 years.

Figure 4.1. 1986 aerial photograph of Higgins Beach, Maine (Maine Geological Survey). Yellow lines denote profile transects. See Figure 1.1 for beach location.

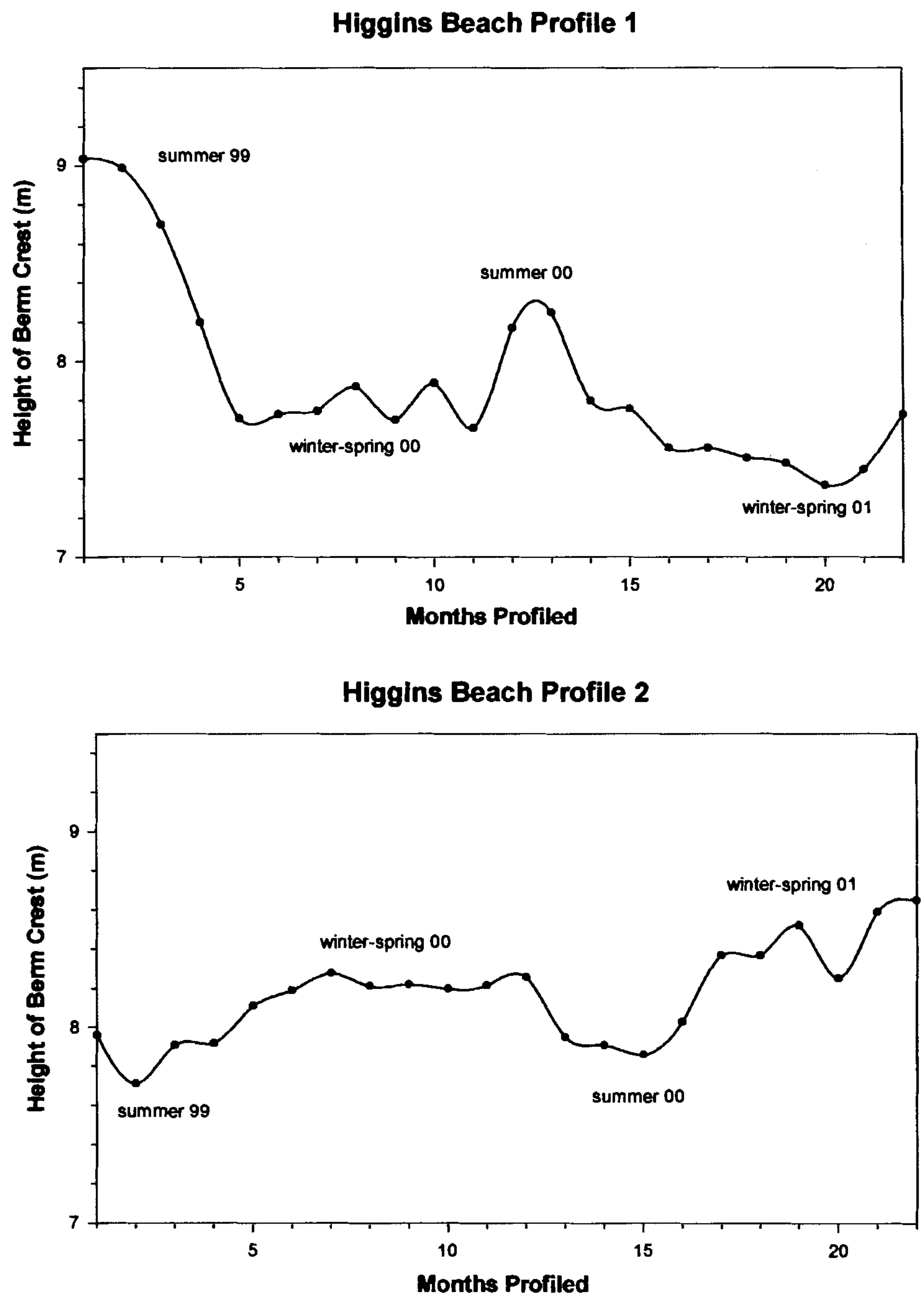


Figure 4.2. Comparison of berm heights during the 22-month sampling interval, Higgins Beach Profiles 1 and 2.

than 2000. Higgins Beach Profile 2 demonstrated exactly the opposite trend with a decline in the berm elevation during the summer months (Figure 4.2).

The berm along Higgins Beach grew laterally (towards the sea) as well as vertically (Figure 4.3). In addition to a greater vertical growth during the summer of 1999 than 2000, the profile also grew farther seaward. Higgins Beach Profile 2 did not show any lateral growth (Figure 4.4). A decline in sediment during the summer resulted in a concave shaped profile. In contrast, the winter months accreted sediment, leaving a gently sloping profile.

Profiles along Biddeford Pool and Fortunes Rocks also showed different responses (Table 4.1). The profiles along Biddeford Pool demonstrated a fall berm buildup, while there was no clear pattern to the changes observed at Fortunes Rocks. The two profiles at Kinney Shores showed different responses as well (Table 4.1); Kinney Shores Profile 1 showed a summer berm buildup while there was no clear pattern to the changes seen along Kinney Shores Profile 2.

Profile responses based on development status

An averaging of the profiles along each beach provided a simple method to compare the beaches based on their level of development. With the exception of Laudholm Beach, which experienced little variation throughout the profiling period, the undeveloped beaches showed a berm increase in the summer or early fall and berm erosion during the winter (Figure 4.5). The slight increase in berm elevation that did occur at Laudholm was during the winter and spring months (Figure 4.5). Higgins Beach spit best demonstrated the summer and winter profiles (Figures 4.3 and 4.5). The

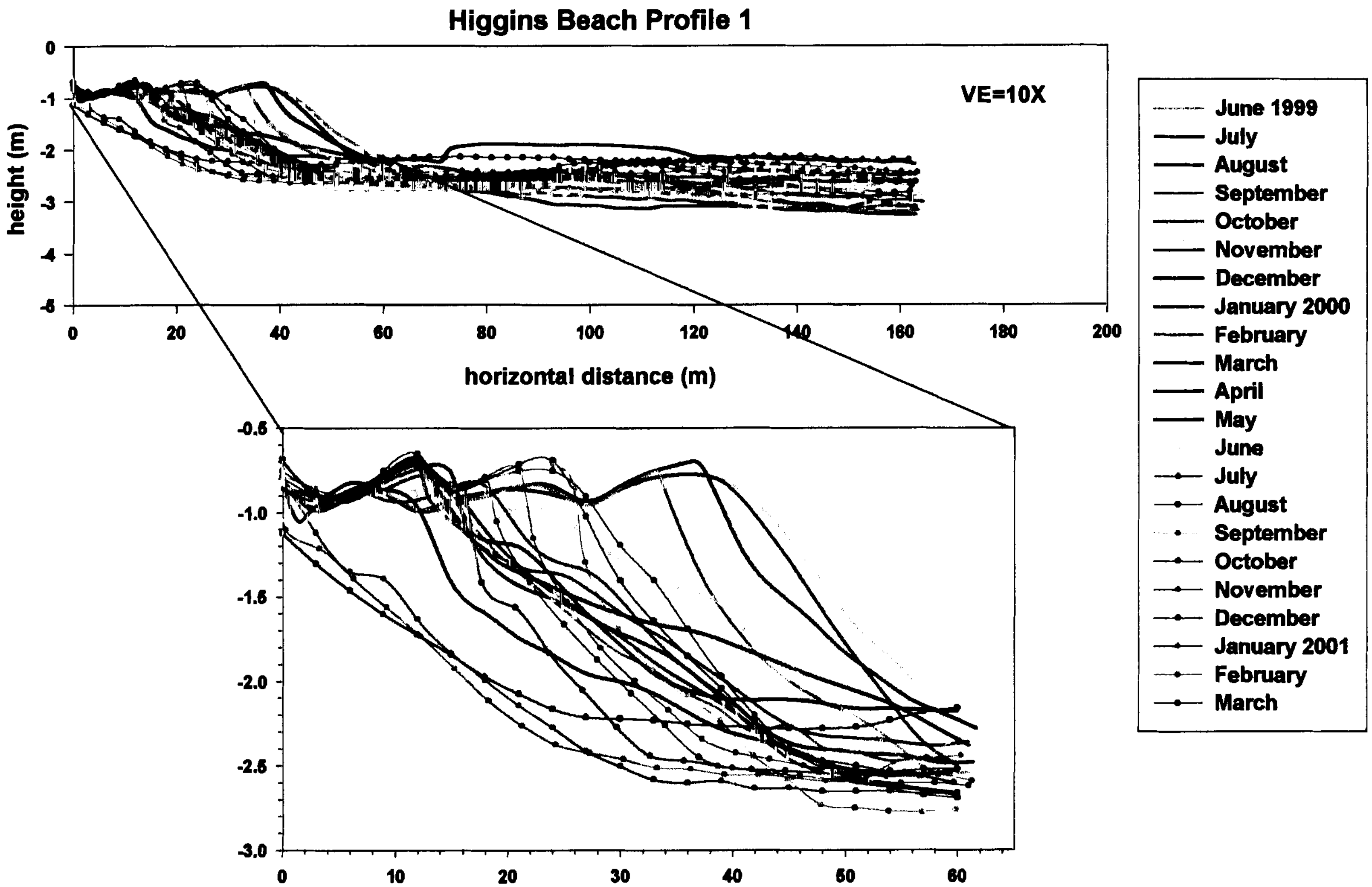


Figure 4.3. Higgins Beach Profile 1 monthly topographic changes (altered to same length).

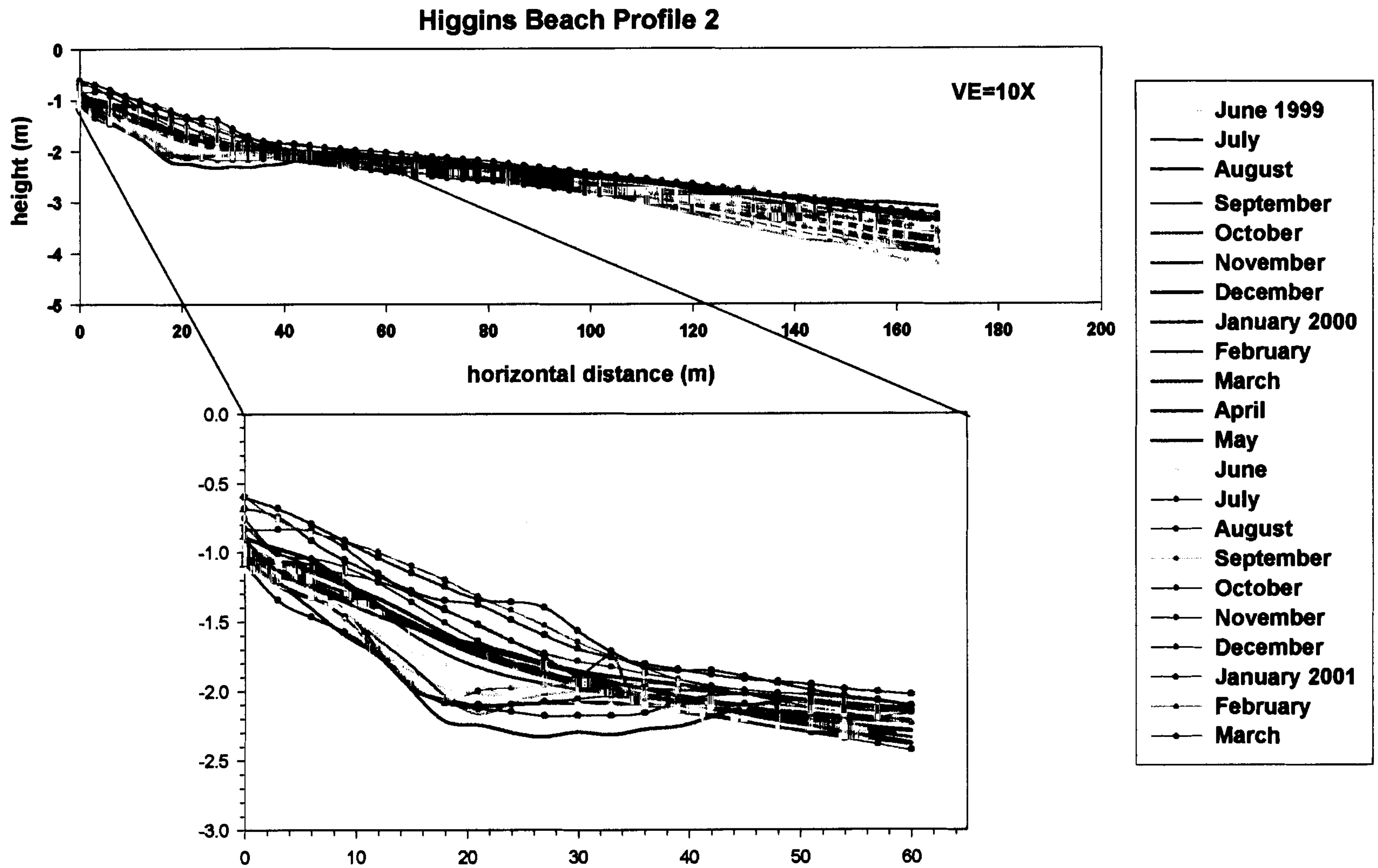


Figure 4.4. Higgins Beach Profile 2 monthly topographic changes (altered to same length).

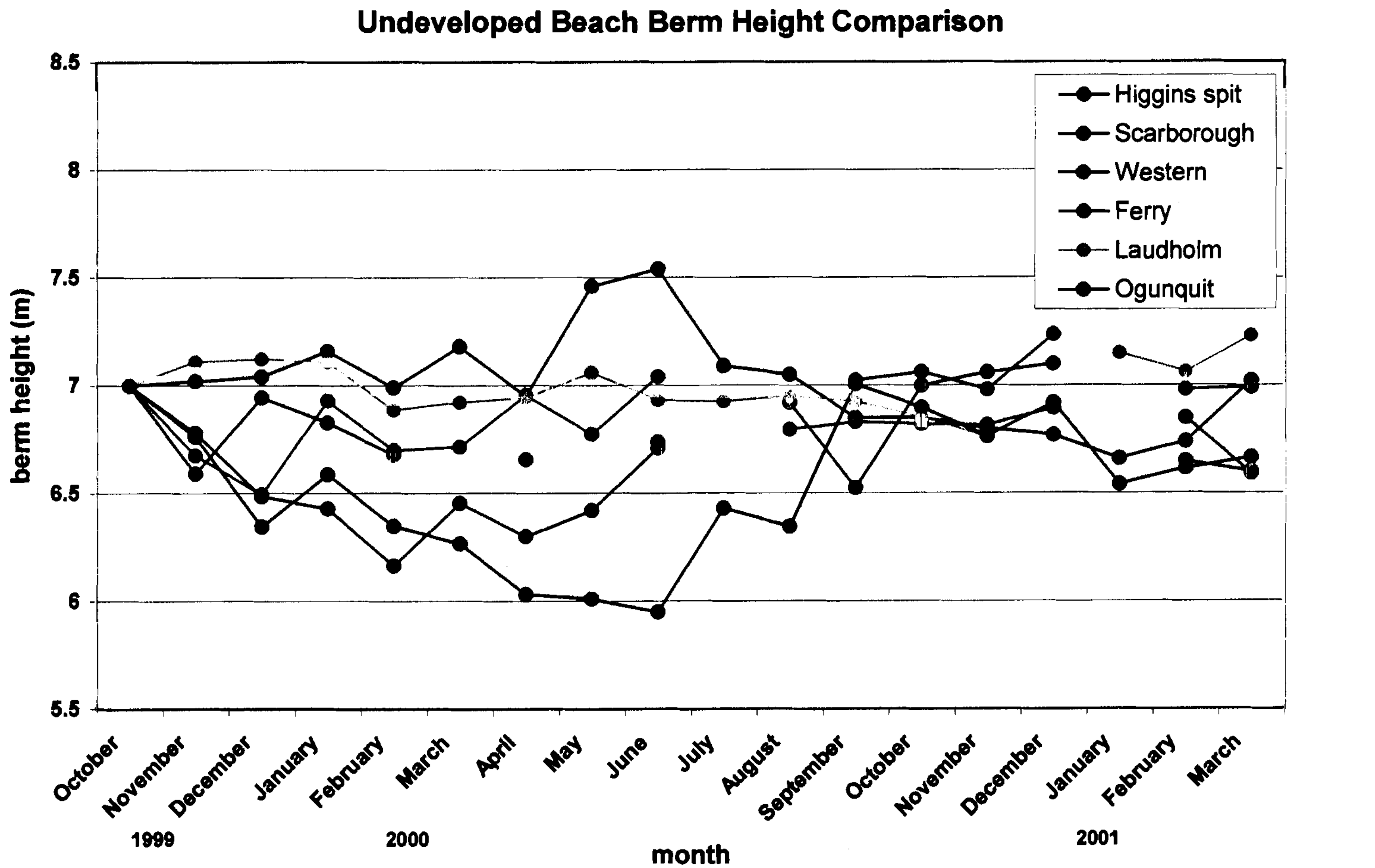


Figure 4.5. Monthly berm heights for undeveloped beaches in the study. The berm heights represent an average of the profiles along each beach. The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

Ferry/Western profiles showed trends very similar to one another, starting with a decline during the fall months, a slight leveling off during the spring and a gradual increase in berm height through the summer. The profiles leveled off again during the fall of 2000 and winter of 2001 (Figure 4.5). Ogunquit Beach responded exactly opposite to Higgins Beach (Figure 4.5). The beach demonstrated a decline in berm height starting in October 1999. The berm then began to build in the spring through the fall of 2000. After this point, the berm slowly decreased in elevation. Ogunquit Beach experienced the largest elevation change over the profiling period with up to 1 m of change (Figure 4.5). The missing data from Scarborough Beach makes it difficult to determine the berm height trends along the beach (Figure 4.5).

All of the moderately developed beaches showed seasonal berm erosion/accretion (Figure 4.6), but the changes at Kinney Shores best documented the traditional summer/fall berm cycle; the berm began to accrete in May and eroded by September with a net change of 0.5 m (Figure 4.6). Biddeford Pool demonstrated the greatest elevation change of close to 1.5 m with the lowest value in June 2000 and the highest value in November 2000. The berm experienced a large decline in elevation from December 2000 to January 2001 (Figure 4.6). The berm changes along East Grand mimicked those along Biddeford Pool, but with a much smaller elevation difference (Figure 4.6).

The developed beaches responded similarly to one another with berm accretion beginning in August and decline in November/December (Figure 4.7). The responses along the developed beaches were almost identical during the first half of the sampling interval, and still very closely resembled one another during the second half (Figure 4.7). Fortunes Rocks experienced the greatest elevation change of close to 1 m. The remaining

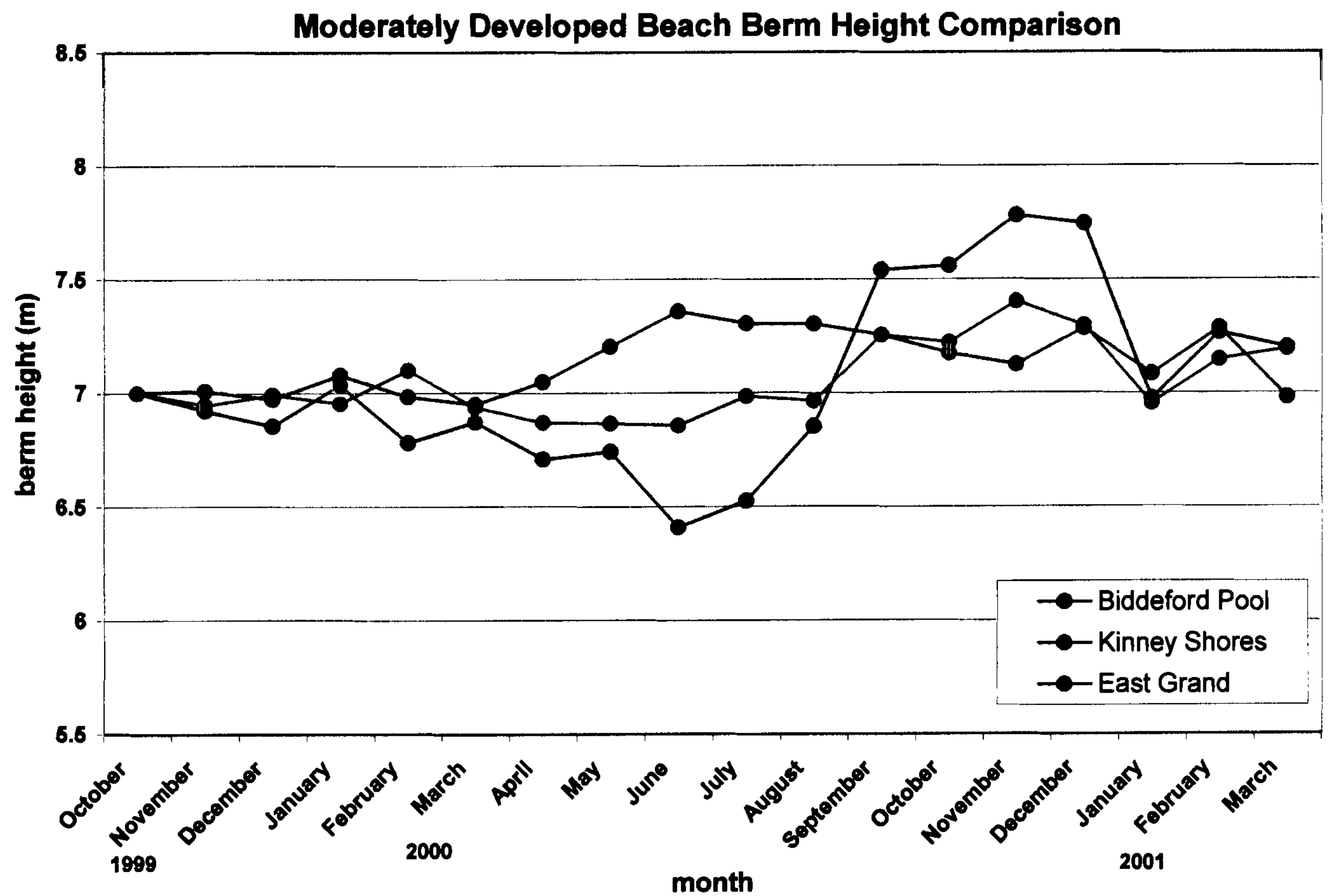


Figure 4.6. Monthly berm heights for moderately developed beaches in the study. The berm heights represent an average of the profiles along each beach. The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

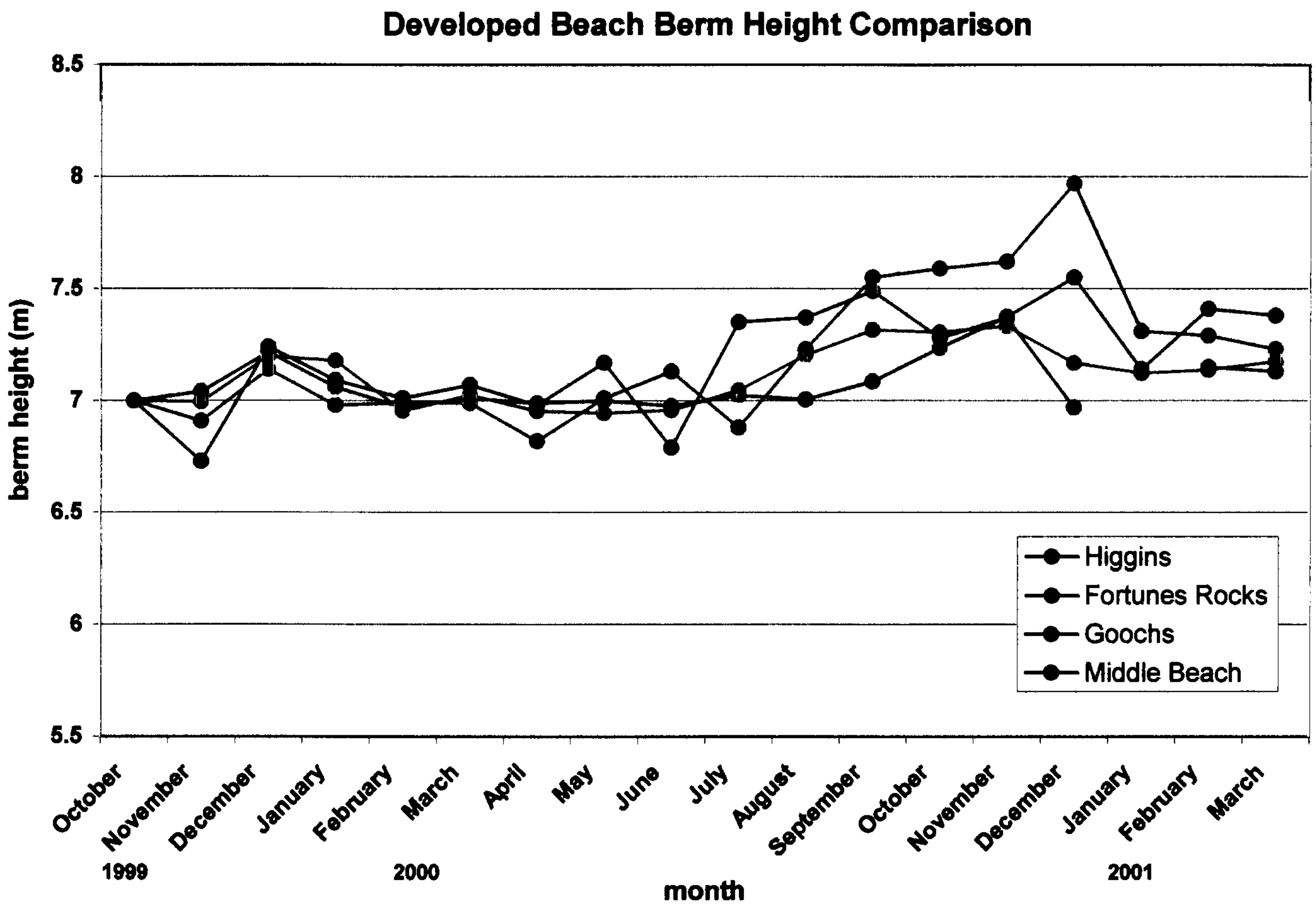


Figure 4.7. Monthly berm heights of developed beaches in the study. The berm heights represent an average of the profiles along each beach.The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

profiles showed an elevation difference of less than 1 m over the entire sampling period (Figure 4.7).

A polynomial (6th order) regression applied to all of the data for each category (based on development level), shows general trends (Figure 4.8). The undeveloped beaches, with an R^2 value of 0.8661, demonstrate a sinusoidal shape and illustrate the classic behavior with berm buildup beginning in early summer and peaking at the end of fall, with a subsequent decline in the winter months (Figure 4.8). The total berm elevation change over the sampling period is less than 0.5 m, and the trend in the fall/winter of 1999-2000 is similar to the fall/winter of 2000-2001 (Figure 4.8).

The highly and moderately developed beaches demonstrated similar shaped trends to one another, although the R^2 value for the highly developed beaches is 0.8804, while the R^2 value for the moderately developed beaches is 0.8372. For both the moderately and highly developed beaches, the berm height reaches a slight peak during January of 2000, but peaks earlier the next year, in November. In addition to the difference in timing, the berm height for the fall in 1999-2000 is 0.4 m less than it is in 2000-2001 for the moderately and highly developed beaches.

Profile responses in Wells Embayment and Saco Bay

An averaging of the profiles along each beach was also useful in comparing the beaches depending on their location within Wells Embayment and Saco Bay. With the exception of Laudholm Beach, the beaches in Wells Embayment showed a berm buildup beginning in June/July, reaching a peak in the late fall, and declining by

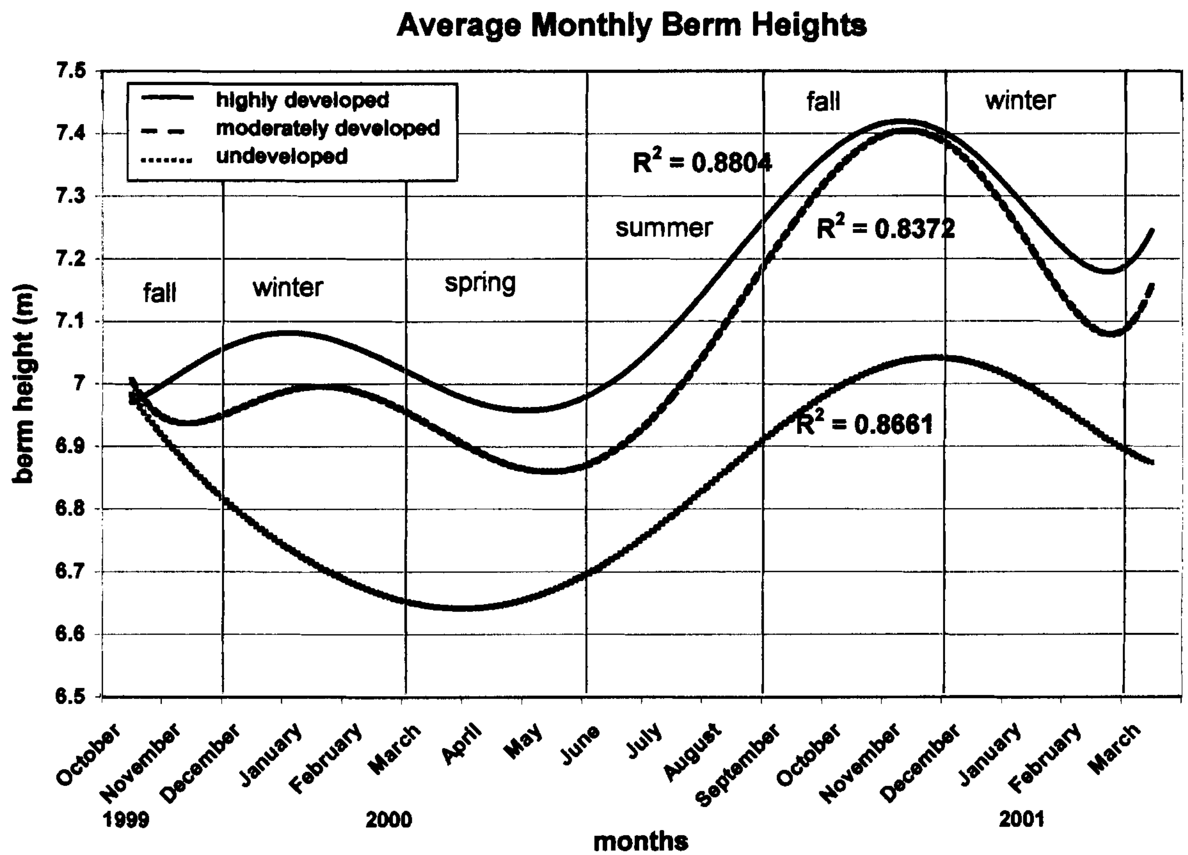


Figure 4.8. Comparison of average monthly berm heights with respect to development level. The berm heights were compiled from an average of the profiles along each beach in a category. The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

December/January (Figure 4.9). In comparison, the berm at Laudholm Beach was highest during the winter months and lower during the summer, although the net elevation change was less than 0.5 m. Ogunquit Beach, Biddeford Pool, and Fortunes Rocks showed the greatest elevation difference with over 1 m of change during the sampling interval (Figure 4.9). Goochs and nearby Middle Beach experienced a net elevation change of 0.5 m over the sampling time.

A polynomial (6^{th} order) regression applied to the average profile of the beaches in Wells Embayment demonstrates the distinct pattern of summer berm accretion and winter berm erosion (Figure 4.10). The R^2 value for the trendline is 0.8866. The shape of the curve closely mimics the shape of the curves for the moderately and highly developed berm heights. The berm height in October 1999 is about 0.4 m less than the berm height in October 2000, which closely corresponds to the difference in berm heights on the moderately and developed beaches during the same months.

There are no clear overall trends to the changes that occurred in Saco Bay (Figure 4.11). However, several of the beaches responded similarly to one another. Higgins spit and Kinney Shores showed the classic response of a beach profile with berm buildup during the summer and a decline during the winter, although the changes along the Higgins spit are more pronounced (Figure 4.11). The Higgins Beach and East Grand profiles tend to covary with only minor fluctuations throughout the first part of the sampling interval, but a 0.5 m increase in berm elevation during the late fall in 2000. Similarly, Western and Ferry Beach responded similarly to one another, with berm buildup beginning in the spring and continuing until the winter of 2001, with a slight decline in elevation in September (Figure 4.11). The profiles along Western and Ferry

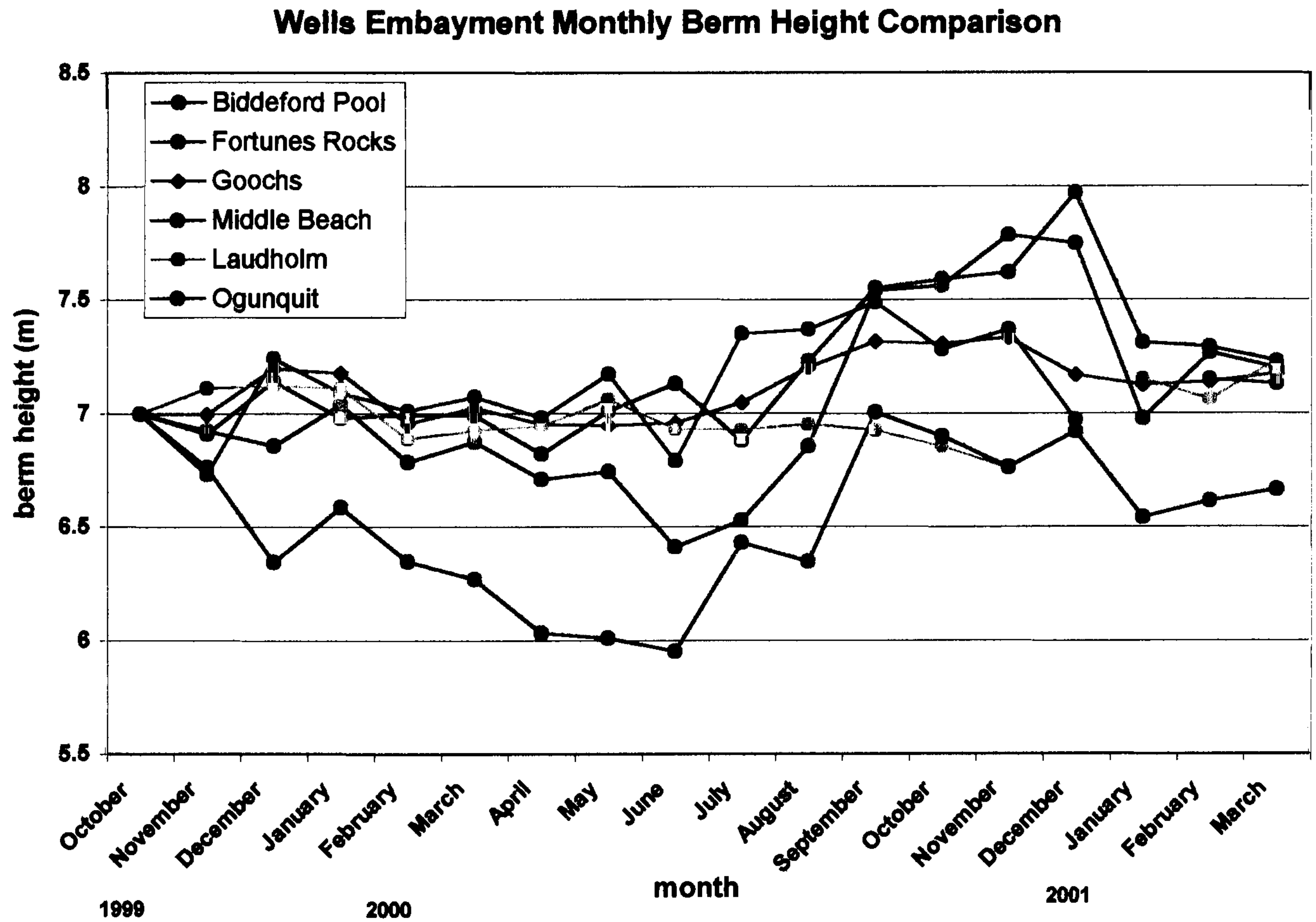


Figure 4.9. Monthly berm heights of beaches in Wells Embayment. The berm heights represent an average of the profiles along each beach. The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

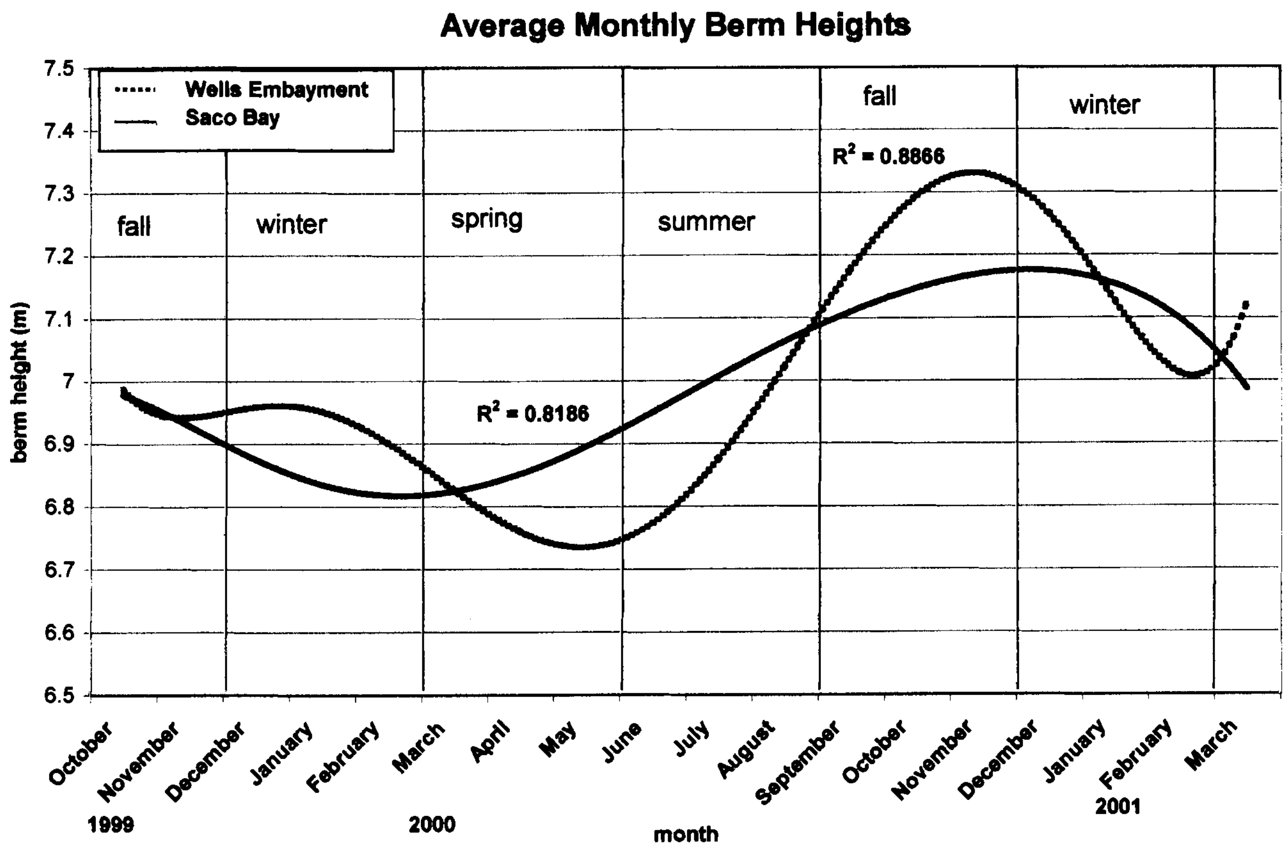


Figure 4.10. Comparison of average monthly berm heights of beaches in Saco Bay and Wells Embayment. The berm heights were compiled from an average of the profiles along each beach within the embayments. The initial heights in October 1999 are fixed, and all other measurements are referenced to them.

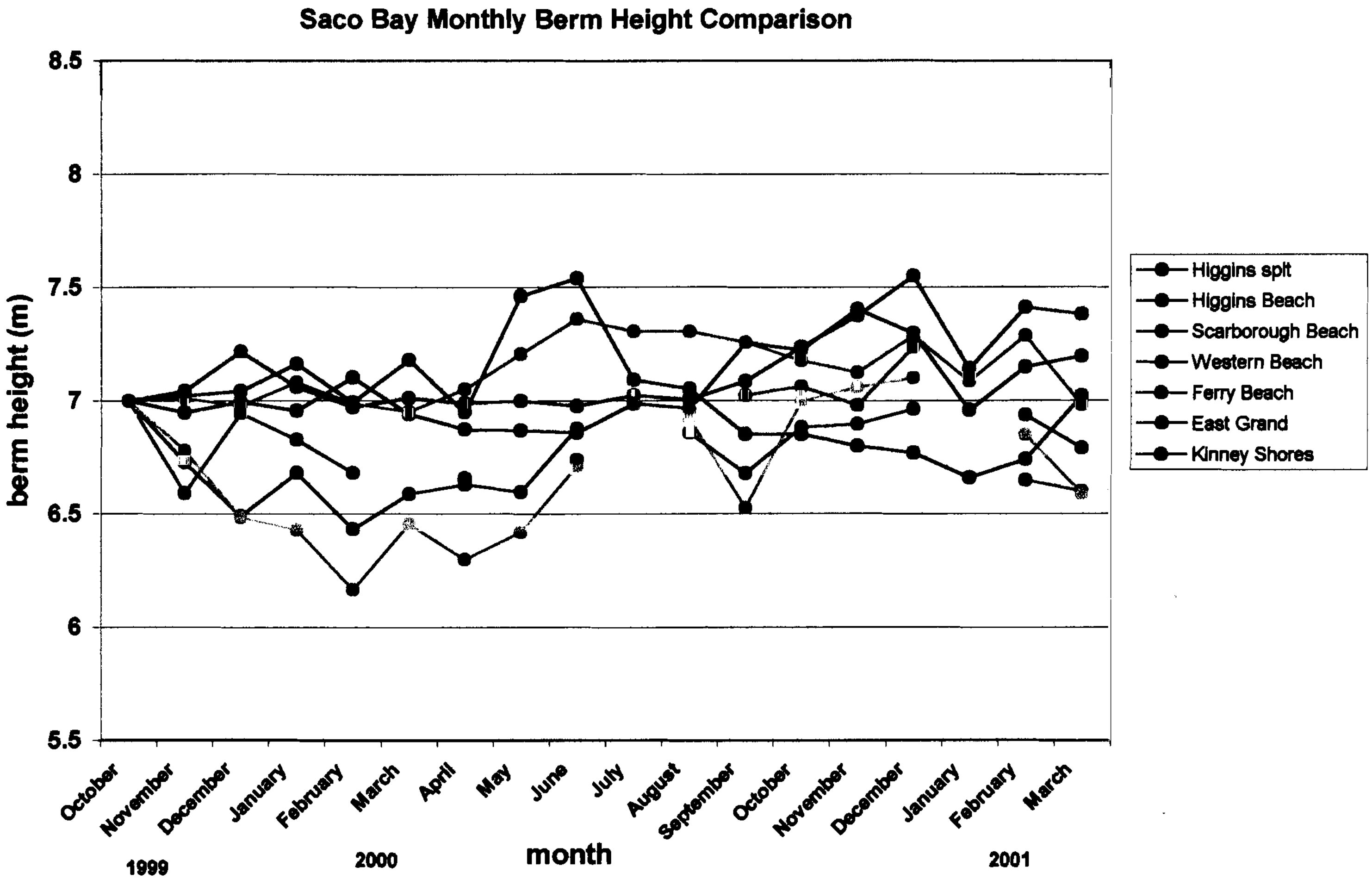


Figure 4.11. Monthly berm heights of beaches in Saco Bay. The berm heights represent an average of the profiles along each beach. The initial height in October 1999 is fixed, and all other measurements are referenced to them.

demonstrated a much larger elevation change than the profiles along Higgins and East Grand Beach. The data from Scarborough are fairly limited because measurements were not made during several months, but the profiles did seem to experiences an increase in berm height starting in early summer and declining after December 2000.

A polynomial (6^{th} order) trendline applied to the average profile of the beaches in Saco Bay demonstrates a pattern of summer berm accretion and winter berm erosion, although the accretionary phase is longer. Also, the elevation change is much less than observed along the beaches in Wells Embayment (Figure 4.10). The R^2 value for the trendline is 0.8186. In addition, the difference in the berm elevation from fall 1999 to fall 2000 is smaller than this same difference at Wells Embayment. The changes along Saco Bay somewhat mimic the changes of the undeveloped beaches.

Active sediment volume

Results from the past 1.5 years show an increase in the volume of active sediment along most beaches (Figures 4.12 and 4.13). Comparison of the volume of active sediment from October 1999 to October 2000 indicates that most beaches gained a significant volume of sand over the course of one year, with Middle Beach gaining between 80-100% more sediment (Figure 4.12). A few places where sediment was lost include Ogunquit Beach, Higgins Beach and Ferry Beach, although the percentage lost along Ogunquit and Higgins fits into the smallest category of sand loss (0-20%).

The amount of sand lost from these beaches was regained within the next six months (Figure 4.13). Comparison of the volume of active sediment from March 2000 to

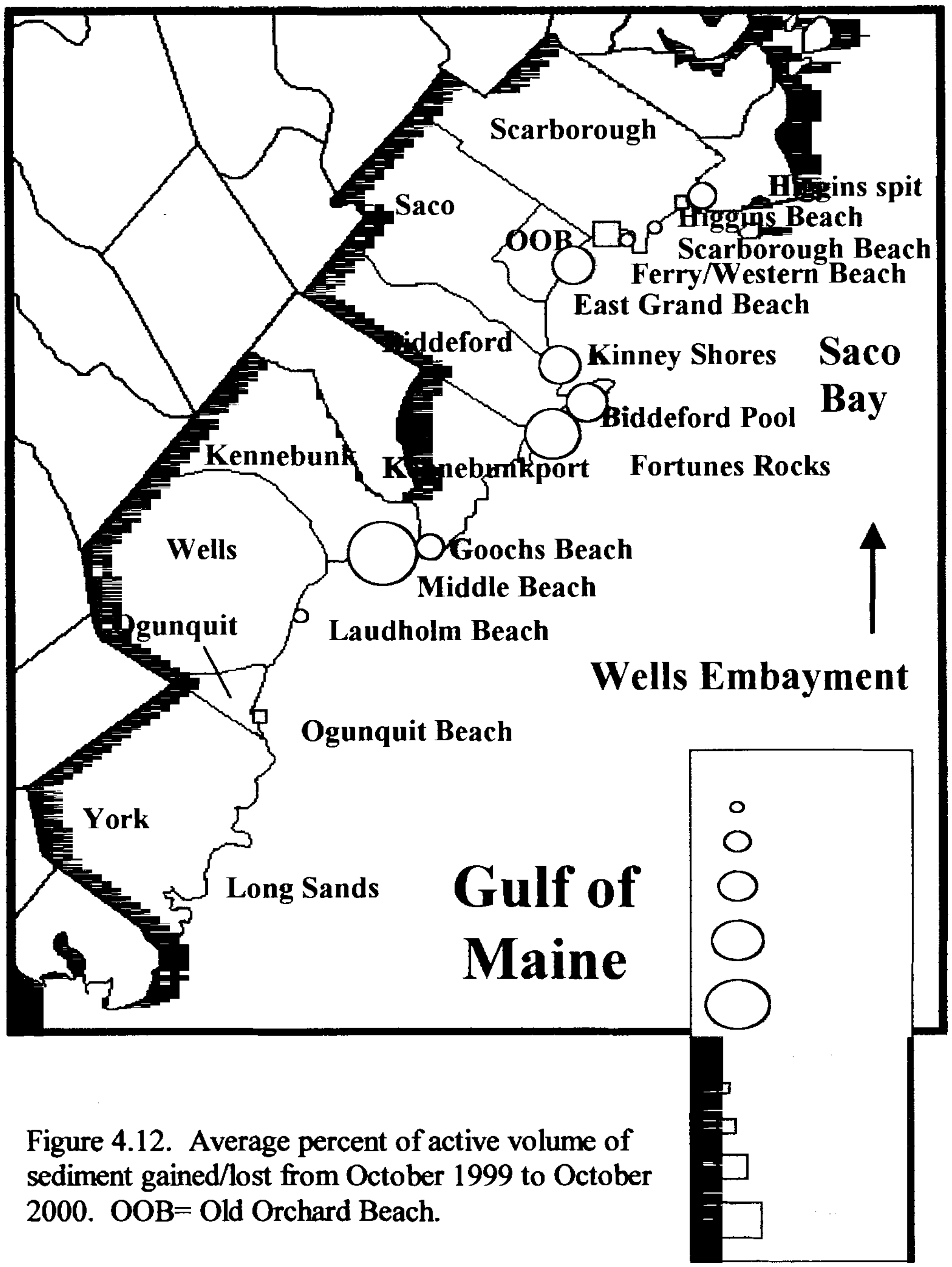


Figure 4.12. Average percent of active volume of sediment gained/lost from October 1999 to October 2000. OOB= Old Orchard Beach.

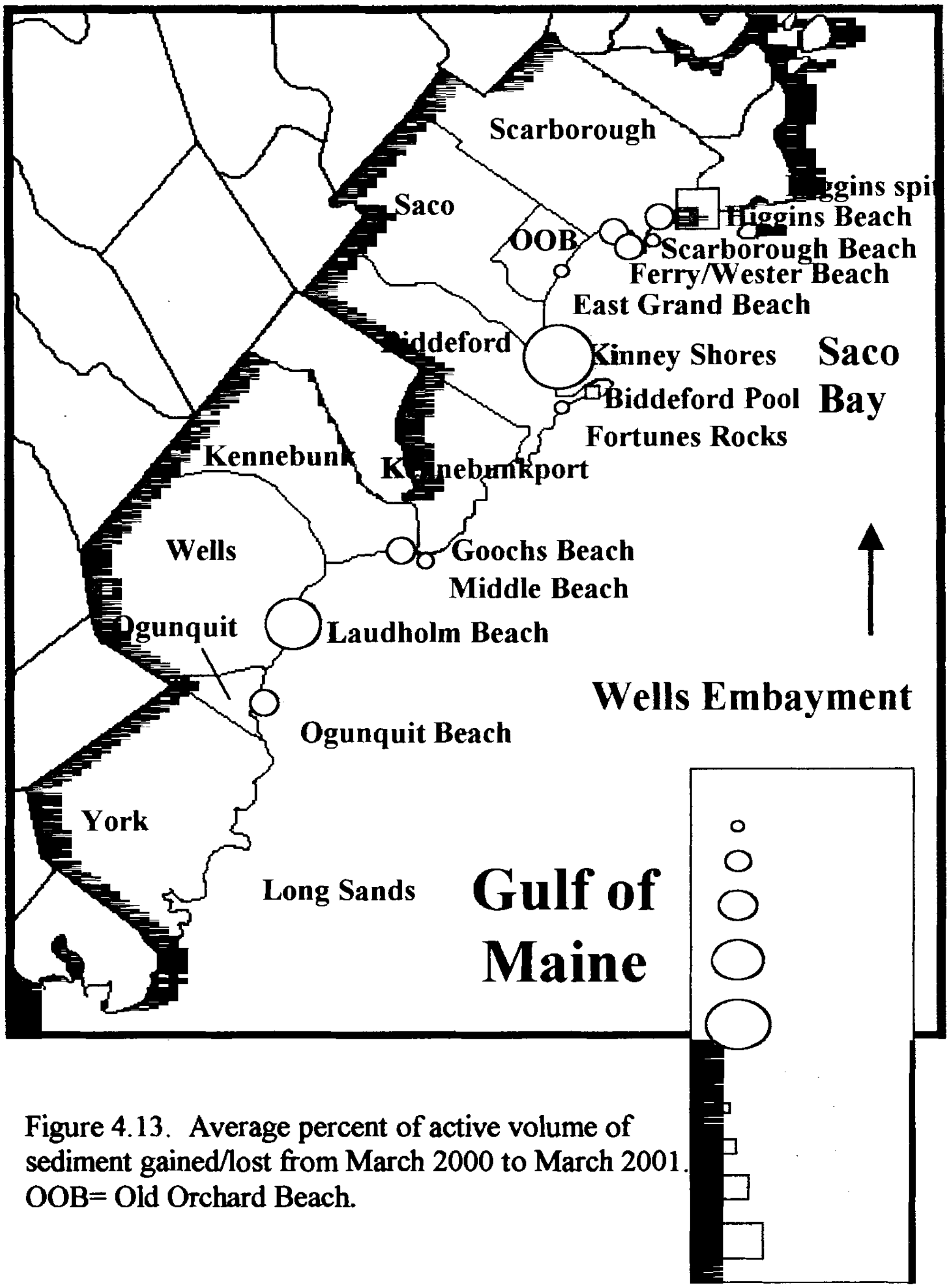


Figure 4.13. Average percent of active volume of sediment gained/lost from March 2000 to March 2001. OOB= Old Orchard Beach.

March 2001 also shows that most beaches gained sediment during this time. A loss of sediment was only documented at Biddeford Pool and along the Higgins spit. The Higgins spit experienced a loss of 60-80% of active sediment. None of the beaches recorded the same volume of sediment from October to March. The distinction between the March and October comparison rests in the incorporation of two winter seasons in the March data.

Profile results following a storm

Five of the volunteer groups made topographic profiles before and after a Northeast storm that hit coastal Maine March 5-6, 2001 (Appendix C). The storm produced changes on all of the beaches, but the results were varied. On the developed beaches (Higgins and Goochs), sand was uniformly eroded along the entire length of the profile (Figure 4.14a). The profile began to build in April and May following the storm, although at this time the profile had not yet reached its pre-storm stage. On the moderately developed beaches (Kinney Shores and Biddeford Pool), sediment was redistributed along the profile and only a small percentage was lost (Figure 4.14b). Following the storm, a distinct berm began to build along these beaches. A redistribution of sediment also occurred along the undeveloped beaches (Ogunquit and Higgins spit), although the most southern two profiles along Ogunquit beach demonstrated distinct erosion without redistribution.

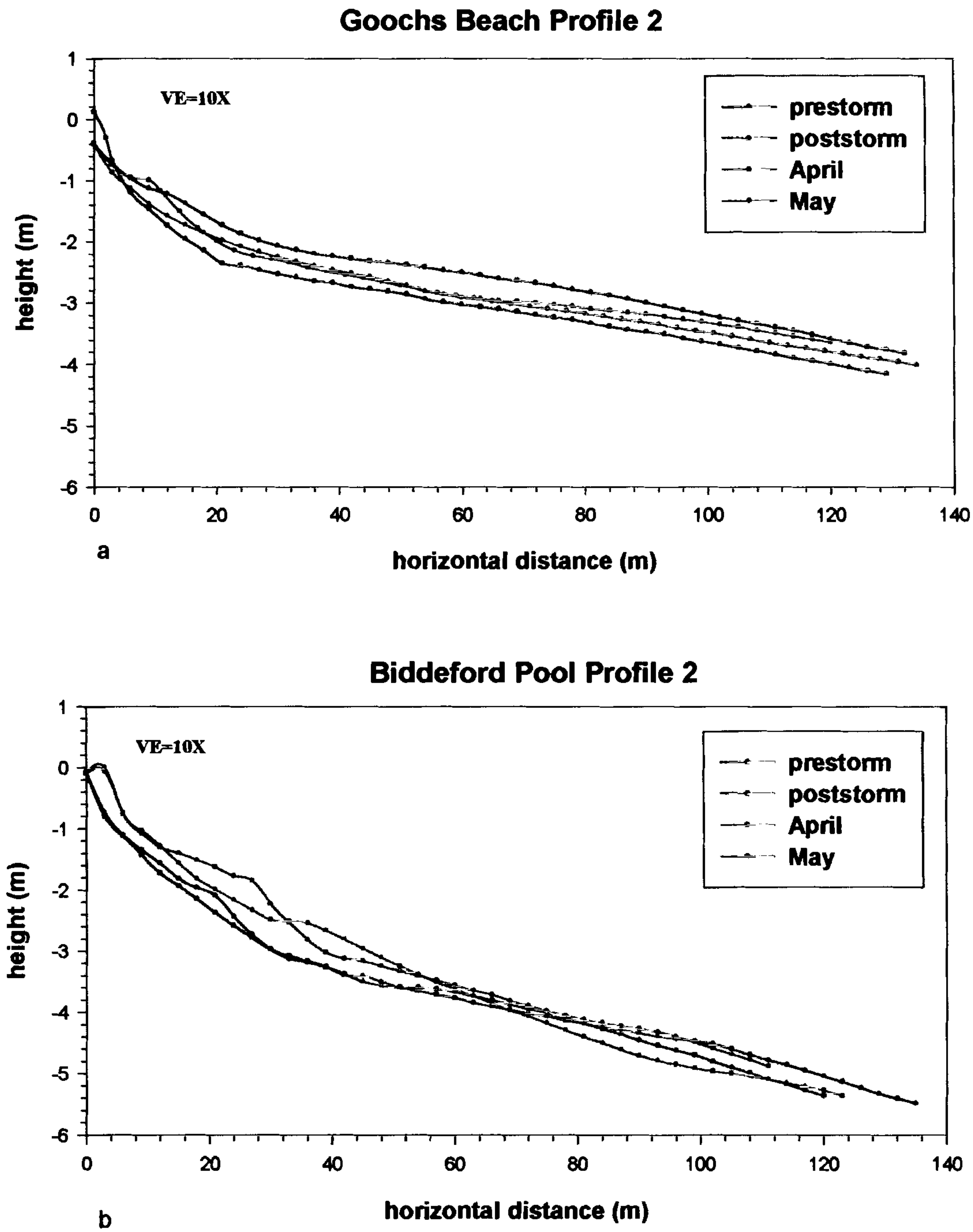


Figure 4.14. Topographic profiles before and after the northeast storm March 5-6, 2001: a. Goochs Beach represents a developed beach. b. Biddeford Pool represents a moderately developed beach.

Summary of profile results

1) Individual beach profiles demonstrated a wide variety of changes over the sampling interval and profiles from any one beach did not necessarily show the same seasonal fluctuations.
2) Overall, the beaches demonstrated a decline in berm height during the winter months and a buildup during the summer months. The undeveloped beaches responded differently from the moderately and highly developed beaches. The berm elevation in October 2000 was much higher than the berm elevation in October 1999 on developed and moderately developed beaches.
3) Most beaches showed an increase in the volume of active sediment over the sampling period.
4) Moderately and highly developed beaches showed a greater elevation change over the sampling time, with faster rates of change, while the undeveloped beaches showed a slower change.
5) The beaches in Wells Embayment showed different trends than those in Saco Bay, and the R^2 value indicates that the beaches in Wells Embayment responded more similarly to one another than the beaches in Saco Bay.

3D Acoustic Current Meters

Current meter data

Four continuous records resulted from the current meter deployments in Saco Bay and Wells Embayment. The current meters documented three types of weather events: frontal passages, southwest storms, and northeast storms. Two types of northeast storms were common; storms that affected the current meters from offshore and storms where the meteorological center of the storm passed directly over the current meter sites. Records from each type of storm show current speed and direction and are described below. Direction of sediment movement is inferred from the net direction of bottom current flow.

During the first deployment in Wells Embayment, the current meter collected 1 Hz burst data for four minutes every six hours, for twenty days (Figure 4.15). During this time, three weather events were recorded. The storms occurred on February 9th, 14th and 19th, 2000 (Figure 4.15), and were classified as a frontal passage, a direct-hit northeast storm, and an offshore northeast storm, respectively. The average wave heights during all three events were between 1.8 and 1.9 m (Table 4.2), but the horizontal speeds during the northeast storms were much higher than those recorded during the frontal passage (Figure 4.16). Bottom currents (1 Hz) reached speeds greater than 40 cm/sec during both northeast storms. The frontal passage resulted in a net bottom current flow to the northeast at speeds up to 25 cm/sec. The direct-hit northeast storm resulted in bottom currents flowing to the southwest.

The northeast offshore storm on February 19, 2000 was the largest event recorded during the sampling interval (Figure 4.17a). The maximum wave height was 2.8 m (Figure 4.17b) and the horizontal scalar speed exceeded 70 cm/sec during the peak of the storm (Figure 4.17a). A four-minute averaging of the 1 Hz burst data shows that average bottom current flow was to the south-southwest (Figure 4.17a), but the 1 Hz burst data demonstrate that the storm resulted in bottom currents flowing in all directions (Figure 4.17b). The threshold velocity of the storm was 18 cm/sec, as indicated by the black

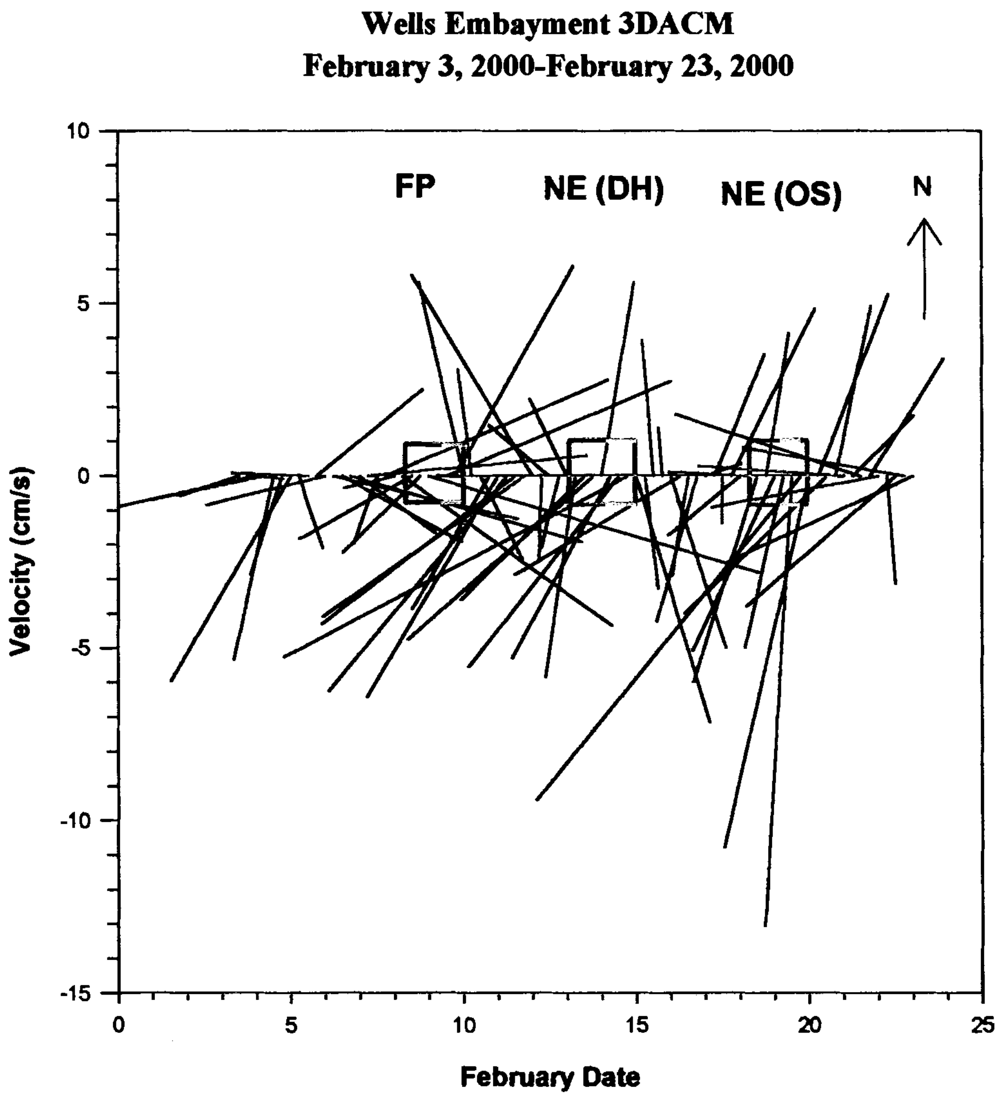


Figure 4.15. Time series of shoreface currents in Wells Embayment, February 2000. Vectors are 6-hourly 4 minute averages of 15 second burst data at 1 Hz (1 m above seabed in 20.2 m water depth). Vectors point in the direction the bottom currents are flowing. FP= frontal passage, NE(DH)= direct-hit northeast storm, NE(OS)= northeast offshore storm. Boxes correspond to specific storm events.

Wells Embayment

Date	Storm Class	Avg Wave Height (m)	Avg Wave Period (s)	Threshold Velocity (cm/s)	Net Sediment Movement	Storm Duration (hours)
2-9-00	Frontal	1.9	7	17	NE	36
2-14-00	NE (DH)	1.8	7	17	SW	36
2-19-00	NE (OS)	1.8	8	18	S	30
12-12-00	SW	1.4	6	16	N	24
12-14-00	NE (DH)	1.6	8	18	E-SE	24
12-17-00	SW	2.9	9	19	N-NW	48
12-31-00	NE (DH)	2.5	8	18	SW	36

Saco Bay

Date	Storm Class	Avg Wave Height (m)	Avg Wave Period (s)	Threshold Velocity (cm/s)	Net Sediment Movement	Storm Duration (hours)
12-12-00	SW	1.4	6	16	W-NW	24
12-14-00	NE (DH)	1.6	8	18	SE	24
12-17-00	SW	2.9	9	19	NW	48
12-31-00	NE (DH)	2.5	8	18	S-SE	36
1-31-01	Frontal	1.3	8	18	S-SE	36
2-5-01	NE (DH)	2.1	9	19	NW	36
2-9-01	SW	1.3	7	17	N	36
2-19-01	Frontal	1.2	6	16	N-NW	48
2-25-01	SW	2.1	8	18	S-SW	24
3-6-01	NE (OS)	3.7	10	20	NE	60

Table 4.2. Characteristics of storms recorded during current meter deployment. Frontal=frontal passage; NE=northeast with two types (OS=offshore, DH=direct hit); and SW=southwest storm

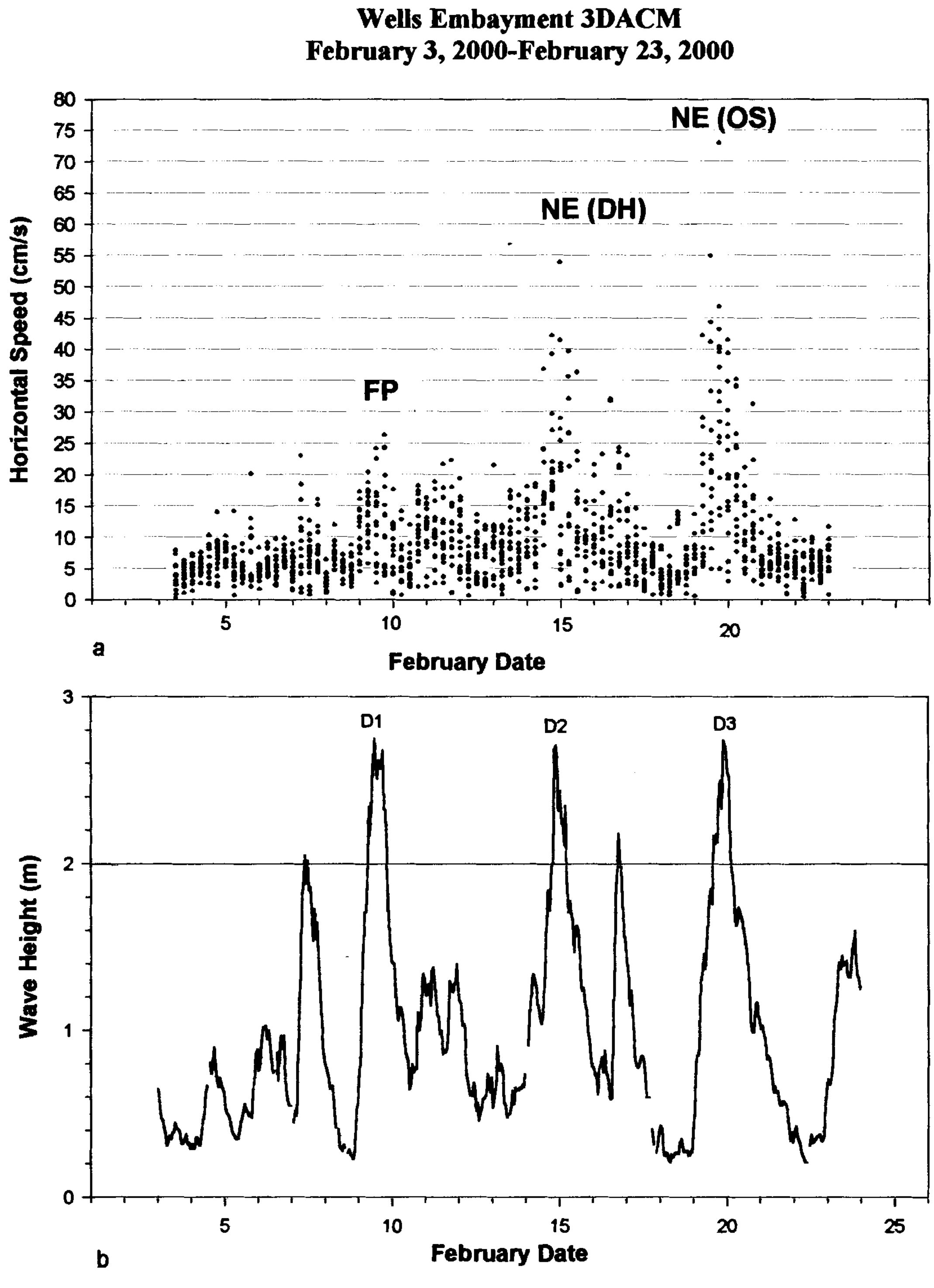


Figure 4.16. Current speed and wave height in Wells Embayment, February 2000. a. Inner shelf current speed from 1 Hz burst data (cm/s) (1 m above seabed in 20.2 m water depth) and b. significant wave height at the NOAA 44007 buoy (Portland, ME). Horizontal line shows minimum criteria for storm selection. Numbers refer to specific storm events (Appendix D). FP=frontal passage, NE(DH)= direct-hit northeast storm, NE(OS)= offshore northeast storm.

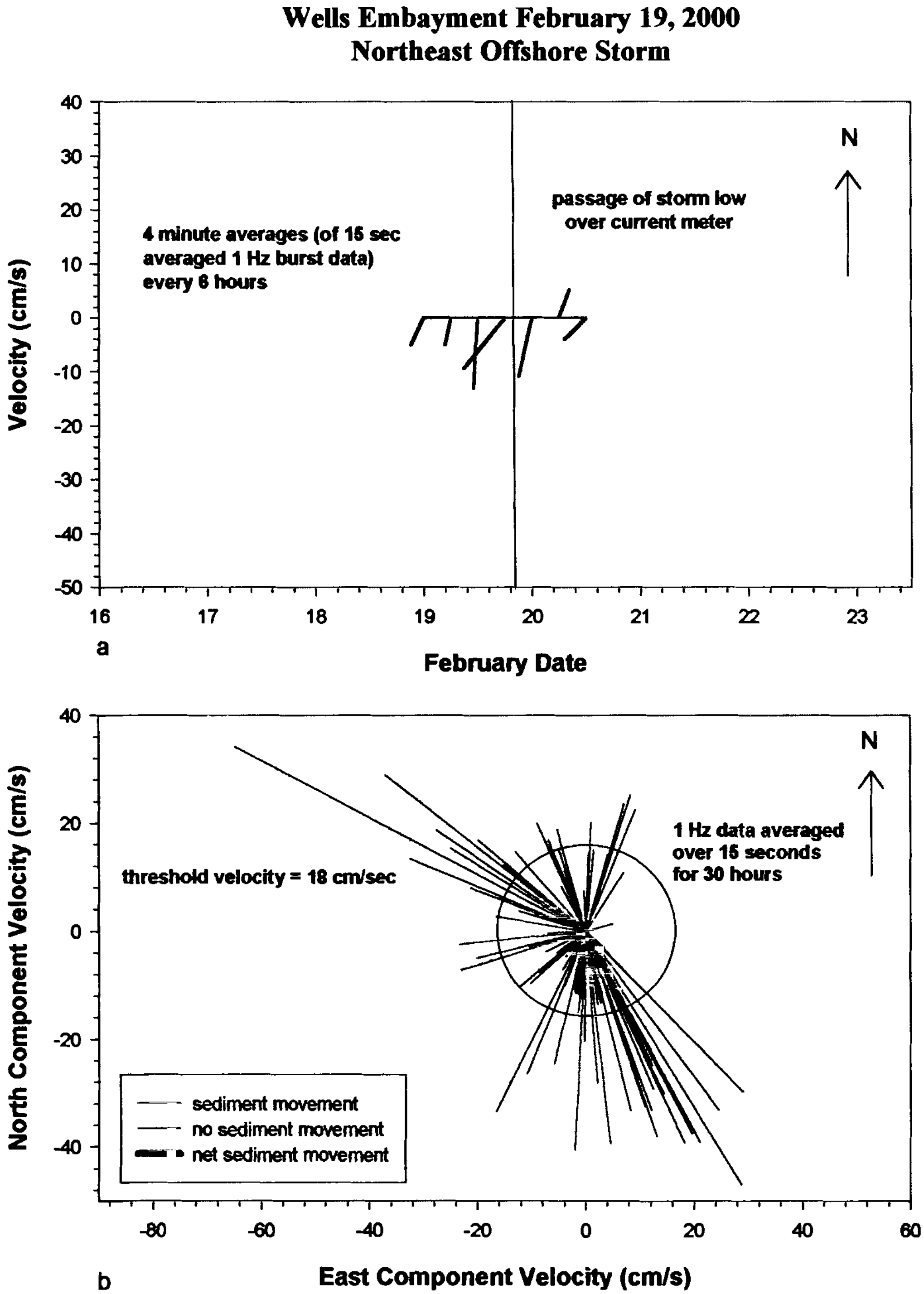
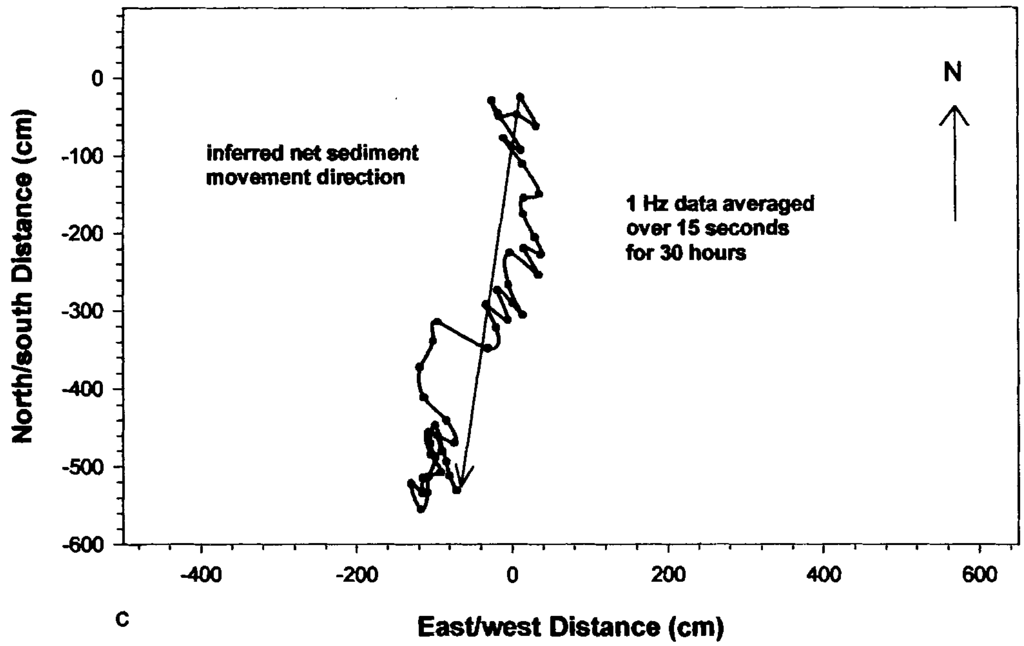


Figure 4.17. Wells Embayment February 19, 2000 offshore northeast storm. a. Combined flow current velocity during the storm and b. burst current velocities during the storm. Vectors point in the direction the current is flowing. Black circle represents18 cm/sec threshold of sand movement.



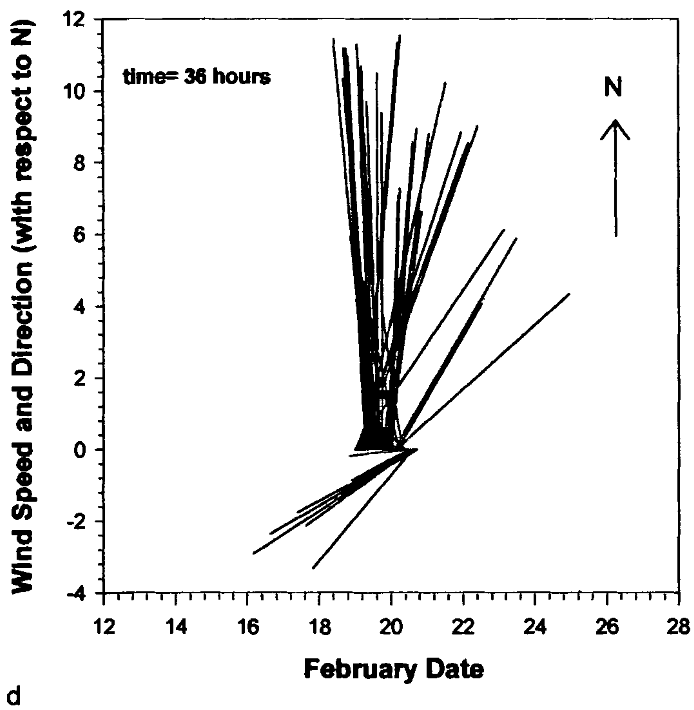


Figure 4.17 (cont). c. Progressive vector plot of combined flow during the February 19, 2000 northeast storm and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

circle (Figure 4.17b); any burst current that exceeded this value was capable of entraining sediment into motion. The net bottom current flow was to the south (Figure 4.17a and b), so it can be inferred that net sediment movement was to the south. The progressive vector plot (Figure 4.17c) shows the estimated path of sediment movement over a 30-hour period. Although the wind field had passed the current meter sites within 24 hours, waves greater than 2 m reached the instruments for an additional 6 hours. The storm persisted over three high tides (NOAA, 2001; NOS, 2001). Winds were from the north through the duration of the storm (Figure 4.17d).

Current meters collected complete records in December 2000 and January 2001 in both Saco Bay (Figure 4.18) and Wells Embayment (Figure 4.19), although the current meter in Saco Bay ran out of memory 8 days earlier than the instrument in Wells Embayment. The current meter in Wells Embayment collected 1 Hz burst data for four minutes every six hours, for 45 days. Due to equipment malfunction, the current meter in Saco Bay collected 1 Hz data at random times during the sampling interval for 37 days. The current meters recorded four storm events on December 12th, 14th, 17th, and 31st, 2000 (Figures 4.18 and 4.19). The storms on December 12th and 17th were classified as southwest storms, while those on the 14th and 31st were northeast storms.

The average wave height during the first two storms exceeded 1.5 m, while the average wave height of the second two storms was 2.9 m (Table 4.2). The highest recorded velocity in Saco Bay was close to 50 cm/sec (Figure 4.20) during a southwest storm on the 19th. In comparison, the highest recorded velocity in Wells Embayment was over 90 cm/sec (Figure 4.21), which occurred during an offshore northeast storm. The two southwest storms recorded a net bottom current flow to the north and/or northwest, in

Saco Bay 3DACM
November 28, 2000- January 10, 2001

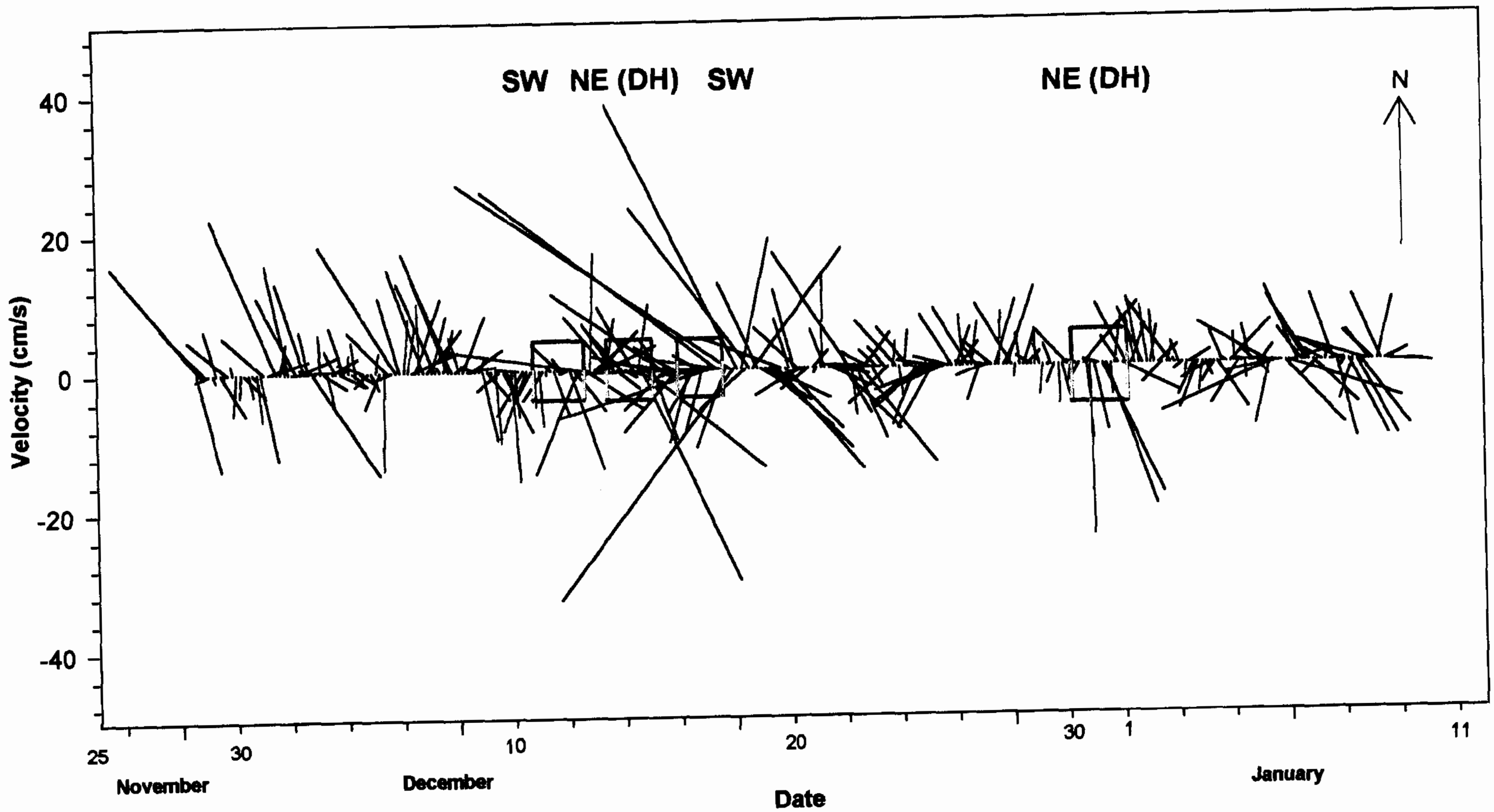


Figure 4.18. Time series of shoreface currents in Saco Bay, November 2000-January 2001. As a result of equipment malfunction, vectors are randomly sampled 1 Hz burst data (1 m above seabed in 20.8 m water depth). Vectors point in the direction the bottom currents are flowing. SW= southwest storms, NE (DH)= direct-hit northeast storms. Boxes correspond to specific storm events.

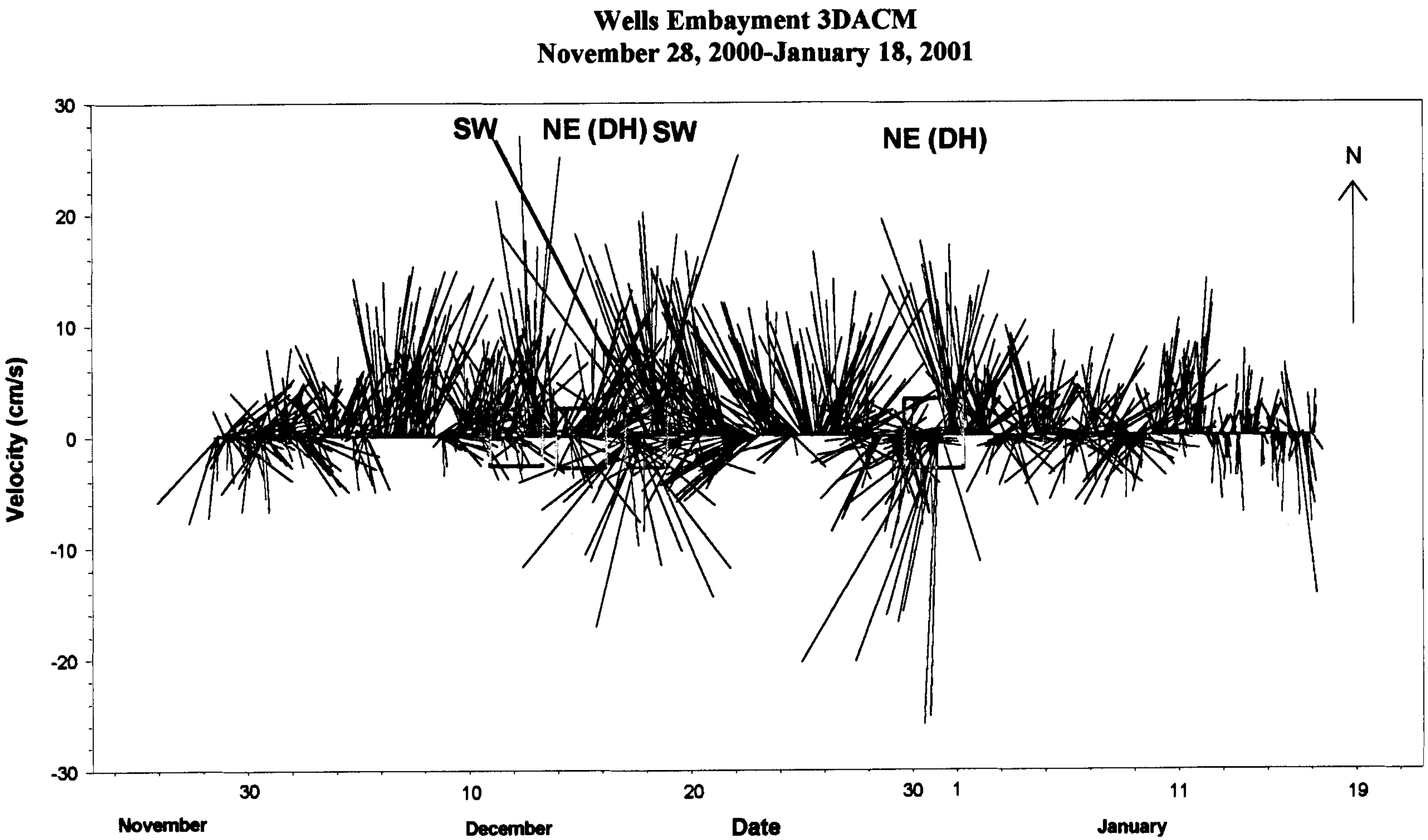


Figure 4.19. Time series of shoreface currents in Wells Embayment, November 2000-January 2001. Vectors are hourly 4-minute averages of 15 second burst data at 1 Hz (1 m above seabed in 21.4 m water depth). Vectors point in the direction the bottom currents are flowing. SW= southwest storms, NE (DH)= direct-hit northeast storms. Boxes correspond to specific storm events.

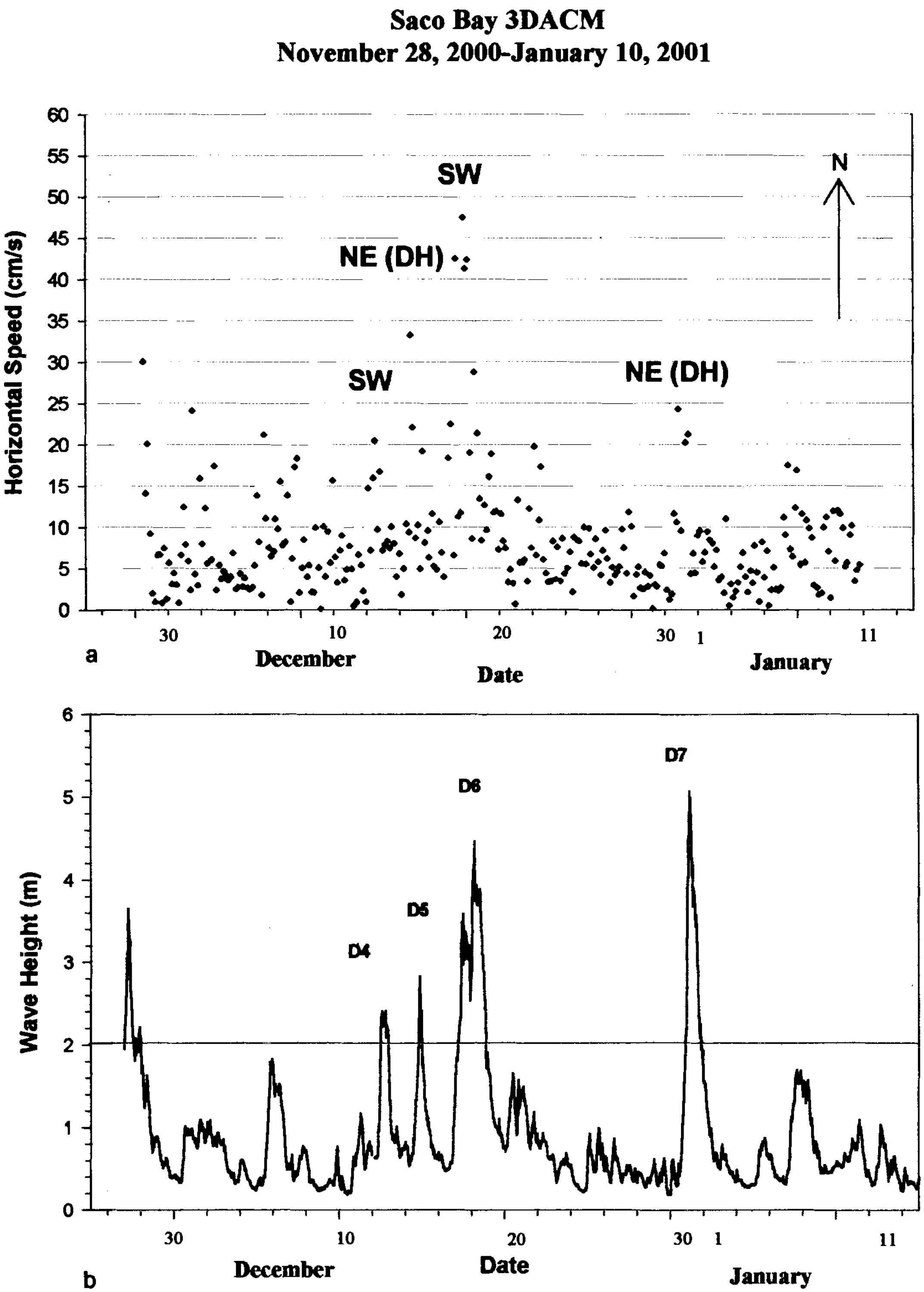


Figure 4.20. Current speed and wave height in Saco Bay, November 2000-January 2001. a. Inner shelf current speed from 1 Hz burst data (cm/s) (1 m above seabed in 20.8m water depth) and b. significant wave height at the NOAA buoy 44007(Portland, ME). Horizontal line shows minimum criteria for storm selection. Numbers refer to specific storm events (Appendix D). SW= southwest storm, NE (DH) = direct-hit northeast storm.

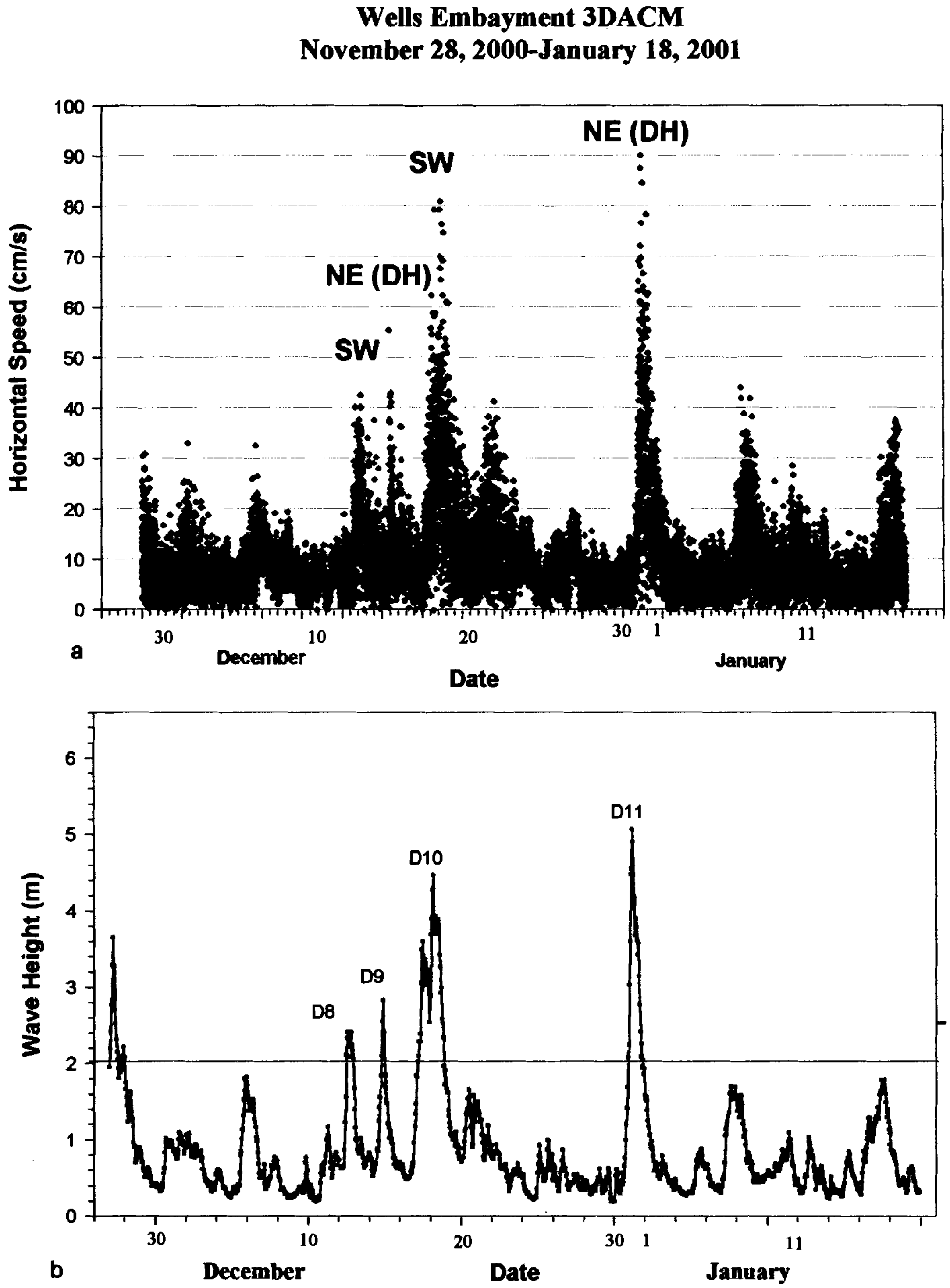


Figure 4.21. Current speed and wave height in Wells Embayment, November 2000-January 2001. a. Inner shelf current speed from 1 Hz burst data (cm/s) (1 m above seabed in 21.4 m water depth) and b. significant wave height at the NOAA buoy 44007 (Portland, ME). Horizontal line shows minimum criteria for storm selection. Numbers refer to specific storm events (Appendix D). SW= southwest storm, NE (DH)= direct-hit northeast storm.

both Saco Bay and Wells Embayment. The northeast storms resulted in a net bottom current flow to the east-southeast in both embayments, with the exception of the northeast storm on December 31st that produced net flow to the west in Wells Embayment.

The record from Wells Embayment during the December 12th, 2000 storm shows the expected response of currents to southwest storms (Figure 4.22a-d). Before passage of the storm, bottom currents flowed to the southeast. Once the meteorological storm center passed the current meters, the bottom current velocity increased and average flow was to the north (Figure 4.22a). The maximum wave height during this storm was 2.3 m (Figure 4.21) and the threshold velocity was 16 cm/sec (Table 4.2), as indicated by the black circle. The instrument recorded horizontal scalar speeds that exceeded 40 cm/sec at one instant (Figure 4.21). Although the storm produced bottom currents flowing in all directions (Figure 4.22b), net flow was to the north (Figure 4.22b and c). The storm lasted for 24 hours and persisted over 2 high tides (NOAA, 2001; NOS, 2001). Winds were from the northeast and southeast before the storm passed over the current meters and then switched to the northwest (Figure 4.22d).

The direct-hit northeast storm that struck the coast on December 31st, 2000 was the largest recorded during the sampling interval (Figures 4.20 and 4.21). In Wells Embayment, current speeds exceeded 90 cm/sec (4.21a). Before passage of the storm, bottom currents flowed to the south-southwest (Figure 4.23a). Upon passage of the meteorological low over the instruments, the bottom currents abruptly switched direction and flowed north-northeast (Figure 4.23a). The maximum wave height during the storm was just over 5 m (Figure 4.21b) and the threshold velocity for sediment movement was 18 cm/sec, as indicated by the black circle (Figure 4.23b). Although currents flowed in

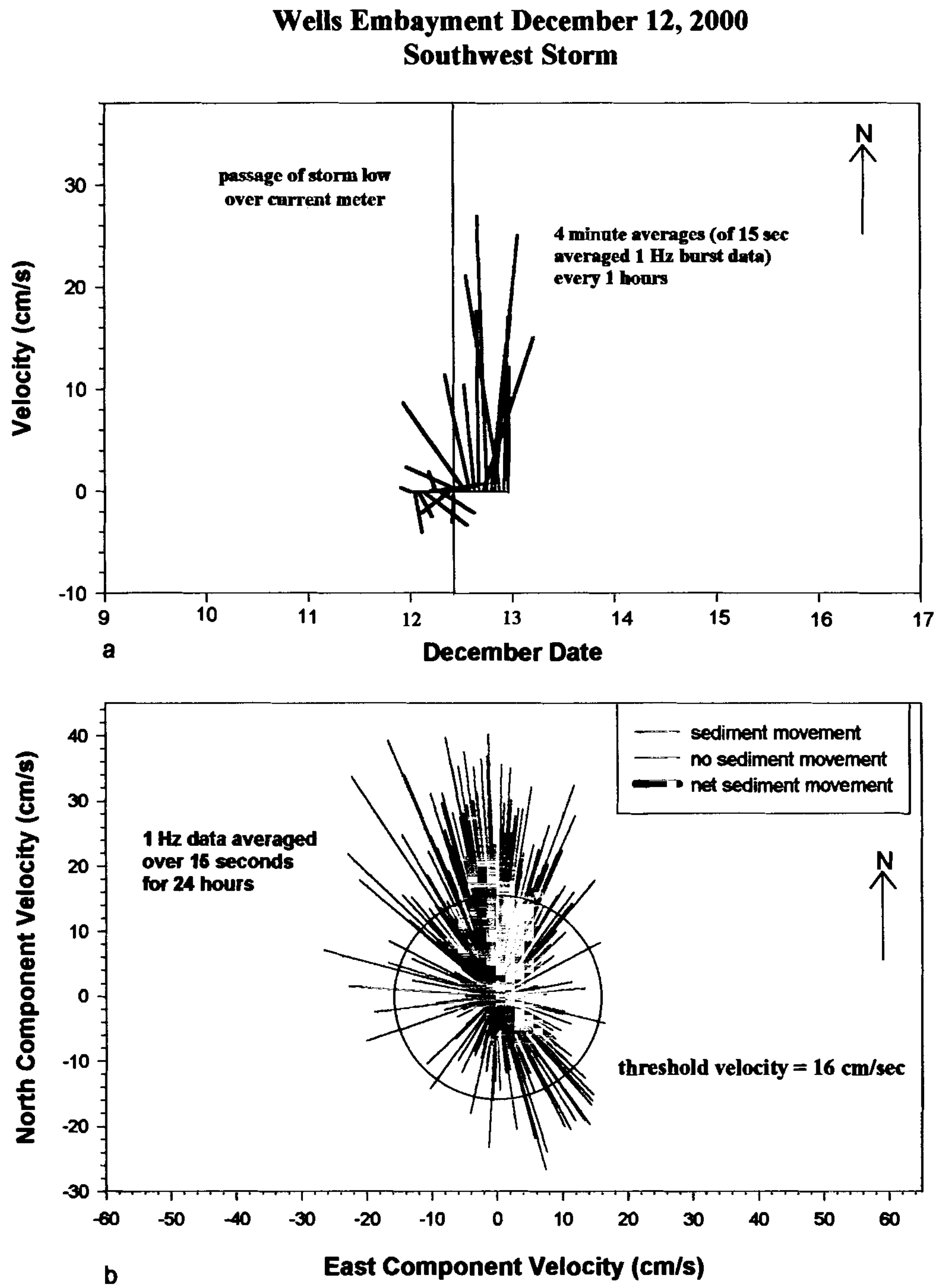
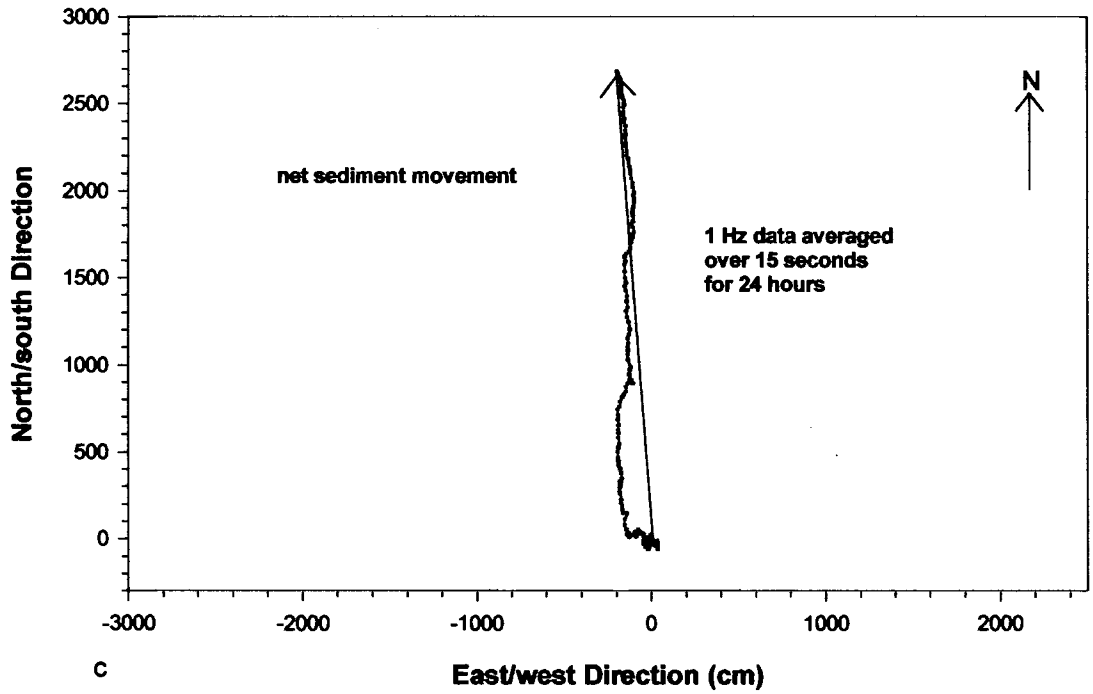


Figure 4.22. Wells Embayment December 12, 2000 southwest storm. a. Combined flow current velocity during the storm and b. burst current velocities during the storm. Vectors point in the direction the current is flowing. Black circle represents 16 cm/sec threshold of sand movement.



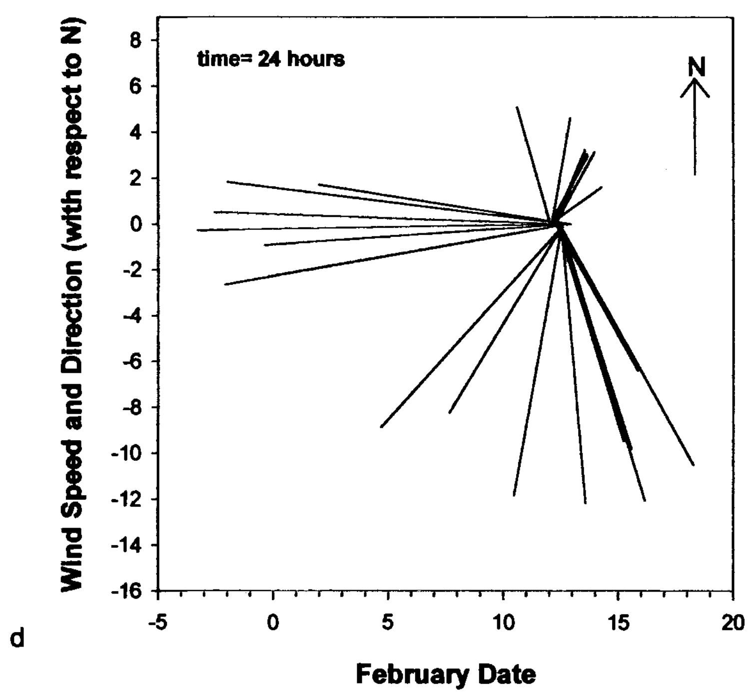


Figure 4.22 (cont) c. Progressive vector plot of combined flow during the December 12, 2000 southwest storm and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

Wells Embayment December 31, 2000
Northeast Storm (direct hit)

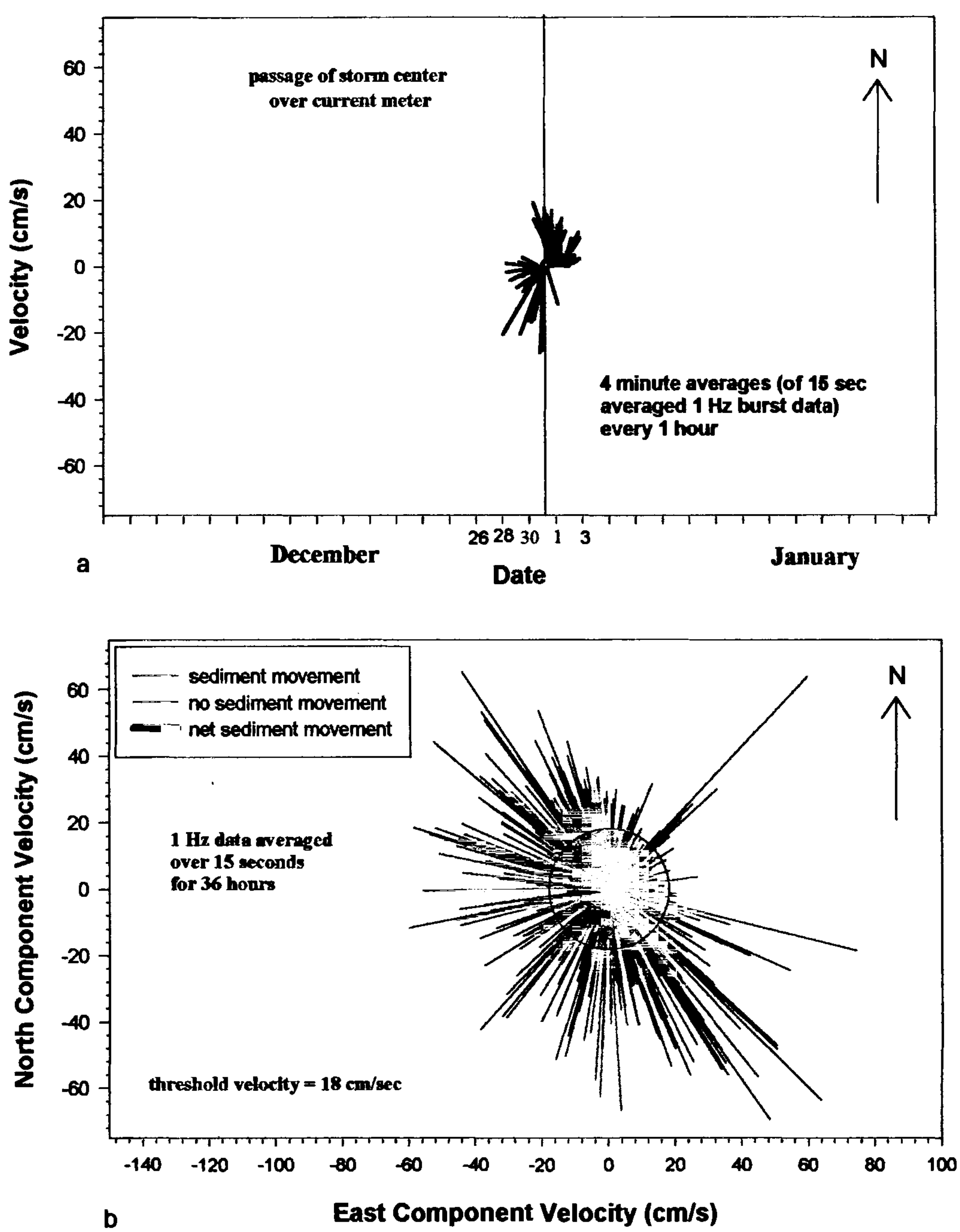
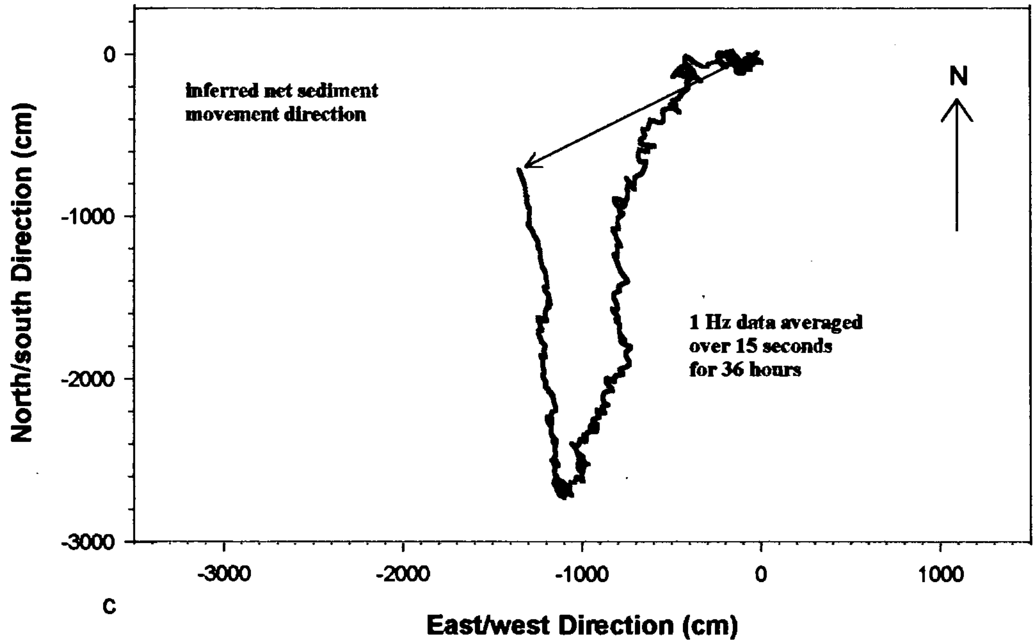


Figure 4.23. Wells Embayment December 31, 2000 offshore northeast storm.
a. Combined flow current velocity during the storm and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.
Black circle represents the 18 cm/sec threshold of sand movement.



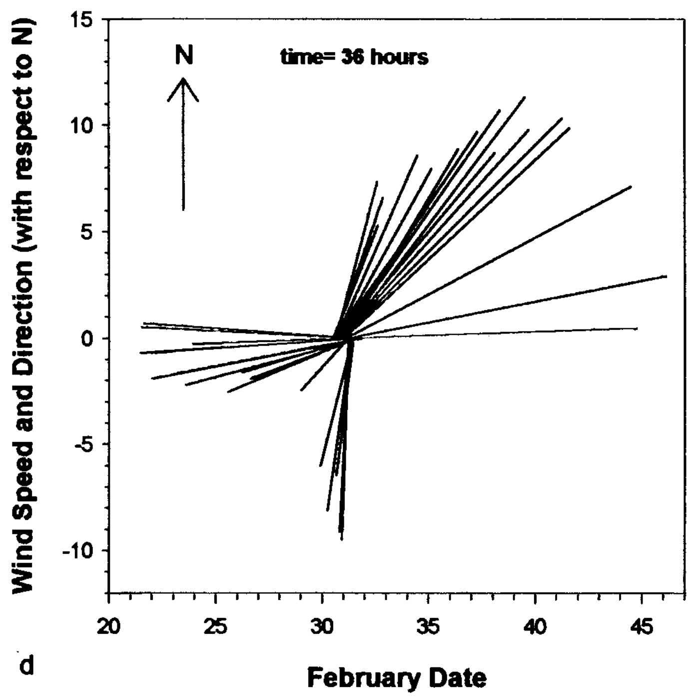


Figure 4.23 (cont) c. Progressive vector plot of combined flow during the December 31, 2000 northeast storm and d. wind direction during the storm from the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

all directions, the net current flow was to the southwest as shown by the burst data (Figure 4.23b) and the progressive vector plot (Figure 4.23c). The storm lasted for 36 hours and persisted over 3 high tides (NOAA, 2001; NOS, 2001). Winds were from the northeast before the storm and from the west upon passage of the storm (Figure 4.23d).

Following retrieval of the current meter in January 2001, the instruments were immediately redeployed. The current meter in Saco Bay was placed in the same location and produced a 45-day record (Figure 4.24). The current meter in Wells Embayment was placed in a new location but a record was not taken as a result of programming errors. The Saco Bay instrument recorded 1 Hz burst data for four minutes every hour. Six storm events occurred: 2 frontal passages on January 31st and February 19th, 2 southwest storms on February 9th and 25th, and 2 northeast storms on February 5th and March 6th (Figures 4.24 and 4.25). The northeast storm in February traveled directly over the current meter, while the storm in March was offshore.

These 6 storm events resulted in a range of wave heights from 1.2 m on February 19th to 3.7 m on March 6th (Table 4.2). The horizontal scalar speeds also showed a wide range from 40 cm/sec to over 100 cm/sec (Figure 4.25). Several of the storms produced unexpected results. The frontal passage on January 31st resulted in a net bottom current flowing to the south-southeast, while the frontal passage on February 19th, showed a north-northwest flow. The two southwest storms documented distinctly different flow directions as well; the storm on February 9th resulted in currents flowing to the north, while the storm on February 25th produced currents flowing to the south-southwest. The northeast storms produced bottom currents flowing to the northwest and the northeast.

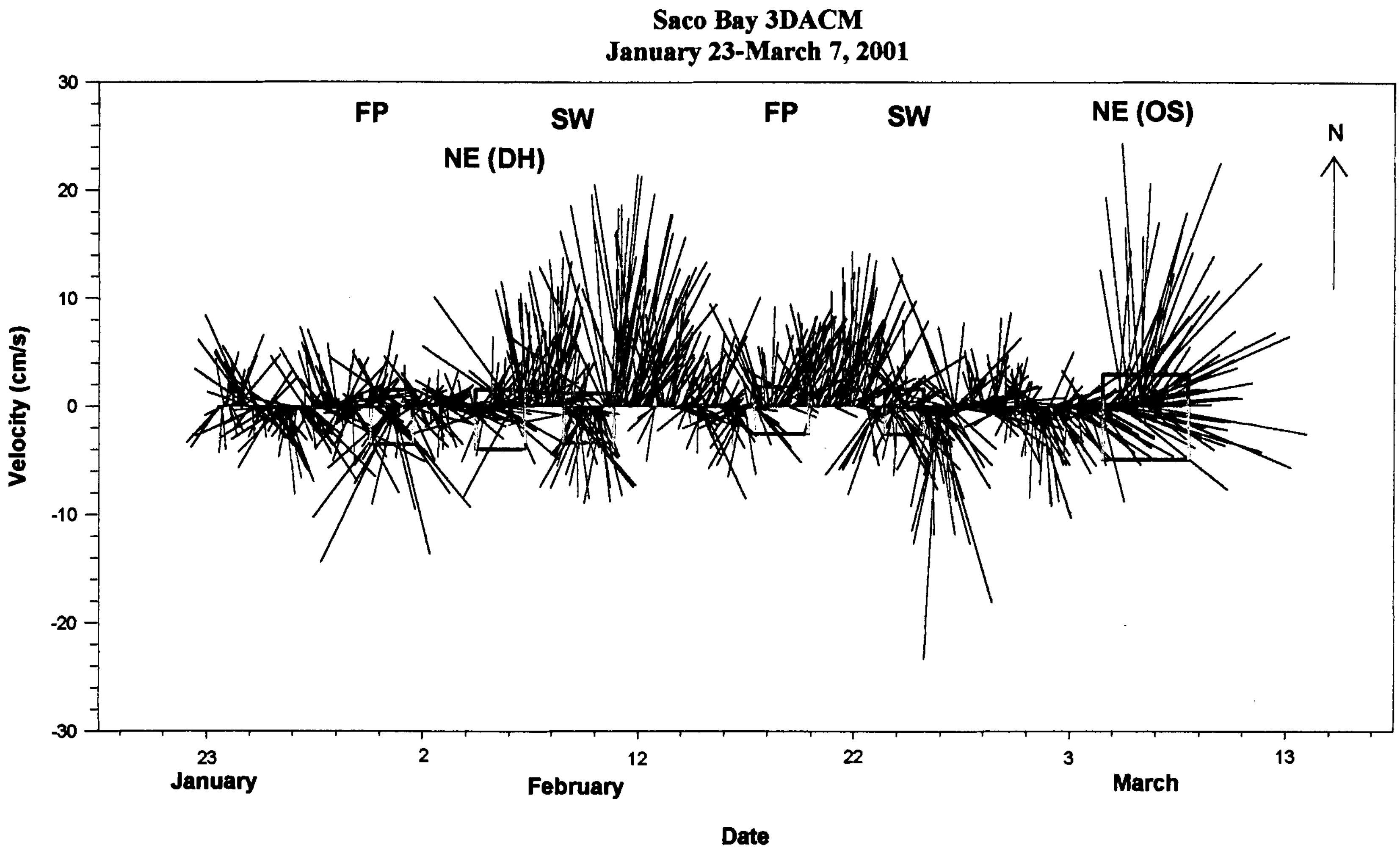


Figure 4.24. Time series of shoreface currents in Saco Bay, January 2001-March 2001. Vectors are hourly 4-minute averages of 15 second averaged burst data at 1 Hz (1 m above seabed in 20.8 m water depth). FP= frontal passage, NE (DH)= direct-hit northeast storm, SW= southwest storm, NE (OS)= offshore northeast storm. Boxes correspond to specific storm events.

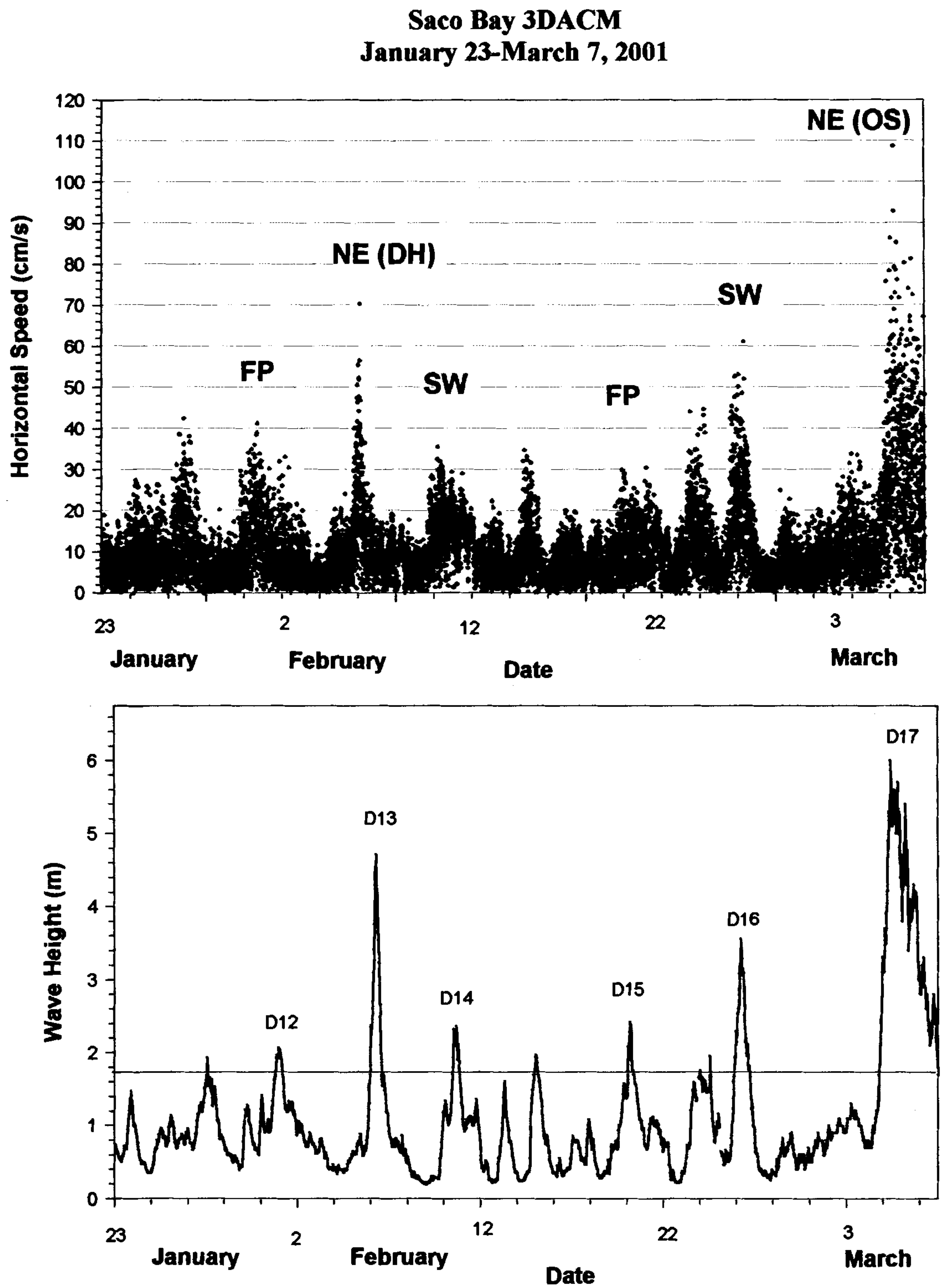


Figure 4.25. Current speed and wave height in Saco Bay, January 2001-March 2001. a. Inner shelf current speed from 1 Hz burst data (cm/s) (1 m above seabed in 20.8 m water depth) and b. significant wave height at the NOAA 44007 buoy (Portland, ME). Horizontal line shows minimum criteria for storm selection. Numbers refer to specific storm events (Appendix D). FP= frontal passage, NE (DH)= direct-hit northeast storm, SW =southwest storm, NE (OS)= offshore northeast storm.

A southwest storm on February 9th-10th, 2001 in Saco Bay produced results similar to the southwest storm in Wells Embayment on December 12th, 2000 (Figures 4.26a-d). Bottom currents flowed to the south initially, and then flowed north at a faster speed upon passage of the storm (Figure 4.26a). The transition between flow directions was abrupt, as it was in the December 12th record. Although currents flowed in all directions, net bottom current flow was directed to the north (Figures 4.26b and c). The maximum wave height during the storm was 2.4 m (Figure 4.25b) and the threshold velocity for sediment movement was 17 cm/sec, as indicated by the black circle (Figure 4.26b). The storm persisted for 36 hours over 3 high tides. Winds were from the southwest before arrival of the storm and from the northwest following passage of the storm (Figure 4.26d).

Summary of current meter results

1) Saco Bay and Wells Embayment showed similar responses to an average of three out of four storms.
2) Over two-thirds of northeast storms resulted in downwelling and net sediment movement to the south. In Wells Embayment, the southwest flow likely stayed in the shoreface paralleling the coast. In Saco Bay, however, some of the sediment may have been transported down the shelf valley.
3) The current meters showed a similar response to northeast storms with an offshore track and northeast storms where the meteorological center passed directly over the current meter. A distinct bi-directional flow was produced with the current direction switching upon passage of the storm center; bottom flow was to the southwest before

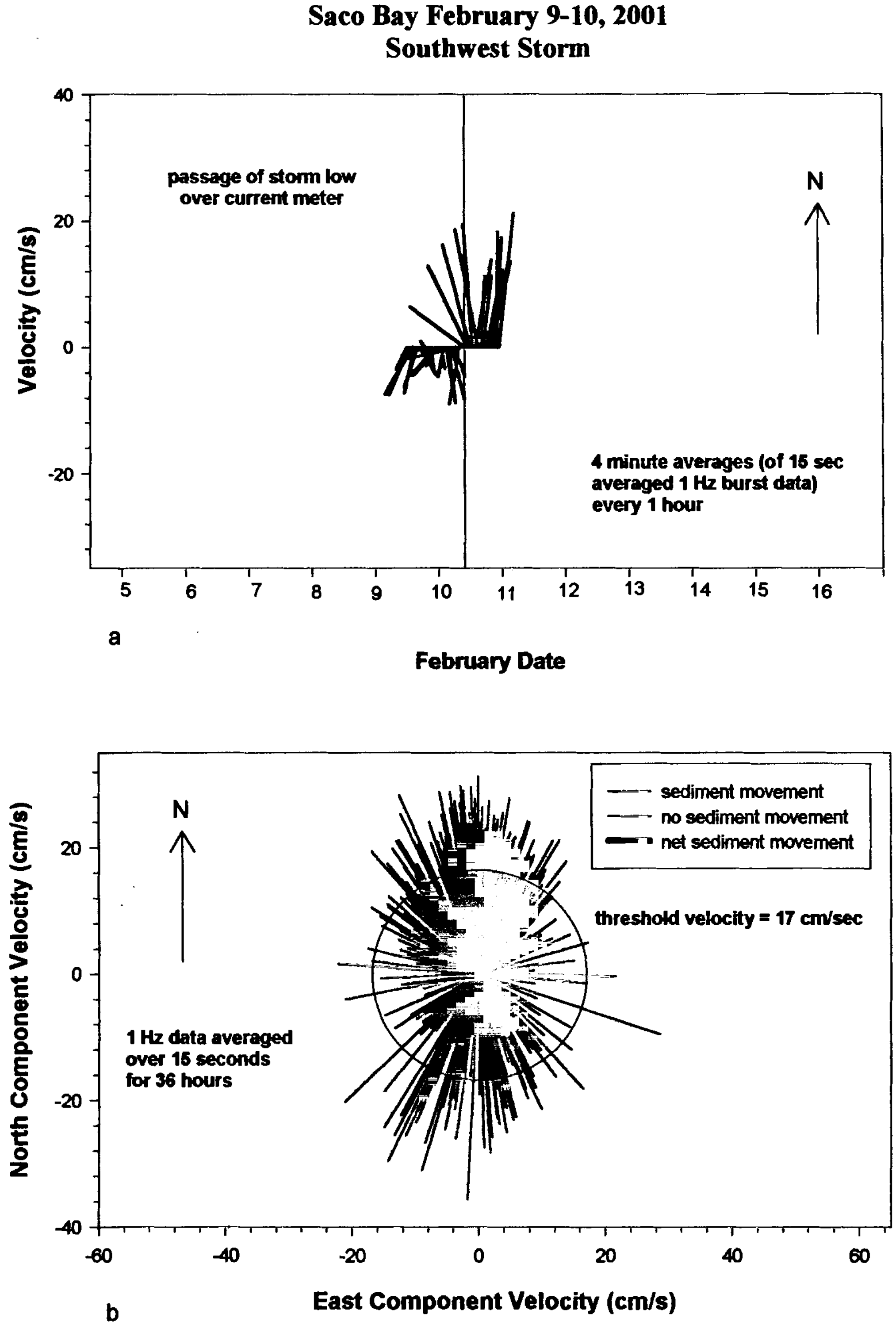
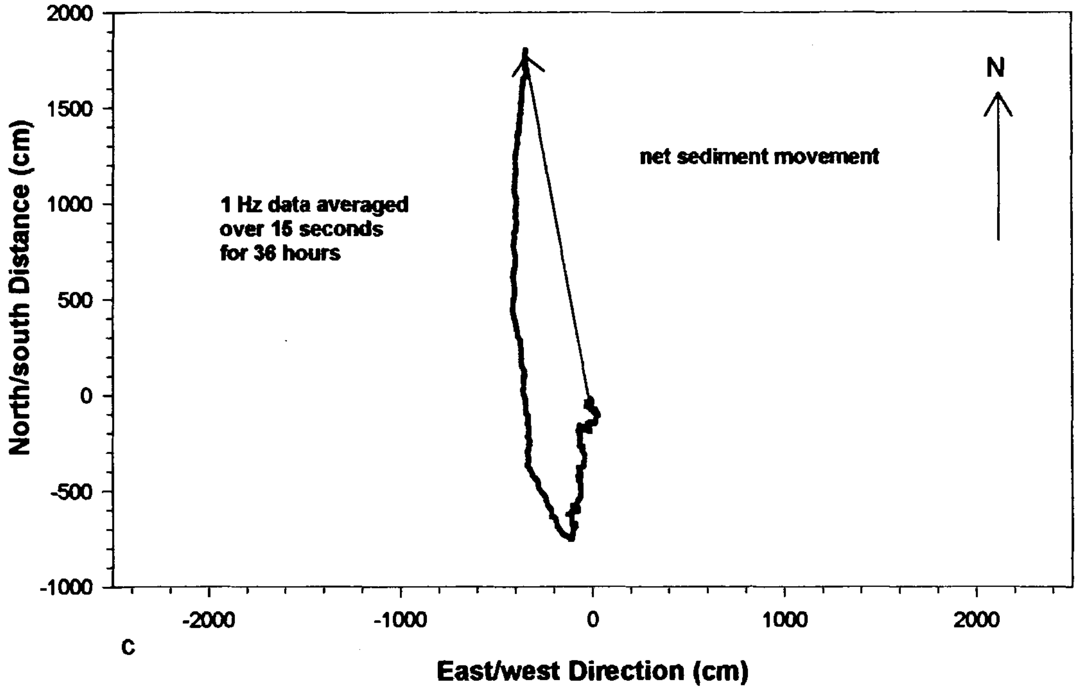


Figure 4.26. Saco Bay February 9-10, 2001 southwest storm. a. Combined flow current velocity during the storm and b. burst current velocities during the storm. Vectors point in the direction the current is flowing. Black circle represents the 17 cm/sec threshold of sand movement.



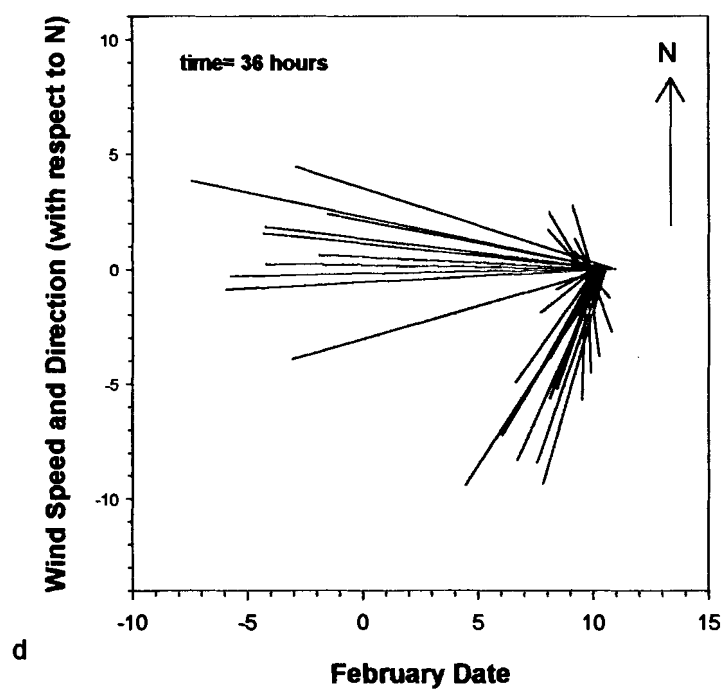


Figure 4.26 (cont) c. Progressive vector plot of combined flow during the February 9-10, 2001 southwest storm and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

4) the storm and to the northeast after passage of the storm. The current velocity was greatest during southwest flow.

5) In general, southwest storms and frontal passages created upwelling and net sediment movement to the north

6) Northeast storms produced the largest average wave heights and strongest currents. The largest average wave height during the study period was 3.7 m during an offshore northeast storm on March 5^{th}-6^{th}, 2001. This storm also produced the strongest currents, over 100 cm/sec.

Significant Wave Height

The mean significant wave height from June 1999-March 2001 (Figure 4.27) showed low values in the summer and high values in the winter. The lowest value during the summer of 1999 occurred in August, from which point the wave height began to slowly increase. The wave height reached a peak in April and then declined significantly. In contrast, the wave height during the summer of 2000 stayed at a relatively constant value until January 2001. After this point, the wave height increased at a much steeper rate, and continued through March. The significant wave heights during the first year were consistent with historical trends (Figure 4.27). This was not the case during the second year, where the wave height did not begin to increase until January, as opposed to August/September.

Significant Wave Height

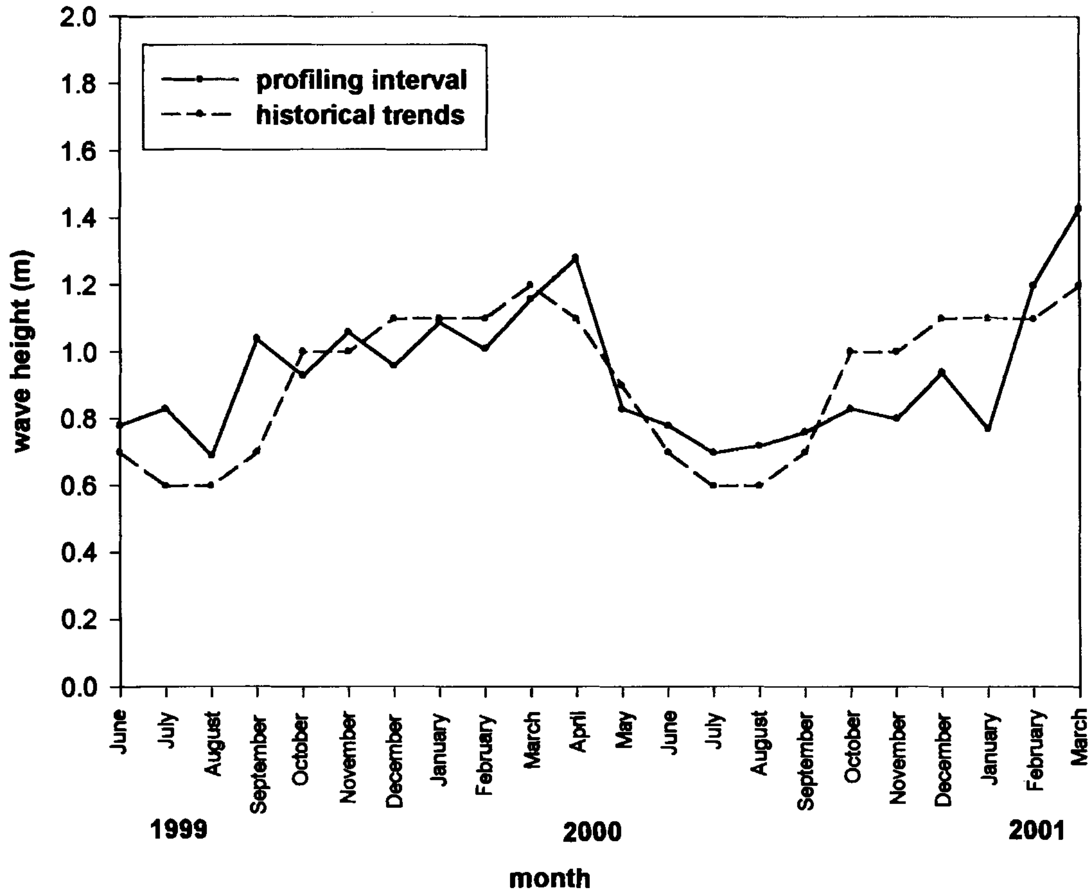


Figure 4.27. Significant wave height from June 1999-March 2001. Blue line represents observed wave heights over the sampling interval. Red line represents historical trends observed at the NOAA buoy 44007 (Portland, ME).

Winter Storms

Knowing the meteorological conditions during the interval when the volunteers made profiles may aid in understanding the changes that occurred along the beaches. Storm events during the winter months (October-March) of 1999-2000 and 2000-2001 were defined as having a wave height greater than 2 m and were classified as frontal passages, southwest storms, offshore northeast storms and direct-hit northeast storms (Figure 4.28). For each storm event, the significant wave height, storm duration, storm surge, and number of high tides where the observed water level was greater than the predicted water level, were determined (Table 4.3). The storm duration was defined by the time the wave height first exceeded 2 m, until it fell below 1.25 m.

There were 19 total storm events from October 1999-March 2000 (Figure 4.29a) and 17 storm events from October 2000-March 2001 (Figure 4.29b). Storms during the first winter mostly occurred during the months of December, January, and February, while storms during the second winter were more evenly distributed throughout the months (Figures 4.29a and b). During the first winter, 40% of storms were frontal passages. Southwest storms comprised 25% of storms, while northeast storms were 35%. In comparison, 53% of storms during the second winter were northeast storms, while the number of frontal passages was equal, each with 23.5% (Figure 4.30).

Three offshore northeast storms in March 2001 produced the largest significant wave heights during the two winters (Table 4.3). The highest significant wave height of 5.89 m was measured on March 22, 2001. Storms on March 6, and March 31, 2001, produced similar wave heights of 4.70 and 4.65 m, respectively. Frontal passages and southwest storms rarely recorded a significant wave height that exceeded 3.5 m (Table

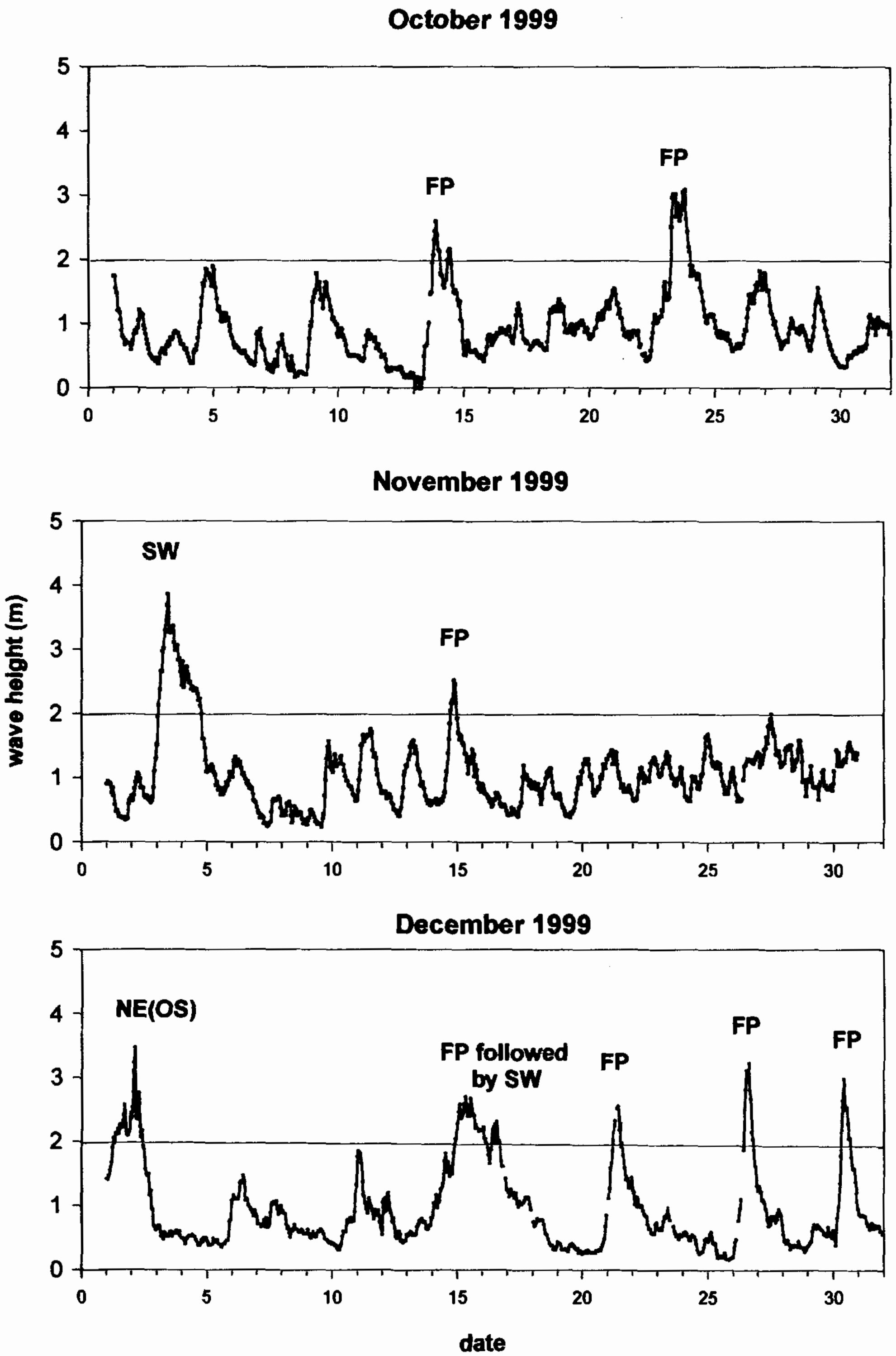


Figure 4.28. Wave heights during October, November and December 1999 at the NOAA 44007 buoy (Portland, ME). Wave heights in excess of 2 m were called storm events. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit)

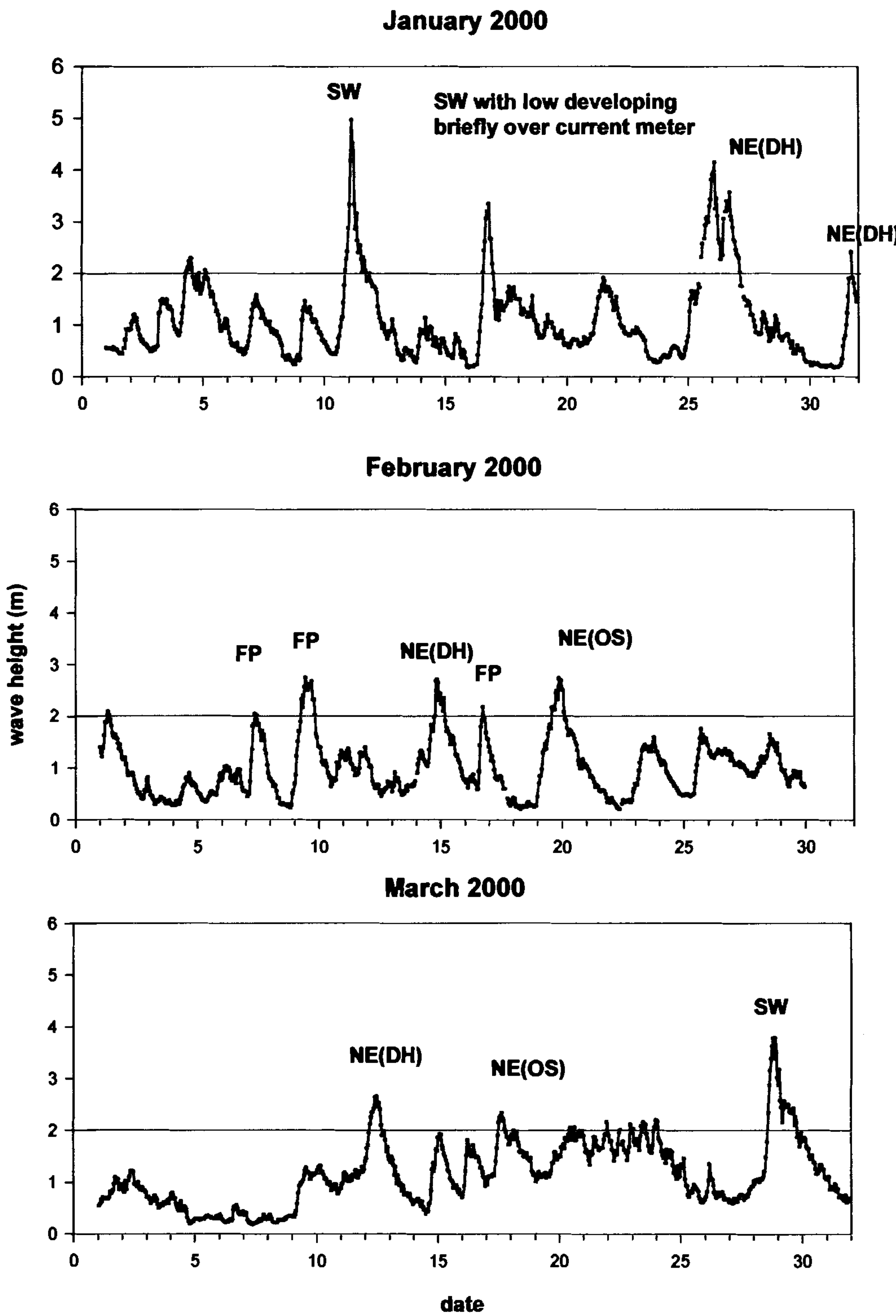


Figure 4.28 (cont). Wave heights during January, February. and March 2000 at the NOAA 44007 buoy (Portland, ME). Wave heights in excess of 2 m were called storm events. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit).

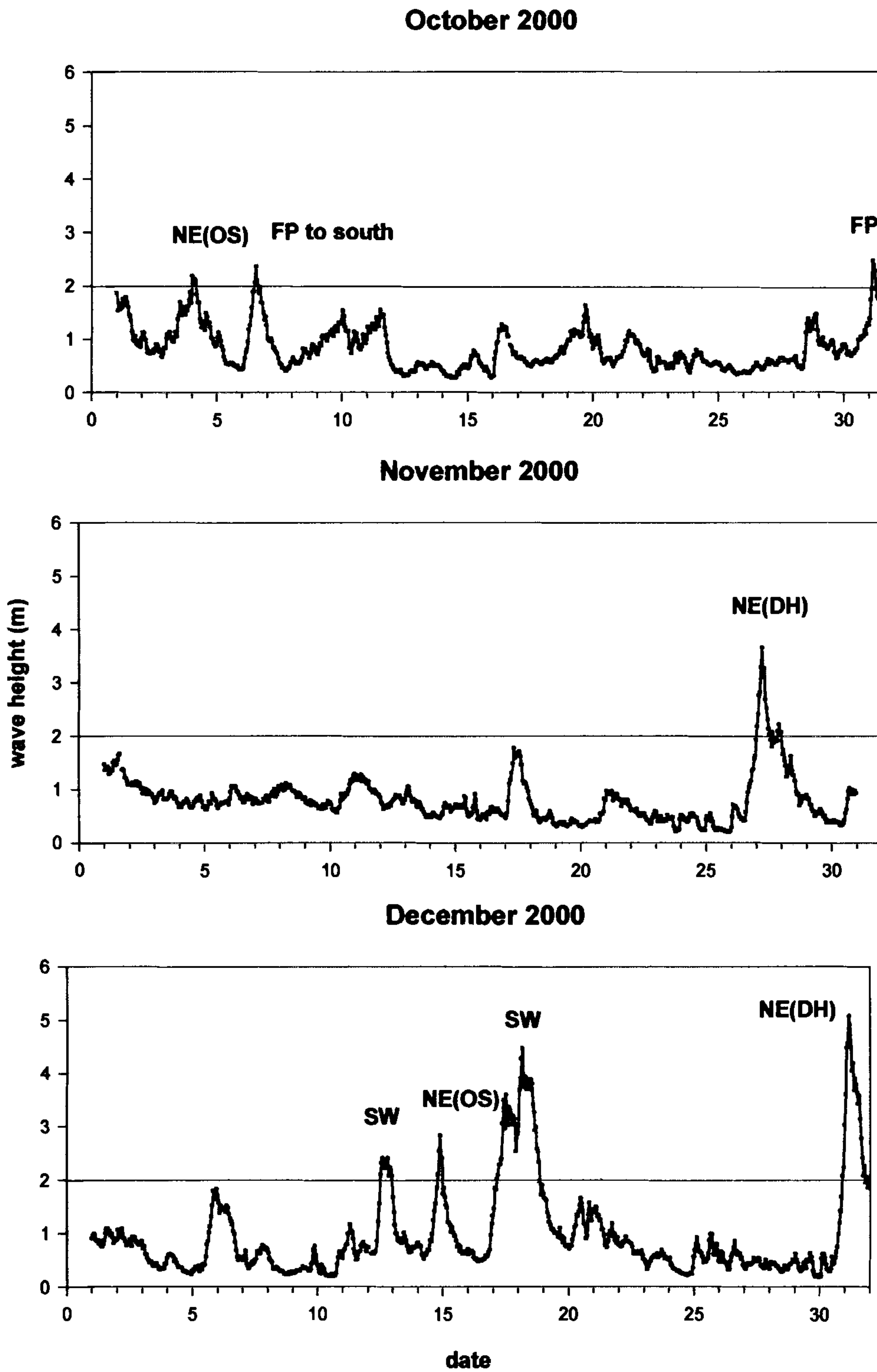


Figure 4.28 (cont). Wave heights during October, November and December 2000 at the NOAA 44007 buoy (Portland, ME). Wave heights in excess of 2 m were called storm events. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit).

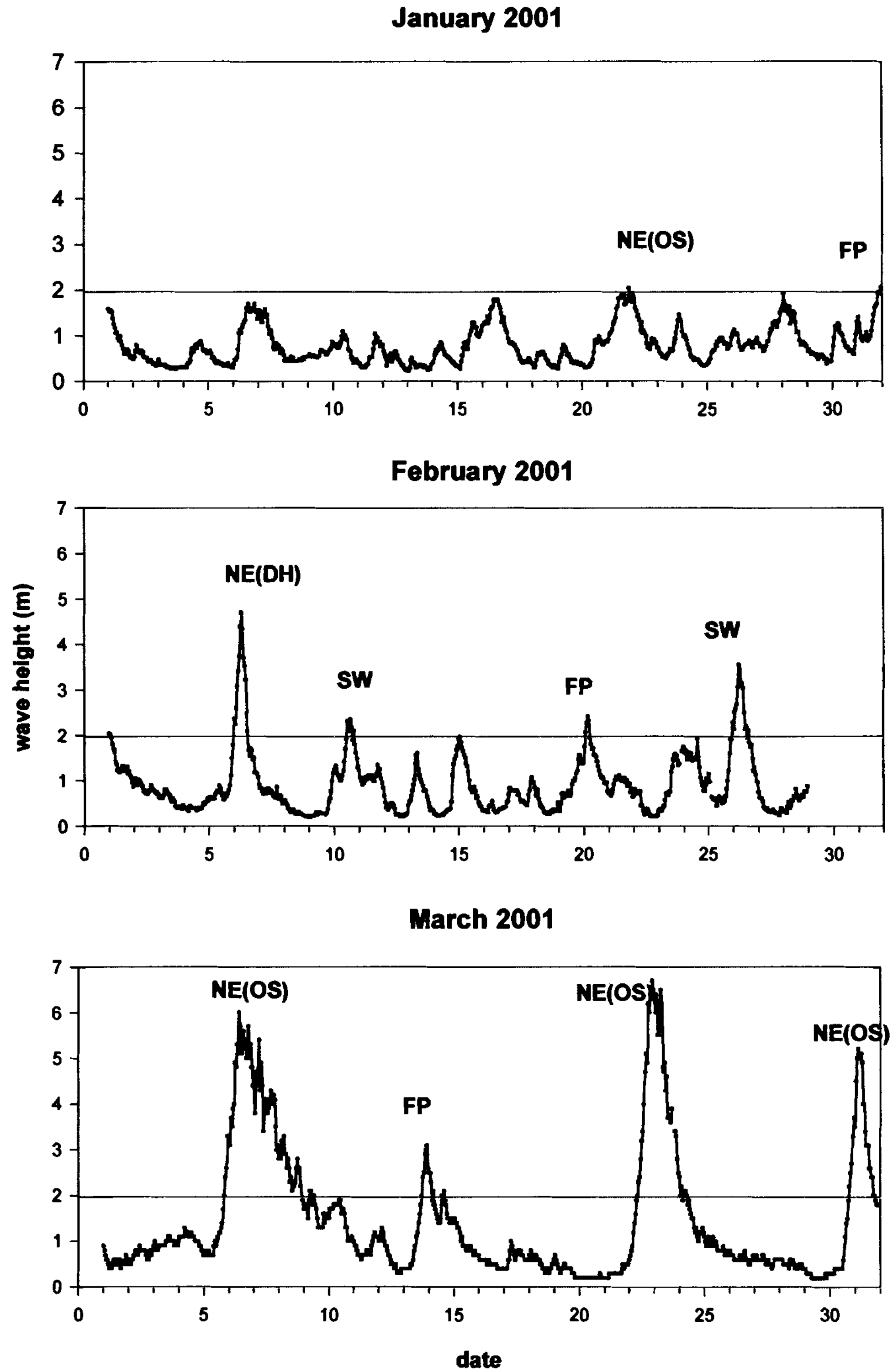


Figure 4.28 (cont). Wave heights during January, February. and March 2001 at the NOAA 44007 buoy (Portland, ME). Wave heights in excess of 2 m were called storm events. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit).

Date	Storm type	Significant wave height (m)	Duration (hours)	Storm surge (m)	# high tides
10-14-99	FP	2.26	26	0.2	2
10-24-99	FP	3.2	31	0.5	4
11-04-99	SW	3.27	46	0.3	3
11-15-99	FP	2.16	23	0.2	5
12-02-99	NE OS	2.64	34	0.5	2
12-15-99	FP-SW	2.52	39	0.2	6
12-21-99	FP	2.36	18	0.1	0
12-26-99	FP	2.93	17	0.1	1
12-31-99	FP	2.65	14	0.1	1
01-11-00	SW	3.53	34	0.5	4
01-17-00	SW	3.1	16	0.2	1
01-26-00	NE DH	3.45	49	0.5	5
01-31-00	NE DH	2.17	07	0.3	1
02-09-00	FP	2.63	20	0.1	2
02-15-00	NE DH	2.46	23	0.3	3
02-20-00	NE OS	2.52	26	0.4	3
03-12-00	NE DH	2.5	24	0.3	2
03-18-00	NE OS	2.16	27	0.2	1
03-29-00	SW	2.99	55	0.5	6
10-04-00	NE OS	1.99	18	0.2	3
10-06-00	FP	2.14	12	0.1	2
10-31-00	FP	2.33	39	0.3	5
11-27-00	NE DH	2.78	36	0.2	2
12-12-00	SW	2.37	13	0.2	1
12-14-00	NE OS	2.6	10	0.1	1
12-17-00	SW	3.79	51	0.6	2
12-31-00	NE DH	4.38	26	0.4	4
01-21-01	NE OS	1.96	11	0.3	2
02-06-01	NE DH	3.99	20	0.5	1
02-10-01	SW	2.24	12	0.1	1
02-20-01	FP	2.21	14	0	0
02-26-01	SW	3.16	21	0.3	2
03-06-01	NE OS	4.70	116	0.7	10
03-14-01	FP	2.46	38	0.2	3
03-22-01	NE OS	5.89	55	0.5	4
03-31-01	NE OS	4.65	29	0.2	6

Table 4.3. Classification of storm events from October-March 1999-2000 and 2000-2001. FP=frontal passage, SW=southwest storm, NE=northeast storm 2000-2002. (OS=offshore, DH=direct hit).

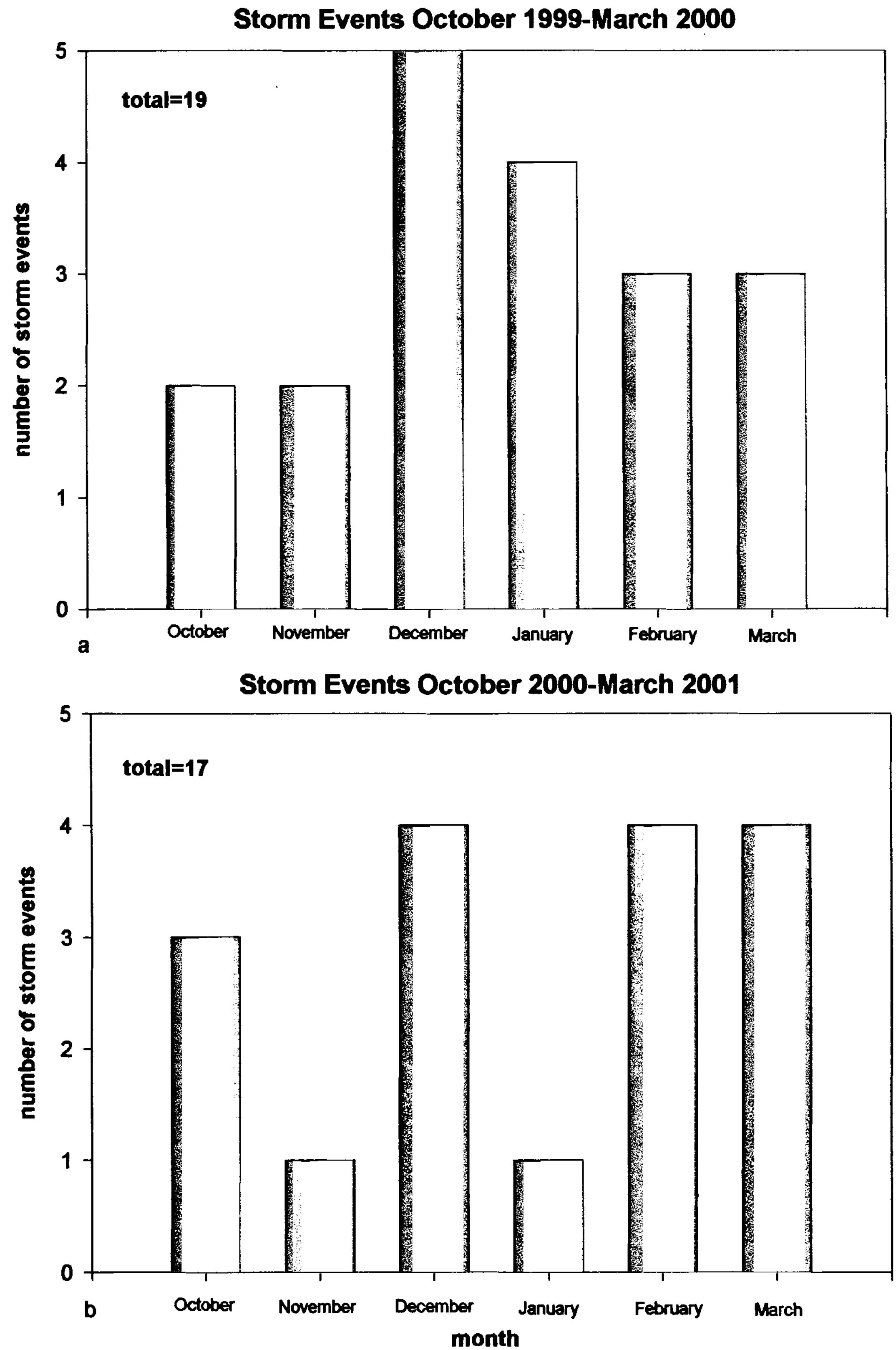


Figure 4.29. Number of storm events per month during the winters of topographic beach profile collection: a. 1999-2000 and b. 2000-2001.

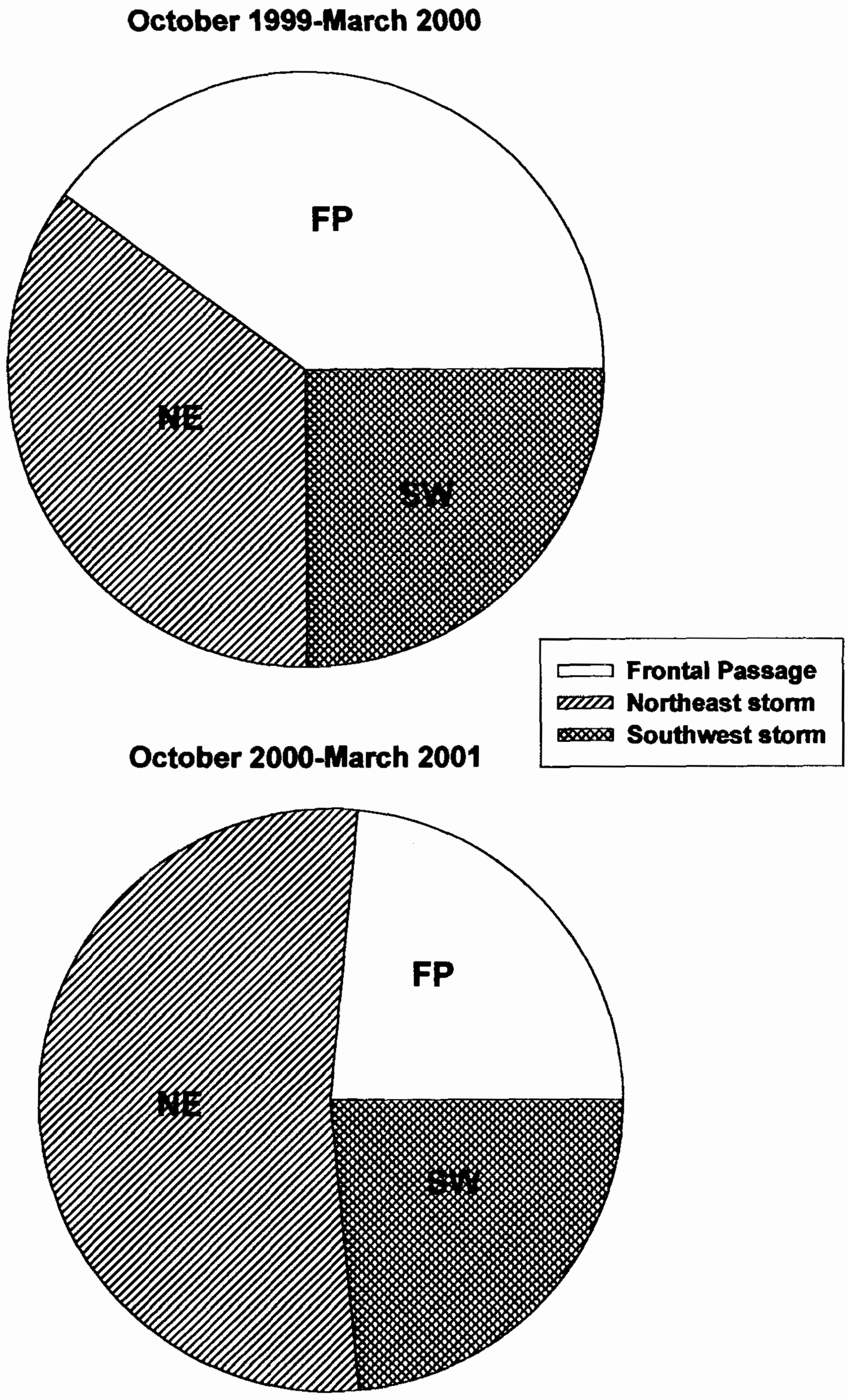


Figure 4.30. Percentage of winter storms during topographic beach profile collection: a. 1999-2000 and b. 2000-2001 NE=northeast storms, FP=frontal passages, SW=southwest storms.

4.3). The duration of storms ranged from a few hours on January 31, 2000 to over 100 hours on March 6, 2001 (Table 4.3). The longer storms persisted over a greater number of high tides. The storm surge also varied greatly. The highest storm surge was 0.7 m, recorded on March 6, 2001 (Table 4.3).

Ground Penetrating Radar

Van Heteren *et al* (1998) looked at a series of natural and developed paraglacial barriers along the coast of New England to identify eight reflection configurations characteristic of mid- to high-latitude environments. They also demonstrated that GPR signals in coastal settings are attenuated by salt water, primarily along the barrier edges. Using the characteristics described by Van Heteren *et al* (1998), in addition to previous studies of barrier systems including the use of GPR and cores (Hulmes, 1981; VanHeteren *et al.*, 1996; Mills, 1997; Hunt, 1998) it was possible to interpret the GPR transects taken along the southern Maine beaches. Offshore seismic lines near the transects were also useful (Belknap *et al.*, 1986; 1987b; Kelley and Belknap, 1991; Barber, 1995; Miller, 1998).

Several different lithologic units characterize the records. Bedrock composes the basement feature on three of the transects. Bedrock has prominent and irregular features and is characterized by hyperbolic reflections. Bedrock outcrops near the transects, such as along Higgins Beach South, were helpful in laterally interpreting the unit. Till, which appears as a chaotic reflector, was a second massive unit seen in the records. This facies is evident in the Laudholm Beach transect (Figure 4.31), and till is actually exposed at the surface near where the record was taken.

One of the most prominent features in most of the records is the glaciomarine Presumpscot Formation. The reflector usually appears draped, mimicking the shape of the material below it. This facies ranges in thickness from 1-10 m. The dune facies is the uppermost unit in the GPR records. It is easily penetrable and it is possible to pick out internal structures such as bedding, resulting from prograding facies and overwash deposits within the sand package. In addition to the geological reflectors, features such as seawalls, dune fences, telephone poles, and underground pipes often caused a distorted and poor signal in the record.

A comparison of two records, Ferry Beach (Figure 4.32), and Higgins Beach South (Figure 4.33), shows the difference between an undeveloped beach (Ferry) and a highly developed beach (Higgins). In the Ferry Beach record, the beach sand facies is underlain by the Presumpscot Formation. The water table coincides with the surface of the Presumpscot Formation. Prograding facies, dune sands and a possible swale and relict channel feature are evident in the record (Figure 4.32). In comparison, bedrock composes the basement of the Higgins Beach record. This unit is overlain by sand, although the seawall prevents the sand from contributing to the beach. The transect was taken along a highly developed road where telephone and sewer lines interrupted many of the signals (Figure 4.33). Salt water caused attenuation of the record at the seaward end of both barriers. Interpretations of the remaining records led to sediment thicknesses comparable to previous estimates (Table 4.4).

Laudholm Beach

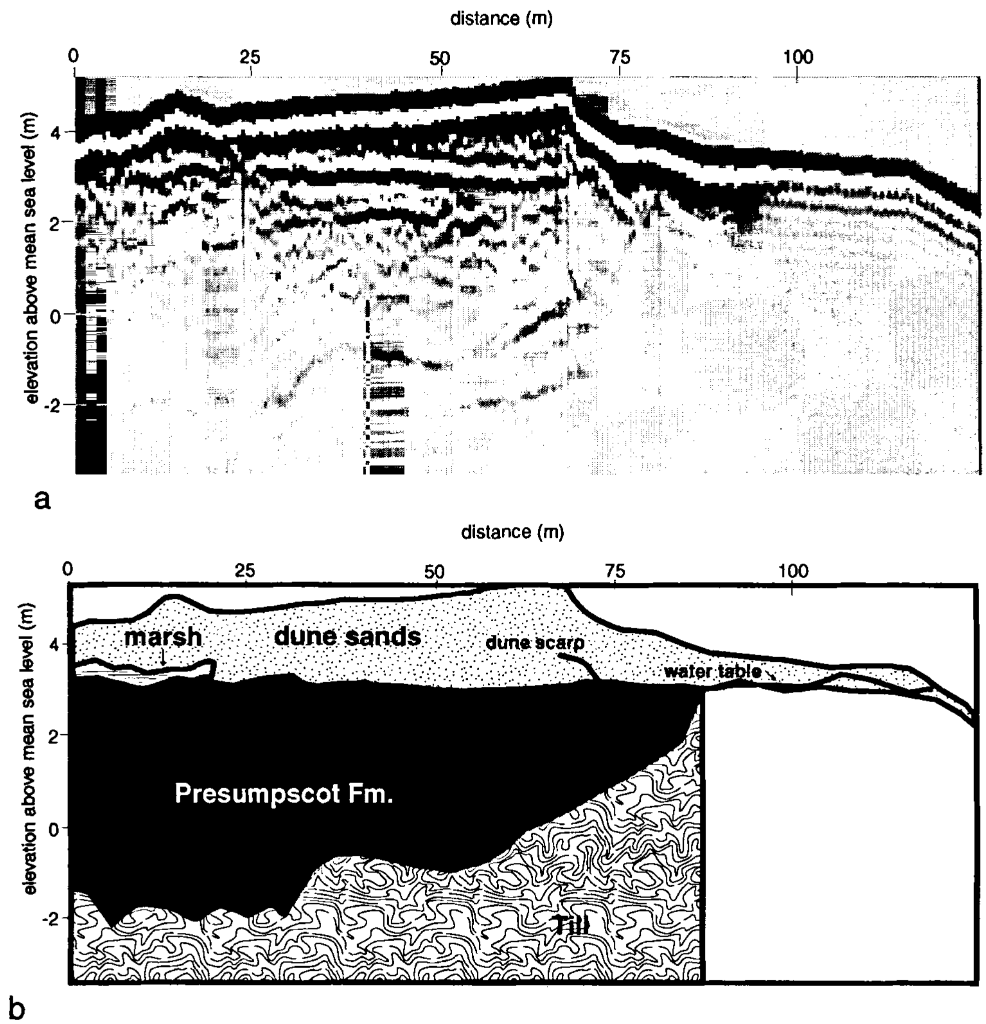


Figure 4.31. GPR transect taken along Laudholm Beach: a. original record and b. interpretation of the record.

Ferry Beach

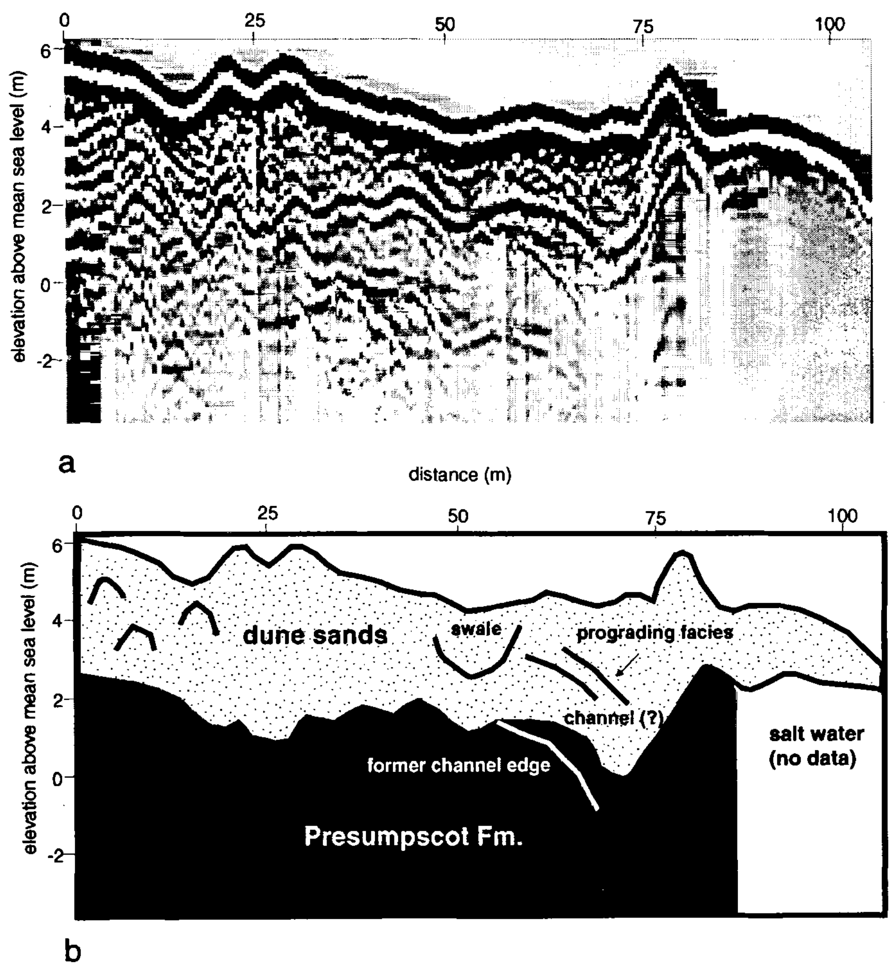


Figure 4.32. GPR transect taken along Ferry Beach: a. original record and b. interpretation of the record.

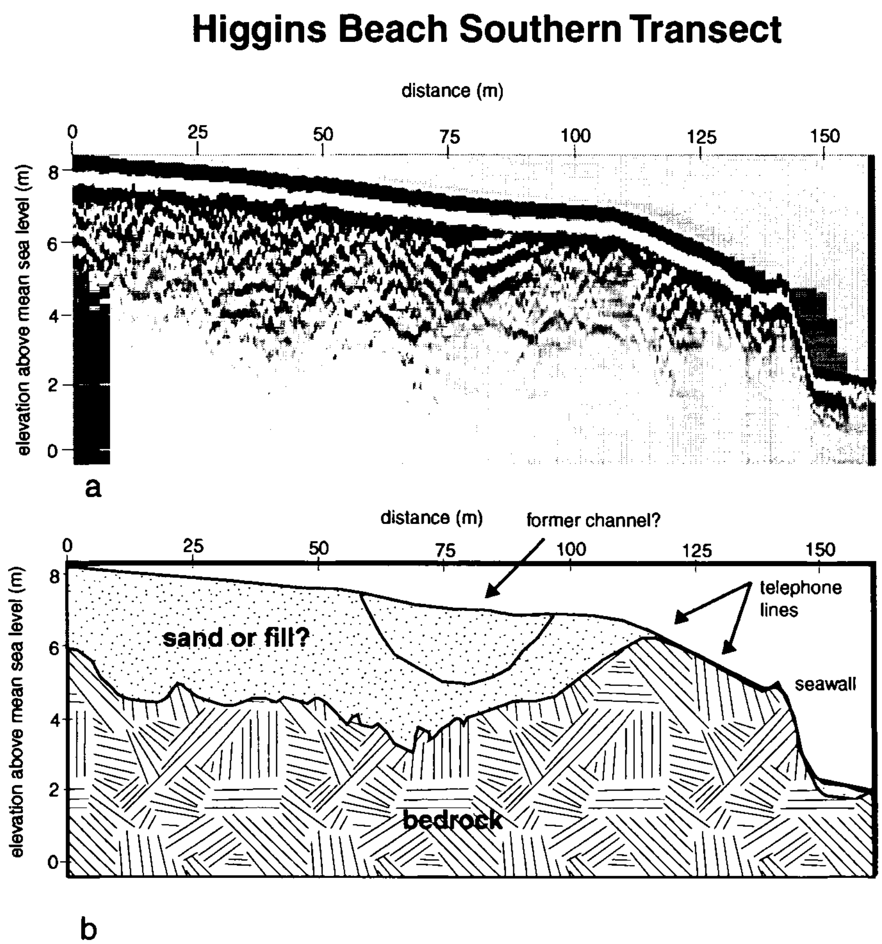


Figure 4.33. GPR transect taken along the southern section of Higgins Beach: a. original record and b. interpretation of the record.

Beach	Average thickness	Average thickness (previous work)	
Higgins	2 m		
Scarborough	3 m		
Western/Ferry	3 m		
East Grand	2 m	2 m	VanHeteren (1996)
Kinney Shores	3 m	4-9 m	VanHeteren (1996)
Biddeford Pool	3 m	5-10 m	Hulmes (1981)
Goochs	2 m	2-4 m	Mills (1997)
Laudholm	1.5 m	1-3 m	Montello (1992)
Ogunquit	5 m	5-9 m	Hunt (1998)

Table 4.4. Average thickness of sand facies determined from the GPR records for each beach in the study and thicknesses reported from previous work for those same beaches.

In addition to using the interpretations to determine an average thickness, it was also possible to quantify a volume of sediment for each barrier using the sand facies (Figure 4.34). This shows the total sand within the barrier, however, and does not define the amount of sand that is actually available to the beach profiles. Seawalls and houses prevent much of the sand from migrating to the beach. A second volume calculation indicates the volume of sand that can contribute to the profile (Figure 4.35). The extent of the sand package was considered seaward of seawalls, roads and/or houses. Comparison of these estimates suggests that Ferry/Western Beaches contain the largest volume of Holocene sand that is available to the system. The two highly developed beaches, Goochs Beach and the southern portion of Higgins Beach contain less sediment than most of the other beaches in the study.

Grain Size Analysis

The grain sizes for each beach range from fine to medium sand, and have varying degrees of sorting (Table 4.5). Several of the beaches demonstrated a consistent

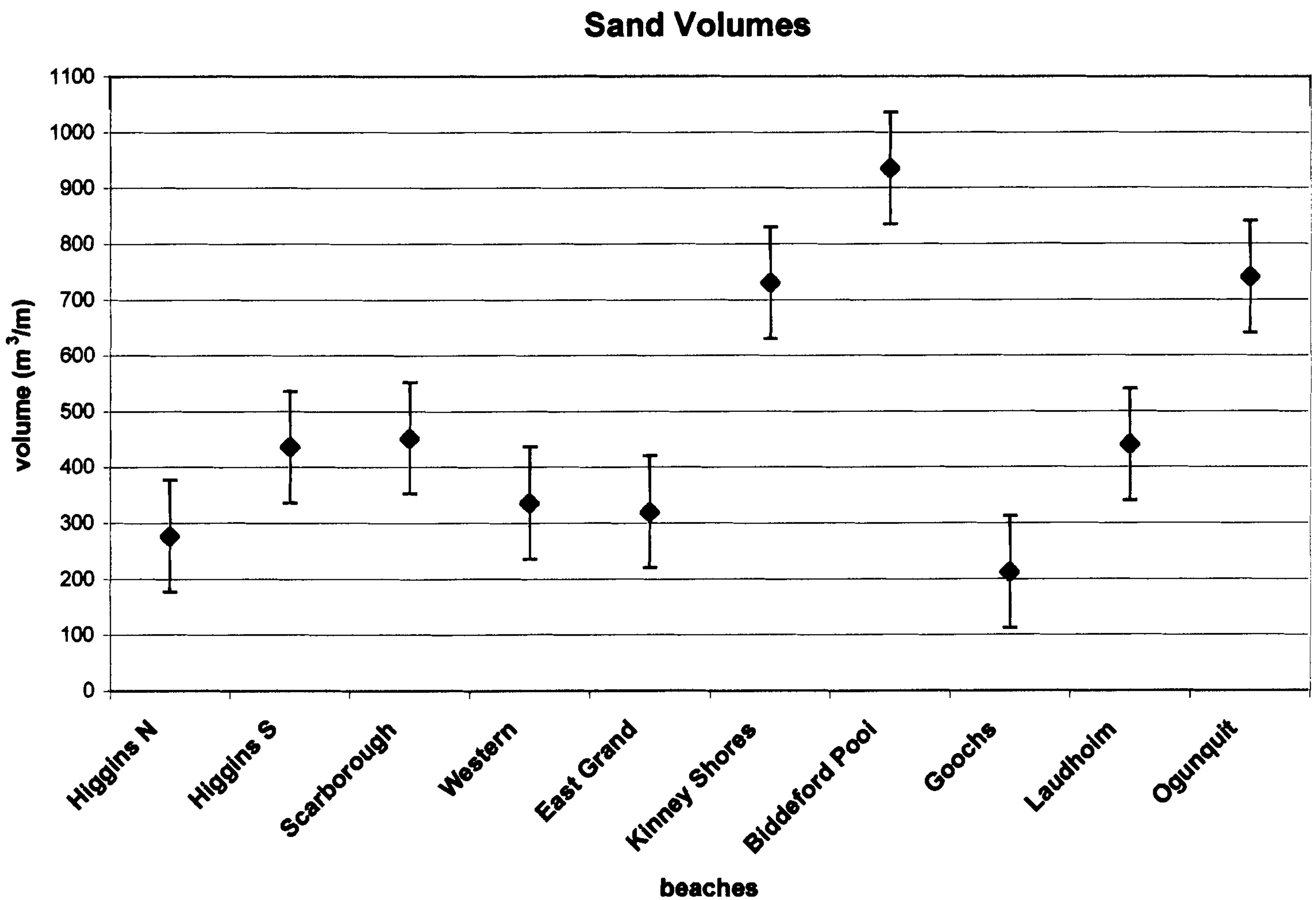


Figure 4.34. Sand volumes for individual beaches, as determined by GPR transects. Dots represent the average and lines are error bars.

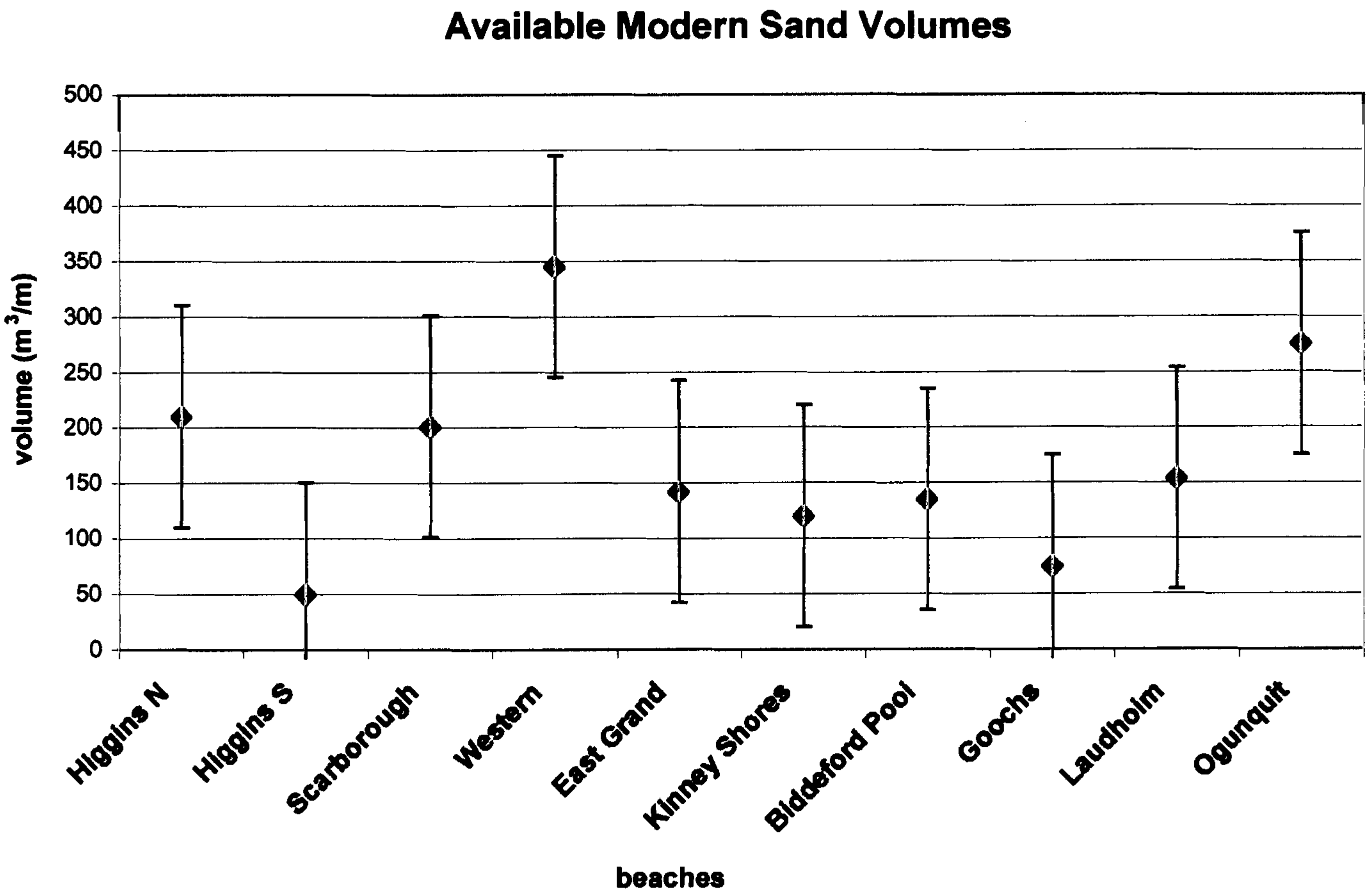


Figure 4.35. Available modern sand volumes for individual beaches, as determined by GPR transects. Dots represent the average and lines are error bars.

	Phi size	Sand Size	Sorting
Higgins Beach			
HBN1	2.10	Fine	VWS
HBN2	2.32	Fine	WS
HBN3	2.19	Fine	WS
HBN4	2.21	Fine	MWS
HBS1	2.41	Fine	VWS
HBS2	2.62	Fine	WS
Scarborough Beach			
SBN1	1.73	Medium	WS
SBN2	1.79	Medium	MWS
SBN3	1.45	Medium	VWS
SBN4	2.00	Medium	VWS
SBS1	1.28	Medium	WS
SBS2	1.69	Medium	WS
SBS3	1.91	Medium	WS
SBS4	2.09	Fine	VWS
Western/Ferry Beach			
WBN1	1.72	Medium	MWS
WBN2	1.99	Medium	VWS
WBN3	1.63	Medium	MWS
WBS1	1.63	Medium	WS
WBS2	1.36	Medium	MWS
WBS3	1.80	Medium	VWS
East Grand Beach			
EGN1	2.26	Fine	VWS
EGN2	1.85	Medium	WS
EGN3	2.24	Fine	MWS
EGS1	1.66	Medium	WS
EGS2	2.13	Fine	VWS
EGS3	2.57	Fine	VWS
Kinney Shores			
KSN1	1.23	Medium	VWS
KSN2	1.18	Medium	MWS
KSN3	1.27	Medium	MWS
KSS1	1.40	Medium	VWS
KSS2	1.12	Medium	WS
KSS3	2.59	Fine	WS

Table 4.5. Phi size, sand size and sorting for each sample taken along the beaches. Samples were taken along the GPR transects, starting landward. Sand size defined by Folk (1974) classification. WS=well sorted, MWS=moderately well sorted, VWS=very well sorted.

	Phi Size	Sand Size	Sorting
Biddeford Pool			
BPN1	1.73	Medium	WS
BPN2	1.93	Medium	VWS
BPN3	1.16	Medium	MWS
BPS1	1.71	Medium	WS
BPS2	1.66	Medium	VWS
BPS3	0.52	Coarse	MWS
Goochs Beach			
GBN1	1.79	Medium	WS
GBN2	2.36	Fine	VWS
GBS1	2.46	Fine	WS
GBS2	2.46	Fine	WS
Laudholm Farms			
LFN1	1.64	Medium	MWS
LFN2	1.63	Medium	MS
LFN3	2.16	Fine	MWS
LFN4	2.64	Fine	WS
LFN5	1.93	Medium	MWS
LFS1	1.65	Medium	MWS
LFS2	1.49	Medium	WS
LFS3	1.99	Medium	VWS
LFS4	2.40	Fine	VWS
LFS5	2.12	Fine	WS
Ogunquit Beach			
OBN1	1.41	Medium	MW
OBN2	2.03	Fine	MWS
OBN3	2.08	Fine	VWS
OBN4	1.86	Medium	WS
OBS1	2.09	Fine	WS
OBS2	1.77	Medium	MS
OBS3	2.01	Fine	VWS
OBS4	2.04	Fine	VWS

Table 4.5 (cont). Phi size, grain size and sorting for each sample taken along the beaches. Samples were taken along the GPR transects, starting landward. Sand size defined by Folk (1974) classification. WS=well sorted, MS=moderately sorted, MWS=moderately well sorted, VWS=very well sorted.

grainsize throughout the beach length. For example, all samples along Higgins Beach and 3 out of 4 samples along Goochs Beach were fine sand, while the analyses from Scarborough, Ferry/Western, Kinney Shores and Biddeford Pool showed medium grain size sand for these beaches. Laudholm Farm, East Grand Beach and Ogunquit Beach showed a mixture of fine and medium sands. Biddeford Pool was the only beach that contained a coarse sample. Overall there is little variation in grain size (Figure 4.36). Kinney Shores and Biddeford Pool show the coarsest grain size. The finest grain size is found along highly developed beaches.

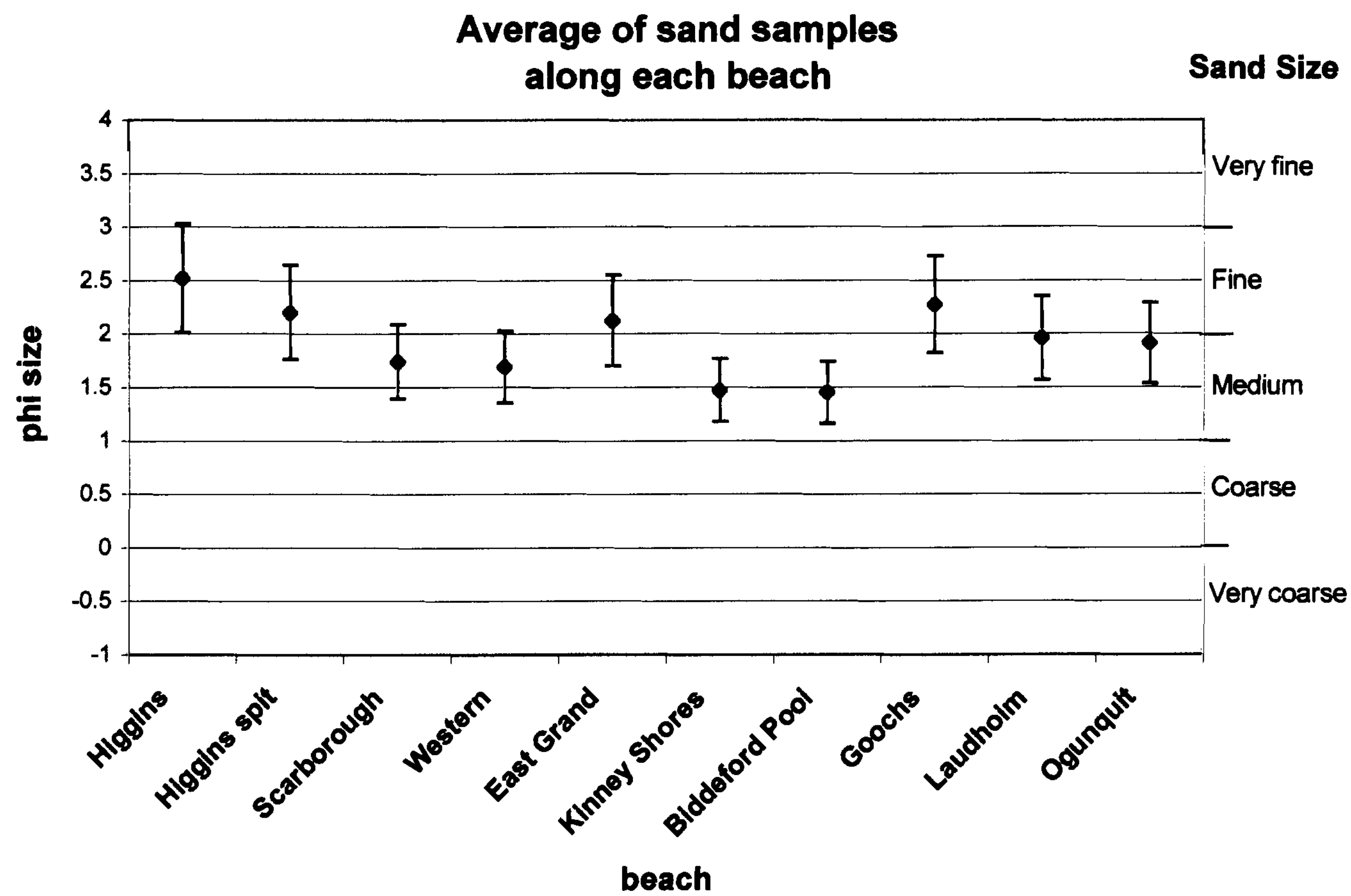


Figure 4.36. Average phi size and sand size of samples from each beach. Sand size is based on the Folk (1974) classification.

Chapter 5

DISCUSSION AND CONCLUSIONS

Barrier systems respond to a wide range of process-response mechanisms that operate on both short- and long-time scales. The barrier tends to maintain equilibrium despite perturbations that may bring the system to a new state. Therefore, true equilibrium depends on the time interval over which the balance is considered (Ritter, 1986). A transgressive process-response model is proposed for the sand beaches in southern Maine (Figure 5.1), based on a model developed by Schumm (1977), that shows different time intervals and associated equilibrium in geomorphic analyses.

Static equilibrium exists over a short steady-time interval, on the order of months and years. Minor fluctuations, like seasonal changes and weather patterns, govern this state, but no net movement of the shoreline occurs over the short-time period. This is the time period of the present study. In steady-state equilibrium, processes are considered for 10's to 100's of years, and are composed of intervals of steady time. Changes do occur, but the system is maintained in an average position until a threshold is exceeded. This threshold could be a major storm that results in temporary disequilibrium and a significant response, such as a shift in the shoreline of several meters. In contrast, dynamic equilibrium occurs over 100's to 1000's of years. Long-term movement of the beach, governed by sea level and sediment supply, represents a response operating on the time frame of dynamic equilibrium. Even though fluctuations within the system occur, they do not offset the general trend of the progressive change.

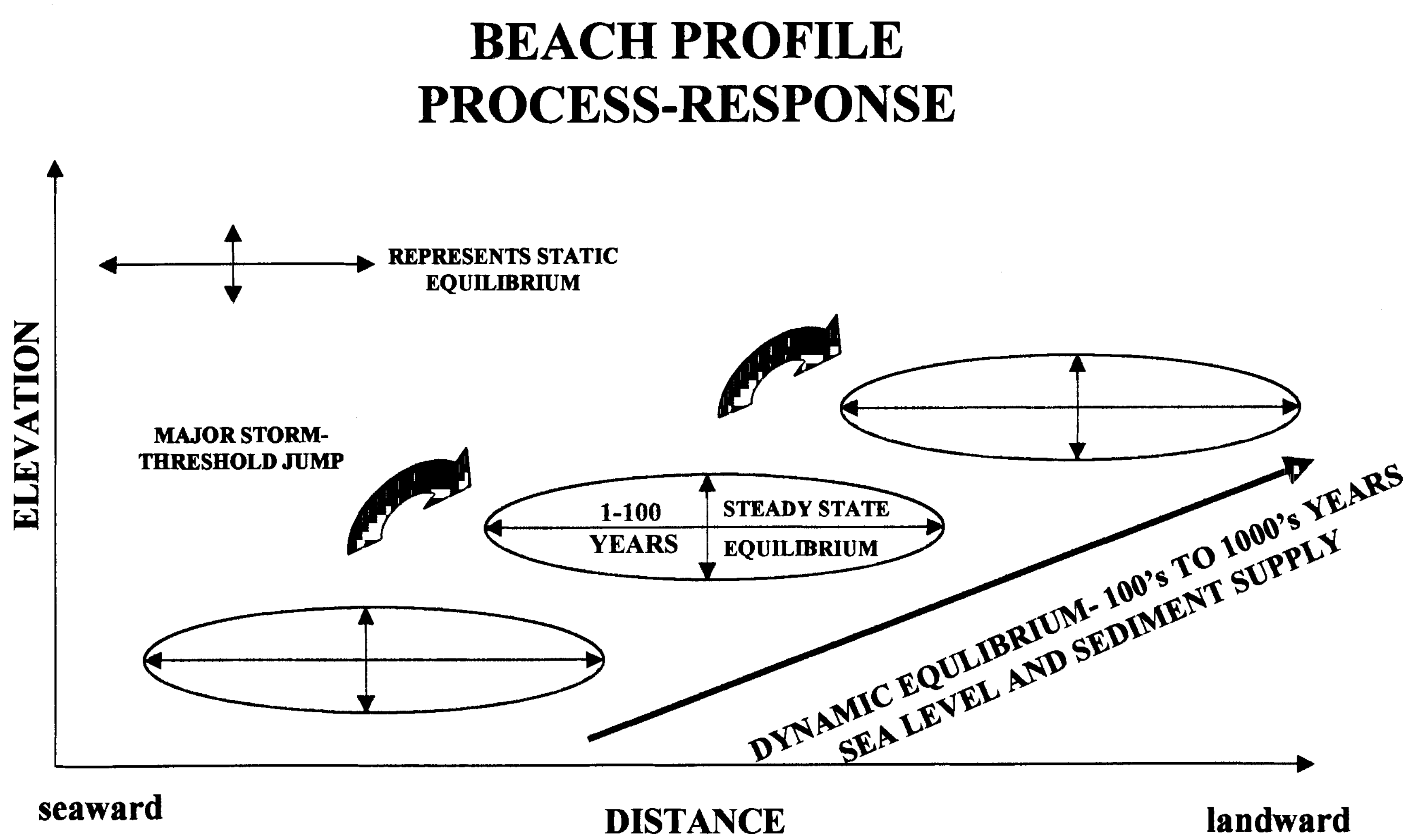


Figure 5.1. Illustration of process-response model proposed for behavior of sand beaches in southern Maine.

STATIC EQUILIBRIUM (MONTHS-YEARS)

There are many factors that contribute to the short-term fluctuations measured by the topographic beach profiles. These include variations in storms, wind and wave regimes, sediment transport patterns (alongshore and cross-shore), and sea-level fluctuations. The location of the beach profiles with respect to an active inlet and the development status of the beach are also important components to profile changes.

Storms

Severe weather patterns in Maine

Storms are one of the most important controls on the cycles of erosion and accretion because of the sediment-transport patterns they induce. Three significant weather events were recorded by the current meters and resulted in various wind and current patterns in Wells Embayment and Saco Bay (Figure 5.2). The figures depict the most common bottom current responses measured by the current meters from this study, as well as from previous work in southern Maine (Dickson, 1999).

Southwest storms are inland storm tracks that travel north through the St. Lawrence Valley (Figure 5.3). Prior to passage of the storm low over the current meter moorings, winds blow from the southeast resulting in northwest directed surface currents and southeast flowing bottom currents. Upon passage of the storm center, the winds shift to the west-southwest, resulting in surface current flowing to the east, upwelling nearshore and net sediment transport to the northwest in both embayments.

Frontal passages travel to the east/southeast through the northern United States and Canada (Figure 5.4). They produce winds from the southeast and bottom currents

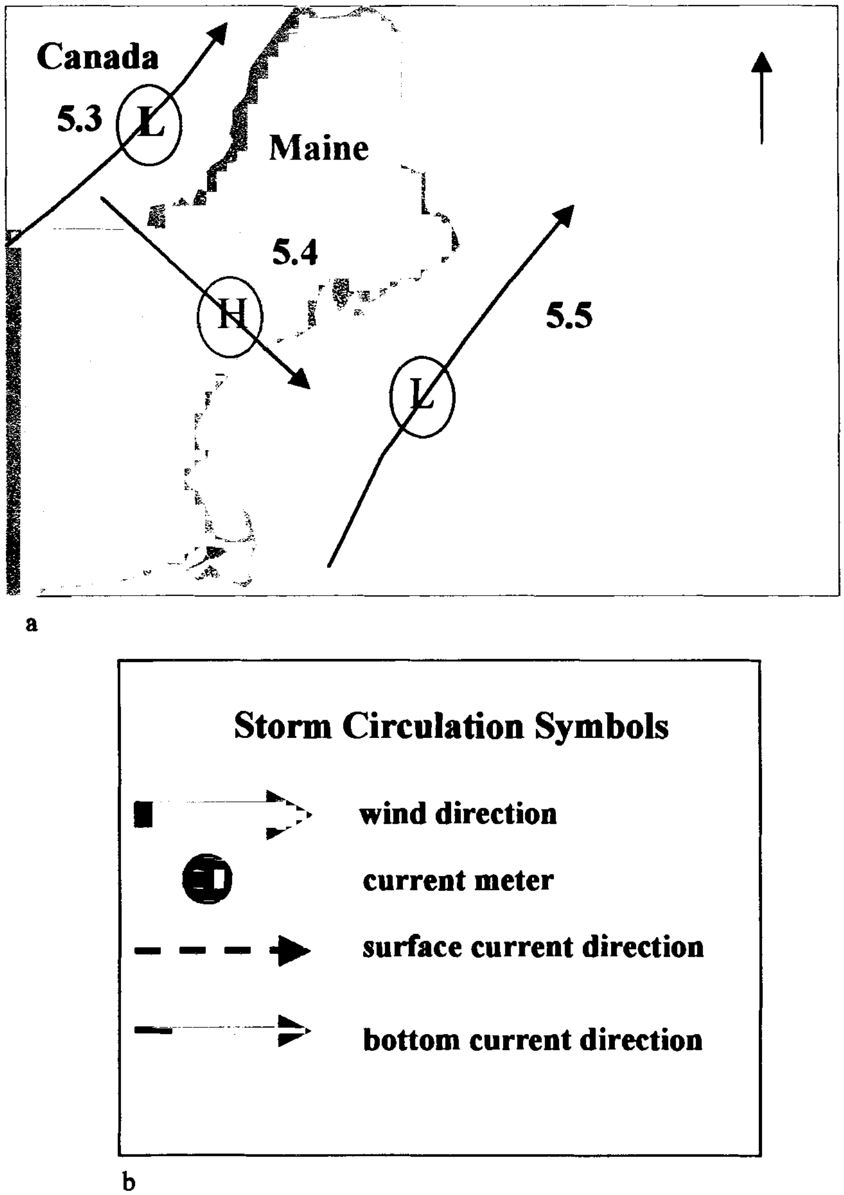


Figure 5.2. Three weather tracks common to the Gulf of Maine. a. Numbers refer to figures that focus on individual tracks. b. Symbols are used in figures 5.3-5.5.

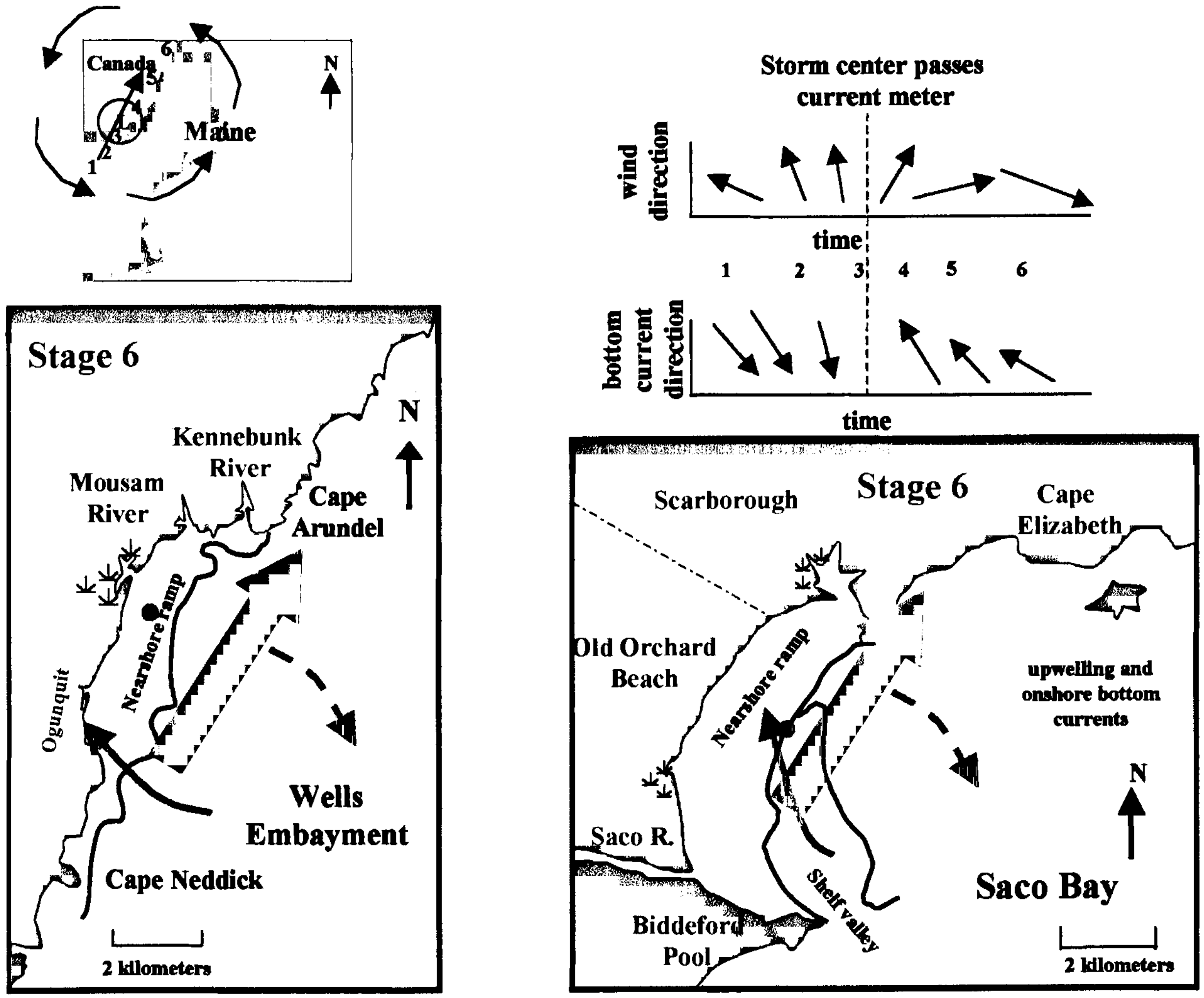


Figure 5.3. Wind and bottom current directions resulting from a storm that moves north through the St. Lawrence Valley (Southwester). Arrows point in the direction of movement. Numbers represent sequential time. Lower diagrams show dominant response of currents in Wells Embayment and Saco Bay.

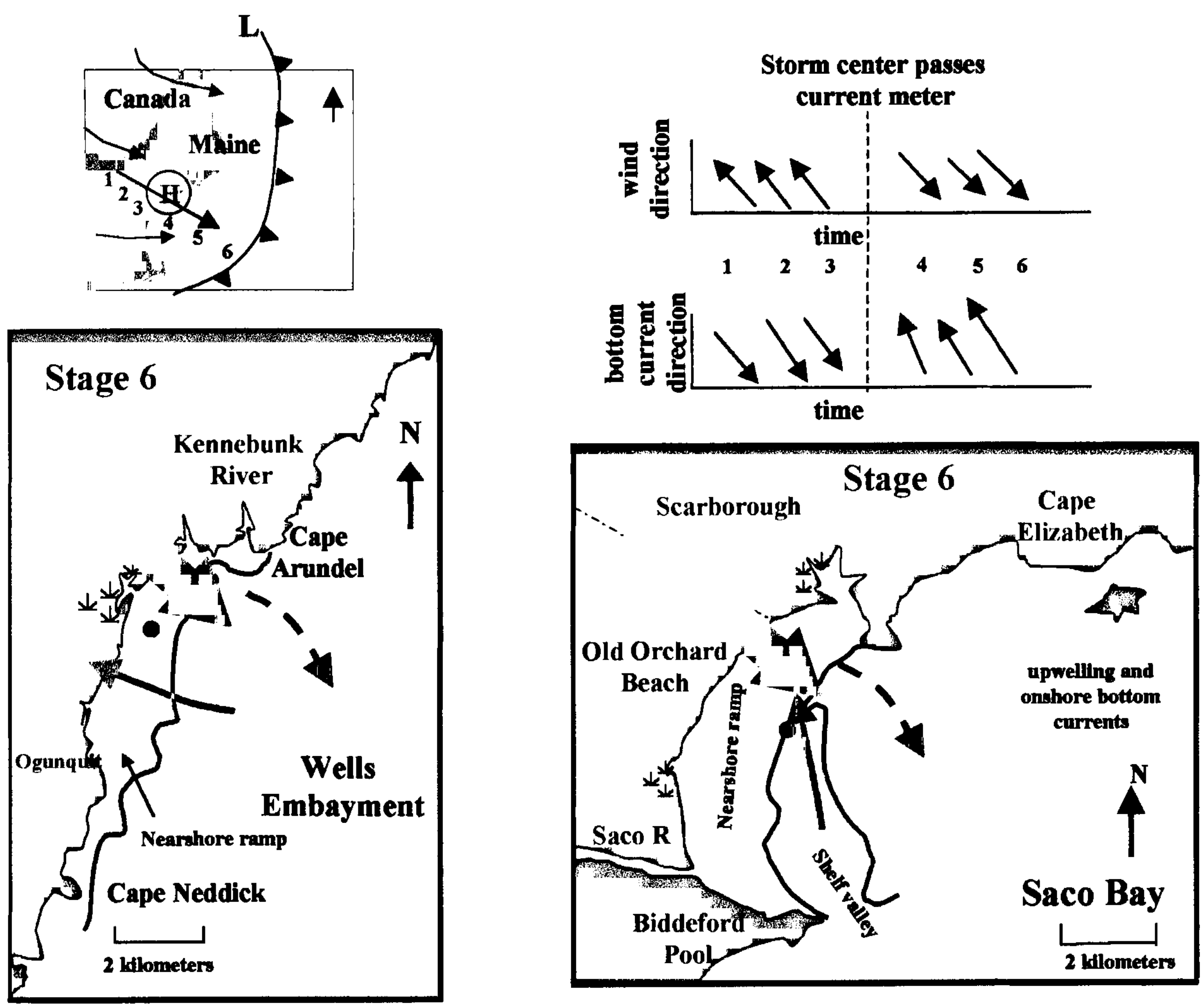


Figure 5.4. Wind and bottom current directions resulting from a cold front that moves east/southeast from Canada. Arrows point in the direction of movement. Numbers represent sequential time. Lower diagrams show dominant response of currents in Wells Embayment and Saco Bay

that flow to the southeast. Upon passage of the storm, winds shift to the northwest, creating surface currents that flow to the southeast. This induces upwelling and onshore currents, to the northwest away from the shelf valley in Saco Bay, and to the west towards the coast in Wells Embayment. The net sediment movement is onshore.

Northeast storms are offshore storm tracks that parallel the coast (Figure 5.5). Before the storm center reaches the current meter, the winds blow from the northeast, resulting in surface current flow to the west-southwest, downwelling, and a net offshore flow to the south-southeast. In Saco Bay, the sediment is transported down the shelf valley (at the current meter site). Following passage of the storms, winds blow from the northwest and produce northwest flowing bottom currents. However, the net sediment transport is offshore.

In general, frontal passages and southwest storms produced upwelling and a net bottom current flow towards the shoreline, while northeast storms resulted in downwelling and a net bottom current flow away from the shoreline. These responses were seen in all of the records from Wells Embayment, but there were a few events that resulted in an opposite net flow direction in Saco Bay. Specifically, the net current flow was to the north during two northeast storms (Figure 4.24).

The change in the direction of current flow is likely a result of wave refraction within Saco Bay. Offshore islands and shoals and changes in bathymetry result in complex current flow directions. Wave refraction is not as significant in Wells Embayment, which may explain why the data recorded by the current meter in this location showed anticipated results. Additional external forcings, such as larger current gyres, may have also caused a difference in flow direction.

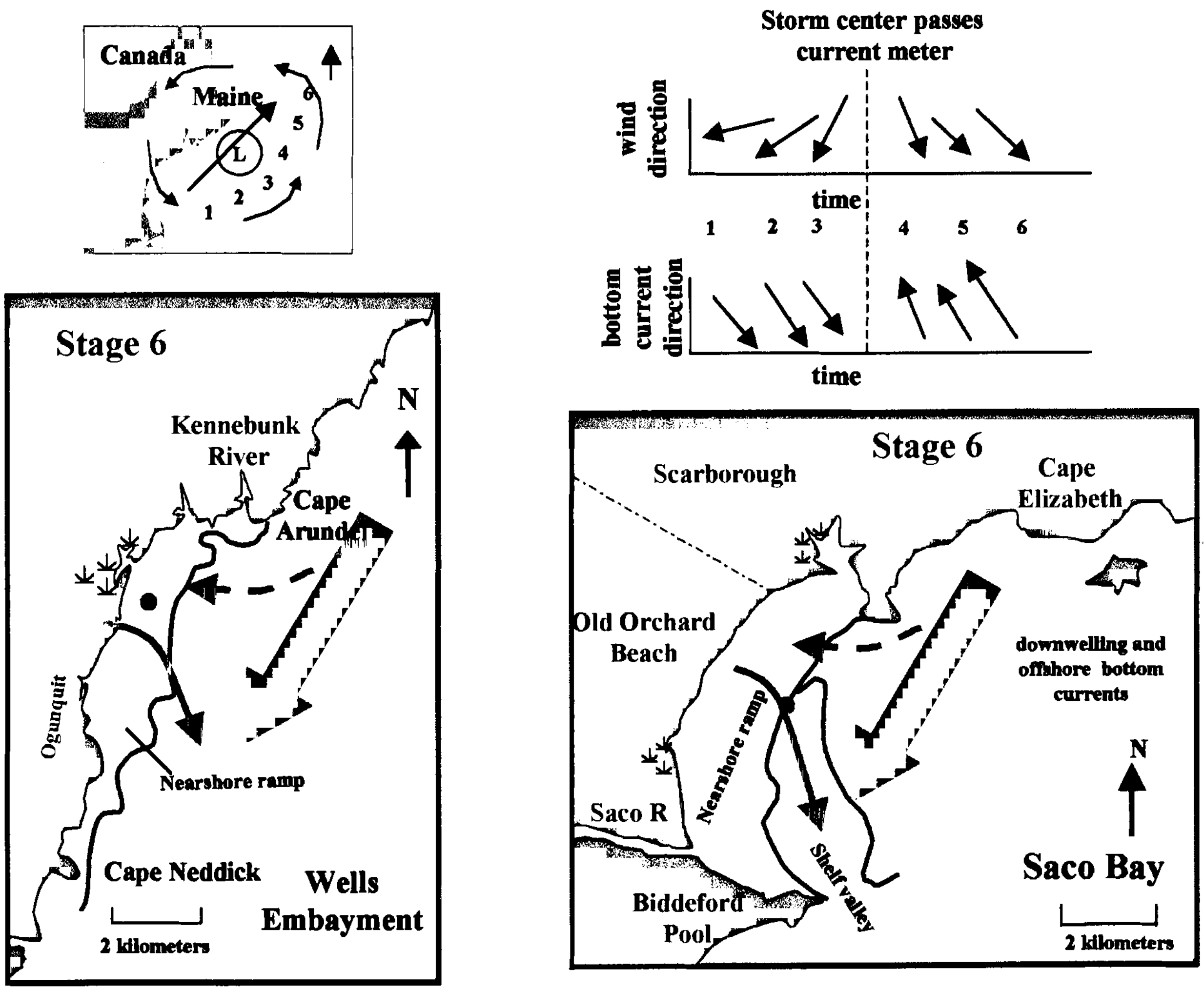


Figure 5.5. Wind and bottom current directions resulting from a storm that parallels the coast offshore (Northeaster). Arrows point in the direction of movement. Numbers represent sequential time. Lower diagrams show dominant response of currents in Wells Embayment and Saco Bay.

Net current directions in Saco Bay and Wells Embayment were similar to one another, specifically during the time frame when the instruments in both embayments were simultaneously taking measurements (December 2000-January 2001). However, the current meters showed different magnitudes of flow for the same storms events. For example, the most significant event in Wells Embayment, a northeast storm on December 31st, 2000 was weak in the Saco Bay record. One possibility is that the current meter in Saco Bay was not recording properly. Because of equipment malfunction, the instrument randomly recorded 1 Hz burst data, and there were possibly periods of several hours when the instrument did not take measurements. In addition, the current meter in Saco Bay was immediately redeployed after the December record, and it produced a solid record during the next 45 days. Although localized factors do play a role, these embayments appear to be responding to large-scale phenomenon at 20 m water depth.

Classification of northeast storms

Dolan and Davis (1992) determined that the significant wave heights caused by severe northeast storms along the U.S. East Coast are about 4-8 m. They also suggested a classification for Northeasters (Table 5.1) based on a power index (Equation 5.1):

$$\text{Equation 5.1} \qquad P = (H_{1/3})^2 t_D$$

where H represents the maximum deep-water significant wave height and t_D is the storm duration. The Halloween Eve storm in 1991 fits into class 5. It was one of only seven New England storms over a 42-year period to reach class 5 conditions (FitzGerald *et al.*, 1994). It is important to recognize that six out of the seven Class 5 storms had relative power values below the mean.

	Frequency		Significant Wave Height (m)		Duration (hr)		Power (m^2hr)		
Storm Class	N	%	x	s	x	s	x	s	Range (m^2hr)
1 Weak	670	49.7	2.0	0.3	8	4.3	32	20	Power ≤ 71.63
2 Moderate	340	25.2	2.5	0.5	18	7.0	107	25	71.63-163.51
3 Significant	298	22.1	3.3	0.7	34	17	353	178	163.51-929.03
4 Severe	32	2.4	5.0	0.9	63	26	1,455	378	929.03-2,322.58
5 Extreme	7	0.1	7.0	1.3	96	47	4,548	2,370	Power > 2322.58

Table 5.1. Characteristics of the five storm classes in the Dolan/Davis Scale. Power is defined as the maximum deep-water significant wave height squared times the storm duration. The mean, standard deviation, and sample size are represented by x, s, and N, respectively (Dolan and Davis, 1992, table 3).

The relative wave power index of each storm was plotted against the frequency to achieve the following return intervals for each storm classification:

Class I	1 every 3-12 days
Class II	1 every month
Class III	1 every 9 months
Class IV	1 every 11.3 years
Class V	1 every 100+ years

Recent work at the Duck Research Facility has produced findings that disagree with the classification proposed above. Zhang *et al* (2001) speculated that storm tides have much more effect on beach erosion than storm waves. They proposed a storm erosion potential index (SEPI) for large storms that includes the combined effects of storm tides, wave energy and duration.

To demonstrate the significance of the SEPI, Zhang *et al* (2001) compared the two most severe storms to influence the Massachusetts coast, the blizzard of 1978 and the

Halloween Eve Storm of 1991. Although field surveys after the two storms indicated that the 1978 storm had a much greater impact than the Halloween storm (FitzGerald *et al.*, 1994), Zhang *et al* (2001) determined that the severity of the two storms were similar. However, the SEPI was twice as large for the 1978 storm than for the 1991 storm. The primary difference results from the coincidence of the 1978 storm with spring tides. Two consecutive high storm tides with heights over 5 m occurred during the 1978 storm, while only one high storm tide over 5 m occurred during the 1991 storm.

Classification of significant weather events during sampling interval

Determination of the storm's power (significant wave height^2 x duration) (Table 5.2) places each significant weather event from October 1999-March 2000 and October 2000-March 2001 into the Dolan and Davis (1992) classification scheme (Table 5.2). The major drawback to classifying these events this way is the use of 2 m as the minimum value for a storm instead of 1.5 m, which Dolan and Davis (1992) used. In addition, the storm duration may be different; Dolan and Davis (1992) did not define their criteria for determining this factor. Keeping these differences in mind, however, close to 50% of the storm events fall into Class 3 (Significant) and approximately 30% fit into Class 2 (Moderate) (Table 5.2). Southwest storms and frontal passages did not exceed category three. Two offshore northeast storms, on March 5-6 and March 22, 2001 were placed into Class 5 and 4, respectively.

Date	Event type	Significant wave height (m)	Duration (hours)	Dolan and Davis scale (m^2/hr)	Storm Class	Positive and Negative Designation	Yearly Net Storm Power (m^2/hr)
10-14-99	FP	2.26	26	132.8	2	132.8	
10-24-99	FP	3.2	31	317.44	3	317.44	
11-04-99	SW	3.27	46	491.87	3	491.87	
11-15-99	FP	2.16	23	107.31	2	107.31	
12-02-99	NE OS	2.64	34	236.97	3	-236.97	
12-15-99	FP-SW	2.52	39	247.67	3	247.67	
12-21-99	FP	2.36	18	100.25	2	100.25	
12-26-99	FP	2.93	17	145.94	2	145.94	
12-31-99	FP	2.65	14	98.32	2	98.32	
01-11-00	SW	3.53	34	423.67	3	423.67	
01-17-00	SW	3.1	16	153.76	2	153.76	
01-26-00	NE DH	3.45	49	583.22	3	-583.22	
01-31-00	NE DH	2.17	07	32.96	1	-32.96	
02-09-00	FP	2.63	20	138.34	2	138.34	
02-15-00	NE DH	2.46	23	139.19	2	-139.19	
02-20-00	NE OS	2.52	26	165.11	3	-165.11	
03-12-00	NE DH	2.5	24	150	2	-150	
03-18-00	NE OS	2.16	27	125.97	2	-125.97	**Oct 99-Mar 00**
03-29-00	SW	2.99	55	491.71	3	491.71	**1415.66**
10-04-00	NE OS	1.99	18	71.28	1	-71.28	
10-06-00	FP	2.14	12	54.96	1	54.96	
10-31-00	FP	2.33	39	211.73	3	211.73	
11-27-00	NE DH	2.78	36	278.22	3	-278.22	
12-12-00	SW	2.37	13	73.02	2	73.02	
12-14-00	NE OS	2.6	10	67.6	1	-67.6	
12-17-00	SW	3.79	51	732.57	3	732.57	
12-31-00	NE DH	4.38	26	498.79	3	-498.79	
01-21-01	NE OS	1.96	11	42.26	1	-42.26	
02-06-01	NE DH	3.99	20	318.40	3	-318.40	
02-10-01	SW	2.24	12	60.21	1	60.21	
02-20-01	FP	2.21	14	68.38	1	68.38	
02-26-01	SW	3.16	21	209.70	3	209.70	
03-06-01	NE OS	4.70	116	2562.44	5	-2562.44	
03-14-01	FP	2.46	38	229.96	3	229.96	
03-22-01	NE OS	5.89	55	1908.07	4	-1908.07	**Oct 00-Mar 01**
03-31-01	NE OS	4.65	29	627.05	3	-627.05	**-4733.58**

Table 5.2. Dolan and Davis (1992) classification of weather events from October 1999-March 2000 and October 2000-March 2001. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit). The Dolan and Davis (1992) scale depends on significant wave height and storm duration. Each frontal passage and southwest storm are designated a positive value, while northeast storms are designated a negative value. A yearly net storm value is determined for the two winter seasons.

Using the current meter results, in addition to previous work (Dickson, 1999), it is assumed that frontal passages and southwest storms result in net sediment movement towards the beach, while northeast storms result in sediment removal, in both Saco Bay and Wells Embayment. To attempt to draw comparisons between the events during the winters of 1999-2000 and 2000-2001, the determined power of frontal passages and southwest storms were designated a positive value and northeast storms were given a negative value (Table 5.2). Simple addition of the weather events results in a positive storm power (1415.66 m^2/hr) during the first winter and a negative value (-4733.58 m^2/hr) during the second winter. If the assumptions are correct, these results indicate that there was net sediment accumulation on the beaches during the first winter and net sediment removal during the second winter.

In addition to placing weather events into the Dolan and Davis classification, a new classification incorporates storm surge and number of high tides, where the observed water level exceeded the predicted water level. The storm's power was multiplied by the storm surge (m) and the number of high tides (Table 5.3). Three classes were defined to further separate weak and strong events:

Weak	1-500 m^3/hr
Moderate	500-2000 m^3/hr
Strong	2000^+ m^3/hr

It is important to point out that this is an arbitrary classification and is strictly used to determine which events were strongest and most likely to cause changes along the beach profiles based on significant wave height, storm duration, storm surge and number of high tides.

Date	Storm type	Dolan and Davis scale (m^2/hr)	Storm surge (m)	# high tides	New classification (m^3/hr)	Class	Positive and Negative Designation	Yearly Net Storm Power (m^3/hr)
10-14-99	FP	132.8	0.2	2	53.12	W	53.12	
10-24-99	FP	317.44	0.5	4	634.88	M	634.88	
11-04-99	SW	491.87	0.3	3	442.68	W	442.68	
11-15-99	FP	107.31	0.2	5	107.31	W	107.31	
12-02-99	NE OS	236.97	0.5	2	236.97	W	-236.97	
12-15-99	FP-SW	247.67	0.2	6	297.20	W	297.20	
12-21-99	FP	100.25	0.1	0	0	W	0	
12-26-99	FP	145.94	0.1	1	14.594	W	14.594	
12-31-99	FP	98.32	0.1	1	9.83	W	9.83	
01-11-00	SW	423.67	0.5	4	847.34	M	847.34	
01-17-00	SW	153.76	0.2	1	30.75	W	30.75	
01-26-00	NE DH	583.22	0.5	5	1458.05	M	-1458.05	
01-31-00	NE DH	32.96	0.3	1	9.89	W	-9.89	
02-09-00	FP	138.34	0.1	2	27.67	W	27.67	
02-15-00	NE DH	139.19	0.3	3	125.27	W	-125.27	
02-20-00	NE OS	165.11	0.4	3	198.13	W	-198.13	
03-12-00	NE DH	150	0.3	2	90	W	-90	
03-18-00	NE OS	125.97	0.2	1	25.19	W	-25.19	**Oct 99-Mar 00**
03-29-00	SW	491.71	0.5	6	1475.13	M	1475.13	**1797**
10-04-00	NE OS	71.28	0.2	3	42.77	W	-42.77	
10-06-00	FP	54.96	0.1	2	10.92	W	10.92	
10-31-00	FP	211.73	0.3	5	317.60	W	317.60	
11-27-00	NE DH	278.22	0.2	2	111.29	W	-111.29	
12-12-00	SW	73.02	0.2	1	14.60	W	14.60	
12-14-00	NE OS	67.6	0.1	1	6.76	W	-6.76	
12-17-00	SW	732.57	0.6	2	879.08	M	879.08	
12-31-00	NE DH	498.79	0.4	4	798.06	M	-798.06	
01-21-01	NE OS	42.26	0.3	2	25.36	W	-25.36	
02-06-01	NE DH	318.40	0.5	1	159.2	W	-159.2	
02-10-01	SW	60.21	0.1	1	6.02	W	6.02	
02-20-01	FP	68.38	0	0	0	W	0	
02-26-01	SW	209.70	0.3	2	125.82	W	125.82	
03-06-01	NE OS	2562.44	0.7	10	17937.08	S	-17937.08	
03-14-01	FP	229.96	0.2	3	137.98	W	137.98	
03-22-01	NE OS	1908.07	0.5	4	3816.14	S	-3816.14	**Oct 00-Mar 01**
03-31-01	NE OS	627.05	0.2	6	752.46	M	-752.46	**-22157.10**

Table 5.3. New classification of weather events from October 1999-March 2000 and October 2000-March 2001. FP=frontal passage, SW=southwest storm, NE=northeast storm (OS=offshore, DH=direct hit). Each event is placed into the Dolan and Davis (1992) classification. A new classification multiplies the Dolan and Davis value by the storm surge and number of high tides. Each frontal passage and southwest storm are designated a positive value, while northeast storms are designated a negative value. A yearly net storm value is determined for the two winter seasons.

Ten significant events are classified as moderate and strong (Table 5.3). Four of them occurred during the first winter and of these four, two were frontal passages and one was a southwest storm. The second winter had two southwest storms and four northeast storms. Again, a positive number was assigned to frontal passages and southwest storms and a negative number to northeast storms. Simple addition of the storm events result in a positive storm value (1797 m^3/hr) during the first winter and a negative value (-22157.10 m^3/hr) during the second winter. Similar to the comparison of storms using the Dolan and Davis (1992) classification, this new classification suggests the potential for a net accumulation of sediment during the first winter and a net loss of sediment during the second winter. A cumulative plot of the weather events over the two winters shows the magnitude of the northeast storms that occurred in March 2001, as compared to earlier events (Figure 5.6).

Net sediment transport

In a previous study off the Kennebec River mouth, the distance of southeast sediment movement from downwelling was similar to the distance of northeast sediment movement from upwelling (Dickson, 1999). In Wells Embayment and Saco Bay, the current meter results did not show this, however. Northeast storms resulted in a net sediment movement that greatly exceeded the movement caused by frontal passages and southwest storms. This result implies a net loss in the active volume of shoreface sand in these bays may occur due to northeast storms. The current meters were not deployed continuously throughout the two winter seasons, but representative meteorological events were recorded.

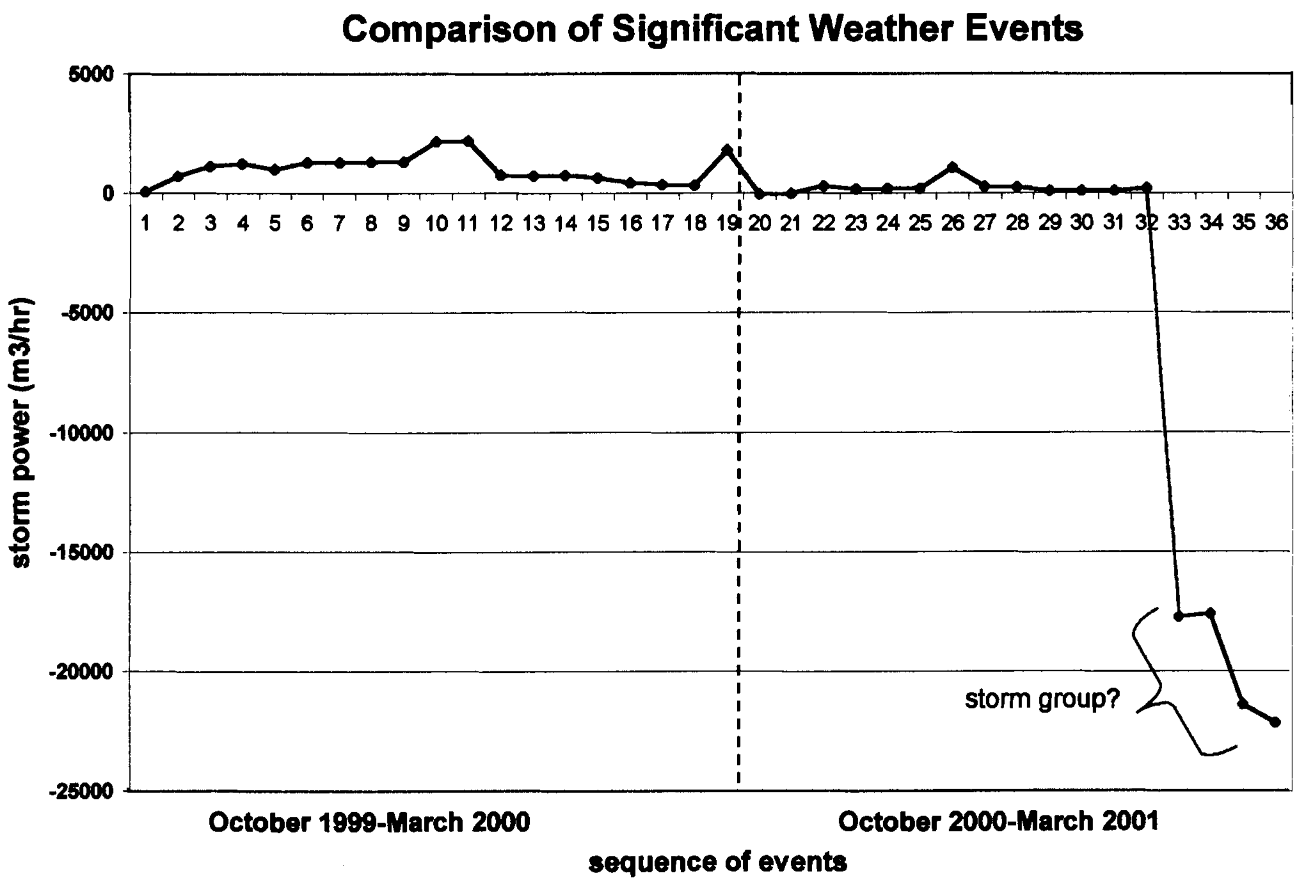


Figure 5.6. Cumulative plot of significant weather events during the sampling interval. Storms are plotted using the new classifiction scheme (Table 5.3). Dashed line represents the break between the first winter (October 1999-2000) and the second winter (October 2000-March 2001).

There are additional factors that affect sand transport within these two embayments. Only events with a wave height in excess of 2 m were considered significant for this study. However, there were a few weather patterns that resulted in strong currents but did not produce waves that exceeded the threshold. For example, a frontal passage on February 12, 2001 (Figure 4.24) resulted in currents that exceeded 30 cm/sec the following day (Figure 4.25). Although not incorporated into this study, these events are also significant in moving sand.

The irregular bathymetry of the two embayments is also important. This complicated offshore bathymetry occurs in both Saco Bay (Figure 2.5) and Wells Embayment (Figure 2.14), and is also apparent through designation of physiographic zones where shelf valleys cut through the rocky seafloor (Figure 2.3). In both embayments, there is the potential for sand to move down the shelf valley where it can no longer be a source of sediment for the beaches. This is particularly true in Saco Bay when northeast storms result in net sand movement to the south. The irregular bathymetry complicates prediction of sand movement as a result of significant weather events.

The beaches did not show a loss of sand, but rather a net gain in the volume of active sand (Figures 4.12 and 4.13), which may be a result of meteorological conditions. During the 1999-2000 winter, frontal passages and southwest storms probably brought enough sand towards the beaches through upwelling, that it was reworked into the beach profiles for several months. The previous winters (1998-1999), which were not investigated by this project, may have also been responsible for bringing sand towards the shore. Strong northeast storms during 2000-2001 caused erosion of the beach profiles, but the magnitude of the storms may not have been significant enough to result in a loss of sand that exceeded the buildup. Historically, northeast storms account for at least 50% of all winter storms (Dolan and Davis, 1992). However, during the 1999-2000 winter season, 65% of storms were classified as frontal passages and southwest storms (Figure 4.30). In addition, the onset of large-scale northeast storms did not occur until the end of March (Figure 5.6), after the profiles were taken for the month.

Northeast storm (March 5th-6th, 2001)

A large-scale northeast storm, the largest event in the new classification scheme (Table 5.3), struck the Gulf of Maine March 5th and 6th, 2001 (Figure 4.24) (Figure 4.25a). An area of low pressure moved north from the southeastern states to the Mid-Atlantic Coast by the morning of March 5th (Figure 5.7). The storm intensified as it slowly moved northward before it stalled off the southern New England coast on the afternoon of the 6th. It then drifted southward again later on the 6th, before moving east of the Gulf of Maine on the 7th (NWS, 2001).

During the storm, currents reached speeds up to 100 cm/sec (Figure 4.25a) and moved sediment in a range of directions from the northwest to southeast, although the net flow direction was to the northeast (Figure 4.24). This contradicts the hypothesis that northeast storms result in a net sediment movement to the south. There is a dominant flow to the northwest and southeast, which may have averaged out to produce a net flow to the northeast.

The storm caused strong northeasterly winds. Sustained winds of 30 to 40 mph and wind gusts of 50 to 60 mph were recorded in Portland, Maine. Waves reached 5-6 m

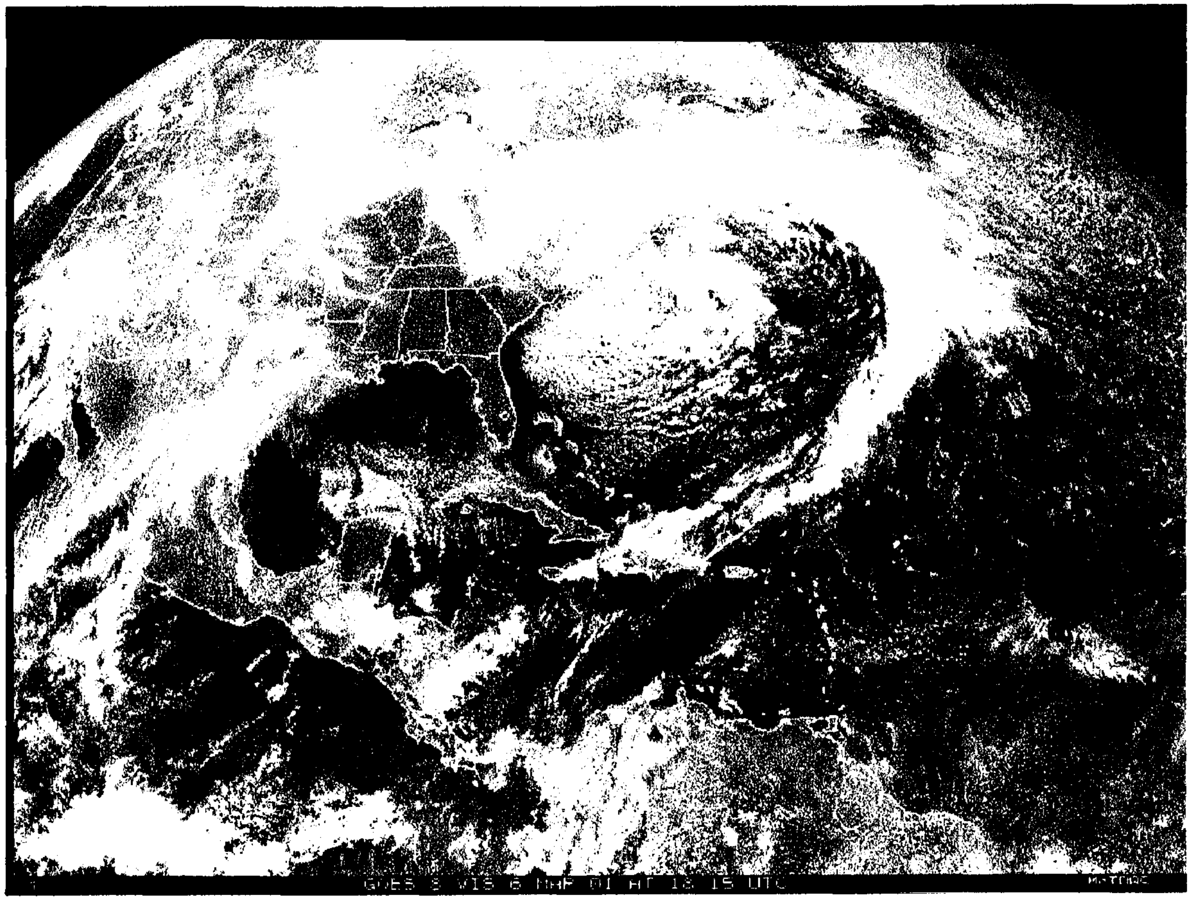


Figure 5.7. Satellite image of a northeast storm that struck the coast of Maine March 5th-6th, 2001. Image taken from NOAA Climatic Archive Data (NOAA, 2001).

at the NOAA buoy 44007 (Portland, ME) and the Portland tide gauge recorded water levels of 3.65 m on the 6^{th} and 3.77 m on the 7^{th}, with the flood stage reaching 3.65 m. A 0.35-0.7 m storm surge combined with high astronomical tides (Figure 5.8) produced coastal flooding and beach erosion along the Maine coast south of Portland. Blizzard conditions were reported with visibilities less than a quarter mile. Snowfall was close to 20 inches along the coast (NWS, 2001). Property damage from the storm was estimated at $20,000.

Profile response to northeast storm

The response of the beaches to the northeast storm (Figure 4.14; Appendix C) suggests that developed beaches in southern Maine do not recover to their pre-storm condition as quickly as undeveloped and moderately developed beaches (Figure 4.14). Erosion along Ogunquit Beach Profiles 3 and 4 may be a result of longshore sediment transport to the north. Ogunquit Beach Profiles 1 and 2 did not lose as much sediment, possibly because additional sediment was supplied from the south. It is likely that the amount of sand that is available to these beaches (Figure 4.35) is the primary reason for the differences in beach response. The undeveloped and moderately developed beaches have a larger storage of sand that can be reworked to rebuild the berm. In comparison, the developed beaches contain very little sand that can contribute to the profiles. Although sand exists in many of the beach systems (Figure 4.34), seawalls, houses and roads prevent it from moving onto the beach.

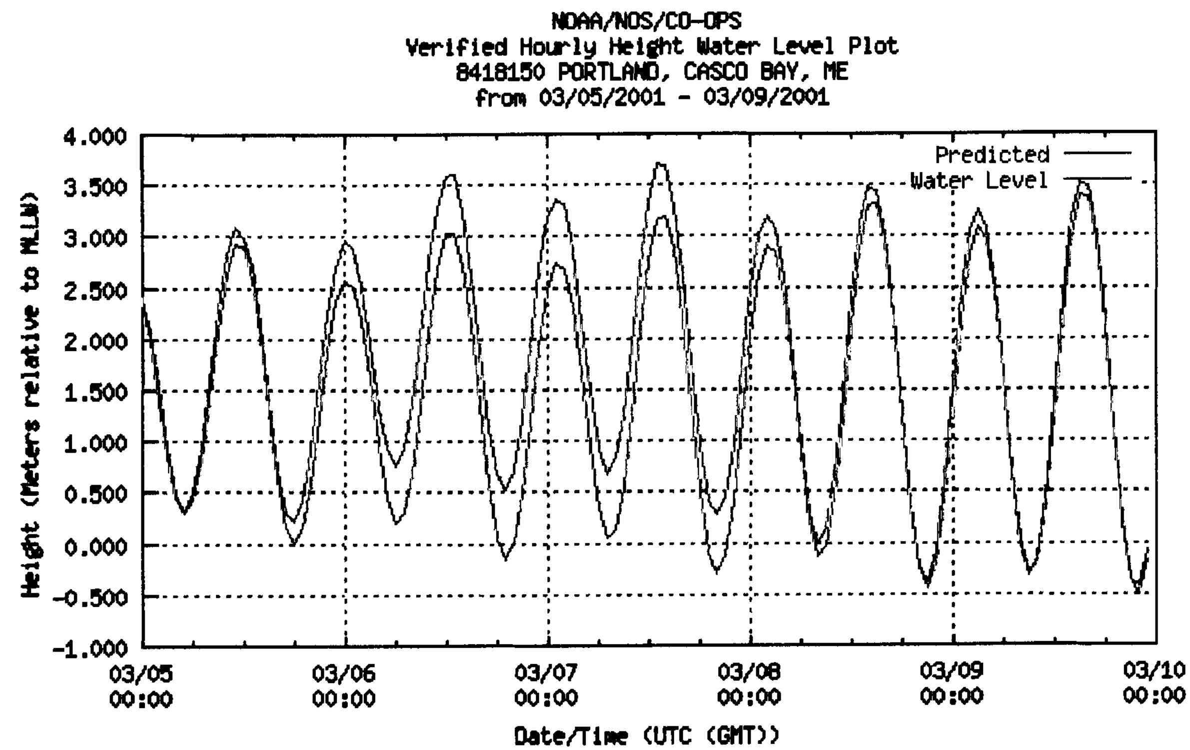


Figure 5.8. Water level during the northeast storm that struck the coast March 5th-6th, 2001. The storm surge is the observed water level minus the predicted value. Data taken from NOAA historical tide data (NOAA, 2001).

Wind and Wave Patterns

Wind and wave patterns may produce topographic profile changes that correspond to the fetch distance of individual beaches. Many of the undeveloped and moderately developed beaches experienced large seasonal fluctuations, but the timing of the berm buildup was not consistent. Scarborough Beach and one of the profiles along Kinney Shores experienced summer berm buildup (Appendix B). Laudholm Beach, Ogunquit Beach and Biddeford Pool (Appendix B), experienced berm buildup during the fall months. The location of these barriers may account for the differences in the timing of berm buildup. The prevailing wind direction during the summer months is southwest (Figure 2.19) (Belknap *et al.*, 1988). Winds from the southwest have a very small fetch in Wells Embayment, with respect to Laudholm Beach, Ogunquit Beach, and Biddeford Pool and there is not enough space for large waves to build. In comparison, winds from the southwest in Saco Bay have a longer fetch and can produce larger waves that reach Scarborough Beach and Kinney Shores and allow the berm to build.

The orientations of the barriers are slightly different; Scarborough and Ogunquit Beaches have a more north-south orientation, while Biddeford Pool and Laudholm Beach have an east-west component, as well. The similar behavior of Ogunquit Beach to Biddeford Pool and Laudholm Beach suggests that these differences in orientation do not directly influence the profile responses. Rather, the location of the barriers within their respective embayments may be the most important factor in the response of the profiles.

Differences in the changes observed along profiles in Saco Bay and Wells Embayment demonstrate the influence of wave and wind conditions. The beaches in Wells Embayment showed responses more similar to one another than the beaches in

Saco Bay (Figure 4.10). The open morphology of the Wells barriers equally exposes the beaches to incoming waves. In contrast, the arcuate nature of Saco Bay and the complex offshore bathymetry is more likely to refract incoming waves, changing the wave energy and the direction of wave propagation.

Cross-Shore Sand Transport

The beaches in the study are both swash and drift-aligned, and are therefore affected by cross-shore and longshore sediment transport, respectively. The profiles did not show volume fluctuations on a one-year (Lacey and Peck, 1998) or a 1.25-year (Haines *et al.*, 1999) period that beaches in other regions experience, related to onshore-offshore sediment transport. Most of the beaches showed a net gain in the volume of active sand during both the fall and winter seasons (Figures 4.12 and 4.13).

The current meter data and winter storm compilation suggests that the beaches in the study did experience cross-shore sediment transport over the sampling interval. Because the beaches showed an overall net gain in the volume of active sediment, the beach profiles may respond to seasonal variability in storm frequency on a time scale greater than 1.25 years. This theory also supports the idea that frontal passages and southwest storms brought sediments toward the shore during the first winter, while the magnitudes of the northeast storms during the second winter were not significant enough to result in net sediment movement away from the shore, until after the last profile was taken in March, 2001.

Another factor indicating that cross-shore transport occurs in this region is the 60% increase in sand volume along Kinney Shores (Figures 4.12 and 4.13). The location of Kinney Shores near the Saco jetties suggests this beach has historically had a net loss in sand volume, or had sufficient sand to maintain the beach, but not an excess of sand. The jetties significantly alter the path of sand movement, and have induced erosion along the most southern beaches (ie. Kinney Shores) and caused accretion to the north as a result of longshore sediment transport. For this beach to gain a significant amount of sediment, it must be receiving additional sand from offshore, or possibly from longshore transport to the south, although the second option is less likely.

Based on the current meter data and the beach profiles, there are three possible scenarios with respect to cross-shore sediment transport: 1) The beaches are gaining sediment on the long term and showing a net accretion, which is what Farrell (1972) found along Old Orchard Beach. This requires cross-shore sediment transport, without any deficits to the offshore, 2) The beaches experience cross-shore transport on a longer cycle than 1.25 years, which is out of the scope of this study, and 3) The beaches do not experience a cross-shore 'cycle' directly related to seasonality and storms. Again, this would require a longer sampling interval.

Longshore Sand Transport

The jetties located in Saco Bay and Wells Embayment are useful in measuring longshore sand transport within these two embayments (see p. 69-72). Evidence indicates the net direction of sand transport is to the north in Saco Bay (Figure 2.23), although there are probably occasional local flow reversals. Longshore transport moves sand to the north and south within Wells Embayment (Figure 2.24), with no obvious net direction. This net sand movement operates on the decadal to century scale, however, and is not a direct indication of seasonal transport patterns. Seasonal fluctuations in longshore sand transport were observed along one Maine beach (Jones, 2000) and along the coast of Rhode Island (Lacey and Peck, 1998).

Longshore sand transport was observed along three of the beaches in southern Maine over the one and a half-year profiling interval. Higgins Beach Profiles 1 and 2 (Figures 4.3 and 4.4) were directly out of phase, which likely indicates longshore transport. However, the location of Profile 1 along a tidal inlet may be the primary reason for the differences, as described below in greater detail. Scarborough Beach Profile 4 showed a delayed response in berm buildup to the first three profiles (Appendix B), suggesting local transport to the south. Although all three profiles along Biddeford Pool demonstrated a fall berm buildup (Appendix B), the maximum berm buildup was offset by a month, with Profile 1 experiencing the earliest berm buildup. This indicates local longshore transport to the south.

Sea-Level Fluctuations

Nelson (1979) suggested that the beaches in southern Maine are retreating as a result of sea-level rise. However, short-term fluctuations in sea level may be evident in the beach profile responses, as well. Using 35 years of data, Lacey and Peck (1998) found a strong inverse relationship between wind velocity/profile volume and wind velocity/sea level. They determined that on the annual scale, prevailing wind direction influenced the regional sea level. During the winter/spring, predominate offshore winds created a setdown, resulting in lower sea level and a lower beach profile volume. The opposite was true during the summer/fall months.

If this relationship is accurate, the sea-level curve over the past two years (Figure 5.9a) is beneficial in understanding the topographic profile responses, particularly the net gain in active sand volume. There was a decline in sea level from October 1999-February 2000, followed by an increase that leveled off during the summer months. The elevation declined in September and there was a sporadic pattern of increase and decrease until March. The lowest elevations over the sampling interval occurred during February of both years. Although there was a slightly higher sea-level elevation during the fall/winter of 2000-2001 than the fall/winter of 1999-2000, the trends do not correlate with the profile data. The relationship that Lacey and Peck (1998) found utilized a much longer record and their data was filtered.

The sea-level history over the past 10 years shows different trends (Figure 5.9b). From 1994-1998, there was a net rise in sea level. Since 1998, sea level has fallen. It is possible that this trend in sea level in the past three years has allowed the beaches to accumulate sediment and accrete. If the beaches are accreting sediment, it is likely a short-term trend, as the rate of sea-level rise has increased in the past 60 years (Belknap *et al.*, 1989).

Location Near an Inlet

Inlet processes potentially cause the greatest amount of shoreline change along adjacent beaches (FitzGerald *et al.*, 1994). Several of the beaches in the study are

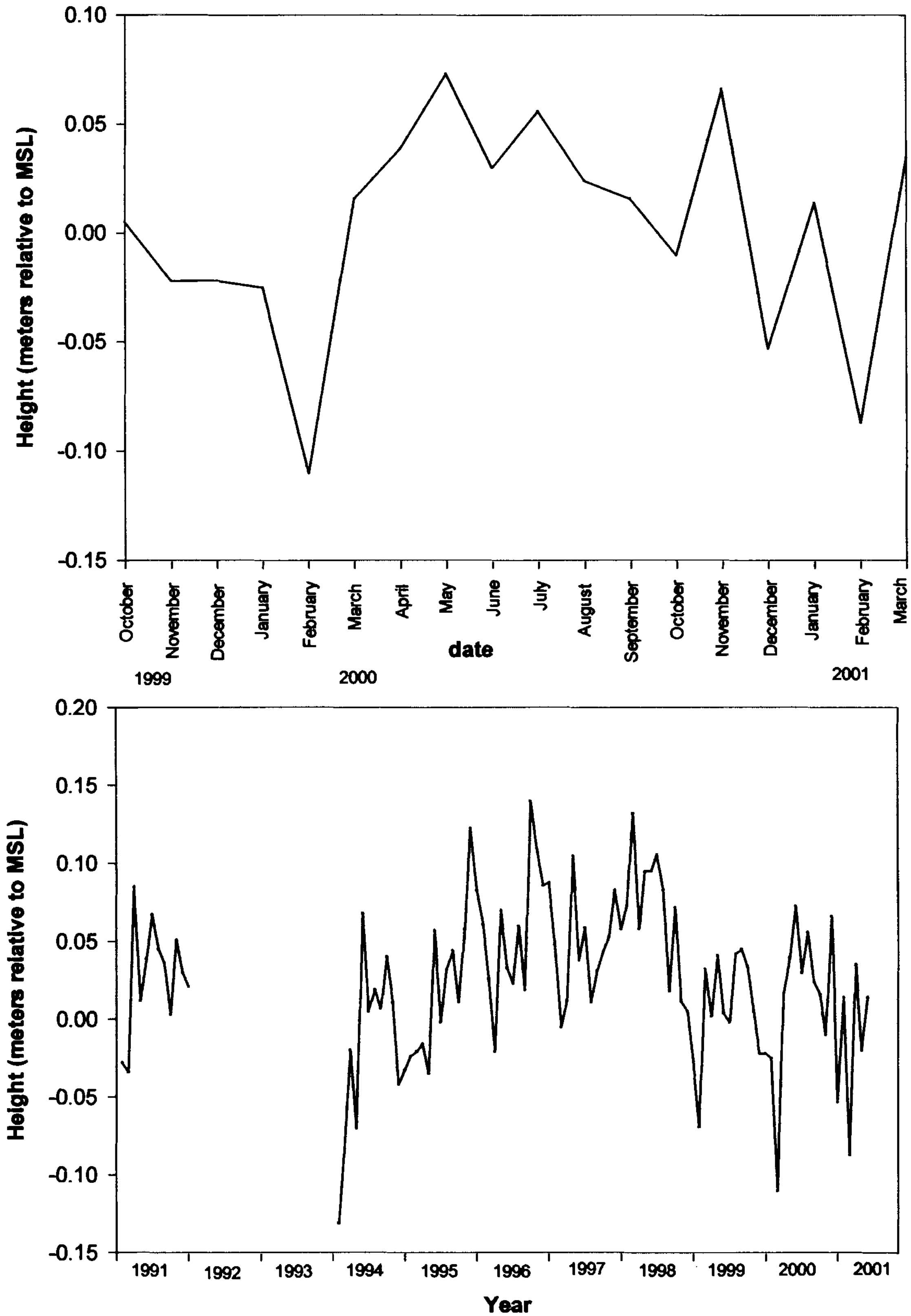


Figure 5.9. Sea-level fluctuations at the Portland tide gauge: a. October 1999-March 2001 and b. 1991-2001 (NOAA, 2001). There is a gap in the record from 1992-1994.

associated with tidal inlets (Table 5.4), although the size of the inlets and their impact on the changes observed along the topographic profiles varied. FitzGerald *et al* (1994) classified tidal inlets in Maine based on their size. Small and medium inlets have single or multiple flood-tidal deltas and poorly formed or nonexistent ebb-tidal deltas, although medium inlets have larger flood-tidal deltas. Large inlets have a flood-tidal delta and well defined ebb-tidal delta.

Beach	**Inlet**	**Size of inlet**	**App. distance of profiles from inlet**
Higgins spit	Spurwink	Medium	0 m
Ferry/Western	Scarborough	Large	0 m
Kinney Shores	Goosefare Brook	Small	180 m
Laudholm Farm	Little River	Small	230 m
Ogunquit	Ogunquit	Medium	1500 m

Table 5.4. Beaches and their associated inlets.

Ferry Beach and the Higgins spit showed the greatest fluctuations between the October and March results (Figures 4.12 and 4.13). From one season to the next, both beaches experienced a volume change close to 100%. Kinney Shores and Laudholm Beach both showed a gain in the active volume of sediment from October to March (Figures 4.12 and 4.13), but did not experience the net loss in sediment that Ferry and Higgins did. Ogunquit Beach showed the least changes.

It appears that the processes associated with tidal inlets, including meanderings of the main ebb channel, spit accretion, and the exchange of sand between the ebb-tidal delta and landward beaches impact the profile changes. For example, the low-tide terraces along Ferry Beach and Higgins Beach are the ebb-tidal deltas of the Scarborough and Spurwink Rivers, respectively. The profiles located closer to the inlets show the largest seasonal fluctuations.

Development Status

If seawalls do not significantly alter beaches, then the profile response on developed and undeveloped beaches should be similar. The developed and undeveloped beaches in this study did not show the same responses (Figure 4.8).

Most of the developed beaches showed very little seasonal fluctuation (Table 4.1). The developed beaches do not contain a large volume of sand, as compared to the undeveloped beaches (Figure 4.35). The small amount of sediment, in addition to the limited beach width imposed by the seawall, makes it virtually impossible for winds and waves to build a significant berm along these beaches.

The sinusoidal shape shown by an average of the undeveloped beach profiles (Figure 4.8) is a strong indication that the beaches responded to seasonal fluctuations. The changes along these beaches averaged themselves out over the course of a year. Meteorological conditions caused a temporary change, but the beaches recovered and regained an equilibrium state. These beaches have a larger volume of sediment available to them within the profile (Figure 4.35), from which the profile can draw upon during extreme changes to the system. For example, during a storm, an undeveloped beach likely undergoes a natural response that prepares the beach for the high wave and wind conditions (Nelson and Fink, 1980). The sediment that is within the dunes and backbarrier provides sand to the system as it rebuilds itself.

STEADY STATE EQUILIBRIUM (1-100 YEARS)

Large Storms in Maine

The storm surge height is a common metric to document the magnitude of coastal storms. The National Weather Service compiled the top ten storm surges at Portland, Maine since 1914 (Table 5.5a), in addition to the frequency of these storms (Table 5.5b) and the months in which they occur (Table 5.5c). The compilation, however, does not take storm duration into account. As a comparison with these records, the largest storm surge during the profiling period occurred during the March 5-6, 2001, and reached only 0.7 m (Table 5.3; Figure 5.8).

Storm Groups

The March 5-6, 2001 storm was not a record storm, but it occurred during a series of several storms (Figure 5.6). Although single storms have the energy to cause major damage, the greatest destruction from storms occurs when there are groups of storms (Birkemeier *et al.*, 1999). The beach does not have sufficient time to recover and the additive impact of storm groups produces changes typical of less frequent, longer duration and more intense storms. Biweekly profiles taken near the Field Research Facility (FRF), Duck, North Carolina from 1981 to 1998, demonstrated the importance of storm sequences in terms of duration, intensity, intervening time interval, and profile response (Birkemeier *et al.*, 1999).

Top Ten Storm Surges, Portland, ME

Rank	Height (ft)	Height (m)	Date
1	4.3	1.3	March 3, 1947
2	4.1	1.25	March 1, 1914
3	3.9	1.2	Dec. 14, 1917
4	3.6	1.1	Dec. 19, 1972
5	3.5	1.07	Oct. 30, 1991
5	3.5	1.07	Feb. 7, 1978
5	3.5	1.07	Nov. 26, 1950
6	3.3	1.01	Nov. 30, 1945
6	3.3	1.01	Aug. 31, 1954
7	3.2	0.98	Dec. 2, 1942
8	3.1	0.98	Mar. 16, 1956
9	3.0	0.91	Feb. 7, 1951
9	3.0	0.91	Jan. 15, 1940
10	2.9	0.88	Nov. 13, 1925

a

Frequency (Return Periods)

Storm surge (m)	Return period (once every)	Last data of occurrence
0.91	4.5 years	October 30, 1991
1.06	10 years	October 30, 1991
1.21	23 years	March 3, 1947

b

Frequency by Month

Oct	Nov	Dec	Jan	Feb	Mar	Aug
1	3	3	1	2	3	1

c

Table 5.5 History of storm events in Maine: a. top ten storm surges since 1914 at Portland, Maine, b. frequency of severe storm events since 1914, and c. frequency of severe storm events by month (NWS, 2001).

For their study, a storm event began when the wave height exceeded 3.0 m and lasted until the wave height fell below 2.35 m (the mean height over the period of study plus two times the standard deviation). Storm groups occurred when the interval between storms was less than 40 days. Storm-group intensity was computed by simple addition of the integrated wave power for the individual storms. The largest storm group had an integrated wave power of 7.5×10^{10} joules and a return period of about 20 years. In comparison, an individual storm of this intensity had a return period greater than 1000 years (Birkemeier *et al.*, 1999). This demonstrates that several high frequency events can combine to produce a lower frequency event given the appropriate wave chronology.

Examples of storm groups that have impacted the coast of Maine include the record storms starting on January 8th, 1978 and culminating a month later with a Blizzard on February 6th-7th, 1978. Together these storms resulted in severe coastal flooding, damage to buildings and structures, and significant beach erosion (Portland Evening Express, 1978). Similar damage occurred to many of the same areas during a northeast storm that struck the coast on Halloween Eve, 1991 (FitzGerald *et al.*, 1994). The passage of Hurricane Bob six weeks earlier presumably left the beaches more vulnerable to the storm (Portland Press Harold, 1991).

DYNAMIC EQUILIBRIUM (100-1000 YEARS)

Construction of sand budgets for Saco Bay, the Kennebec River mouth, and Wells Embayment in the 1990s (Kelley *et al.*, 1995a, 1995b, 1998, 2001; Barber, 1995; vanHetern *et al.*, 1996; Barnhardt *et al.*, 1998; Miller, 1998) utilized seismic data, side-scan sonar records, and a series of cores to determine shoreface sand volumes for Saco

Bay and Wells Embayment (Table 5.6). Although the volume in Wells Embayment is 10^6 m^3 larger than in Saco Bay, the area that was covered in Wells Embayment is close to four times the area in Saco Bay (Table 5.6).

Ground Penetrating Radar (GPR) surveys and cores were critical in calculating the volume of sand contained in the Saco and Wells barriers (Table 5.6) (Montello *et al*, 1992a; Van Heteren *et al.*, 1996). An isopach map of the barriers within Saco Bay shows that the sediment is unevenly distributed throughout the barrier (Van Heteren *et al.*, 1996). Two-thirds of the volume is contained within the northern and southern ends, and there is a high degree of segmentation. The total volume including the barrier and shoreface is greater in Saco Bay than in Wells Embayment, indicating more potential available sediment for the Saco Bay barrier.

	Area km^2	Barrier volume 10^6 m^3	Shoreface volume 10^6 m^3	Total volume 10^6 m^3
Saco Bay	28	22 van Heteren *et al,* 1996	56 Barber, 1995	78
Wells Embayment	>100	18 Montello, 1992	66 Miller, 1998	84

Table 5.6. Barrier and shoreface volumes for Saco Bay and Wells Embayment.

Beaches in Wells Embayment generally have less available sand per beach length than those in Saco Bay (Table 2.1). In addition, the Saco River is a source for new sediment to the system and the two headlands that frame Saco Bay likely cause sand to stay within the system. The sinusoidal shape of the Saco Bay profile responses (Figure

4.9) may indicate that on average, the beaches are showing seasonal variability in Saco, as a result of a sufficient sediment supply.

CONCLUSIONS

Four primary hypotheses were proposed for the sand beaches in southern Maine based on previous work in the area, as well as along other barrier systems in New England:

1. The beaches will show seasonal fluctuations with accretion and a significant berm buildup during the summer, followed by erosion and a concave upward profile during the winter.

2. The net volume change of active sediment over the course of one year will be close to 0. The number of storms taking sediment from the beach will be balanced by the number of storms and long periods of fair-weather swells responsible for bringing sediment closer to shore.

3. Developed and undeveloped beaches will show responses similar to one another (if seawalls do not enhance changes that occur along the beach). Undeveloped beaches will experience the greatest change over a year.

4. Beaches within Saco Bay and Wells Embayment will not respond similarly to one another because of their level of exposure.

Hypothesis 1 was disproven by the topographic profile results over the past year and a half. Individually, moderately developed and undeveloped beaches showed the classic response of berm accretion, but berm buildup occurred during the fall rather than during the summer along most beaches. The developed beaches experienced very little change over the sampling interval. An average of the profiles for each category demonstrates that the undeveloped beaches experienced regular seasonal fluctuations and a consistent berm elevation from one fall to the next. The moderately and developed beaches also showed seasonal fluctuations, but the berm during the fall 2000 was close to 0.5 m higher than the berm in fall 1999, a response that was not observed on the undeveloped beaches.

A compilation of the topographic profiles demonstrated that hypothesis 2 was incorrect as well. The high sand volumes in the summer and low volumes in the winter that were expected were generally not observed along any of the barriers. Eight out of the nine beaches showed a net gain in the active volume of sediment during the sampling interval. This may be a result of meteorological effects. The current meters documented three unique types of storms: frontal passages, southwest storms, and northeast storms. In general, the current meter results indicated that frontal passages and southwest storms were responsible for bringing sediment towards the shore, while northeast storms resulted in a net movement of sediment away from the beach. During the 1999-2000 winter, there was a greater percentage of frontal passages, while during the 2000-2001 winter, there were more northeast storms.

The profile results suggest that the first statement of hypothesis 3 was incorrect, while the second statement was true. Highly developed and moderately developed beaches showed similar trends to one another, but these trends were not observed along the undeveloped beaches. Specifically, topographic measurements made before and after a northeast storm demonstrated that developed beaches experienced a loss of sediment during the storm, while sediment was redistributed along the profile on moderately developed and undeveloped beaches. Two months after the storm, the profiles along the developed beaches had not reached their pre-storm elevation. In comparison, the moderately developed and undeveloped beaches regained more of the sediment that was lost. The profile along one beach reached and exceeded its pre-storm elevation and began to show berm buildup characteristic of the summer months.

Hypothesis 4 was the only hypothesis that was proven true. Trends of profile responses in Saco Bay and Wells Embayment suggest that the beaches in Wells Embayment are responding more similar to one another than the beaches in Saco Bay. The volume of sediment available to the beaches is likely the reason for this. The larger amount of sediment in Saco Bay allows the barriers to naturally respond to external changes on an individual basis.

It appears that many processes controlled the responses of the beach profiles during the study period. Based on the short sampling interval and the unexpected results, however, it was difficult to determine which factors were dominant. In addition to the development level of the beach and its location within an embayment, the sediment transport patterns, local sea-level fluctuations, and the location of the beach with respect to an active inlet were also important controls on the beach profiles.

The beaches in southern Maine can be placed in the process-response model proposed for the barriers (Figure 5.1). Short-term fluctuations, such as seasonal cycles and weather patterns, were responsible for the changes observed along the beaches. The magnitude of these changes were not significant enough to bring the beaches out of equilibrium and into a new state. Profiling efforts need to continue into the future to minimize the effects of seasonal and other short-term changes and to determine whether the beaches are in a stable state. It is probable that the barriers are currently in equilibrium with human-induced alterations and a significant storm event is necessary to cause extreme erosion and movement of the shoreline.

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Appendix A

AERIAL PHOTOGRAPHS

1986 aerial photographs of each beach (Maine Geological Survey).

Topographic beach profile locations.

Ground penetrating radar (GPR) transect locations.

Figure A.1. 1986 aerial photograph of Higgins Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

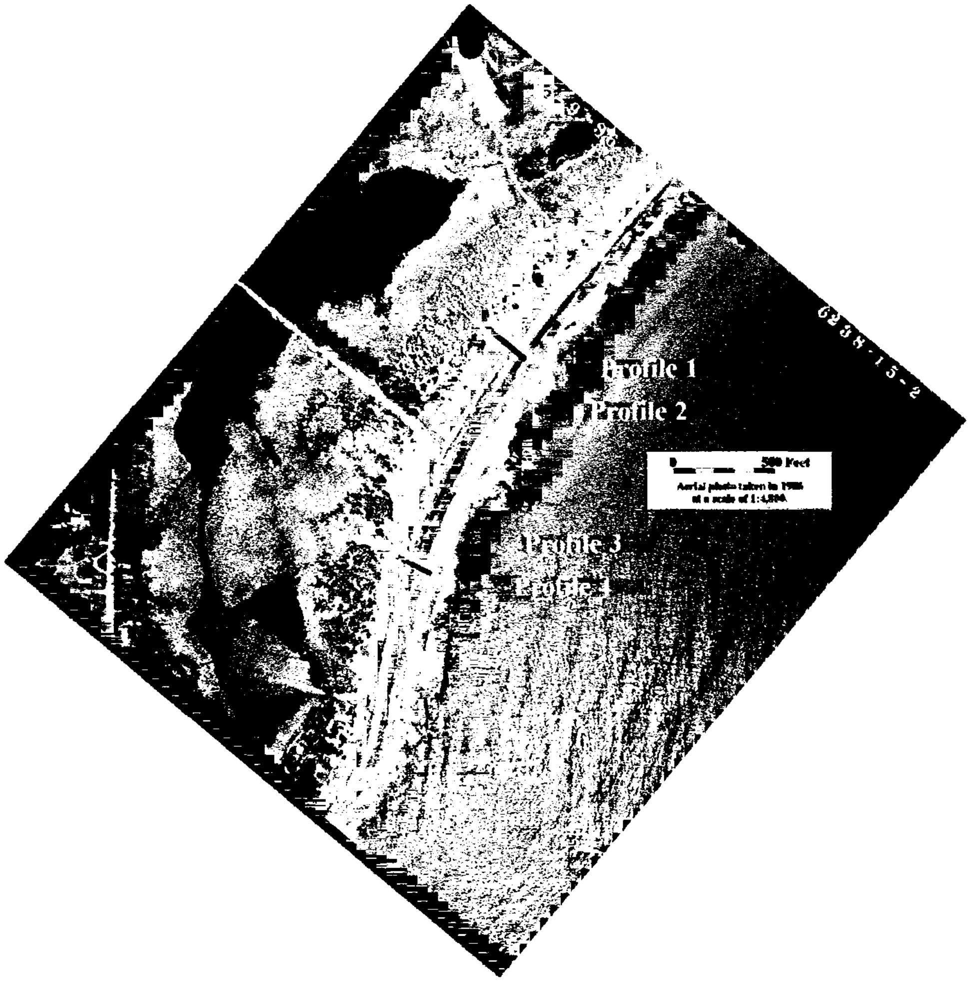


Figure A.2. 1986 aerial photograph of Scarborough Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

Figure A.3. 1986 aerial photograph of Western/Ferry Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

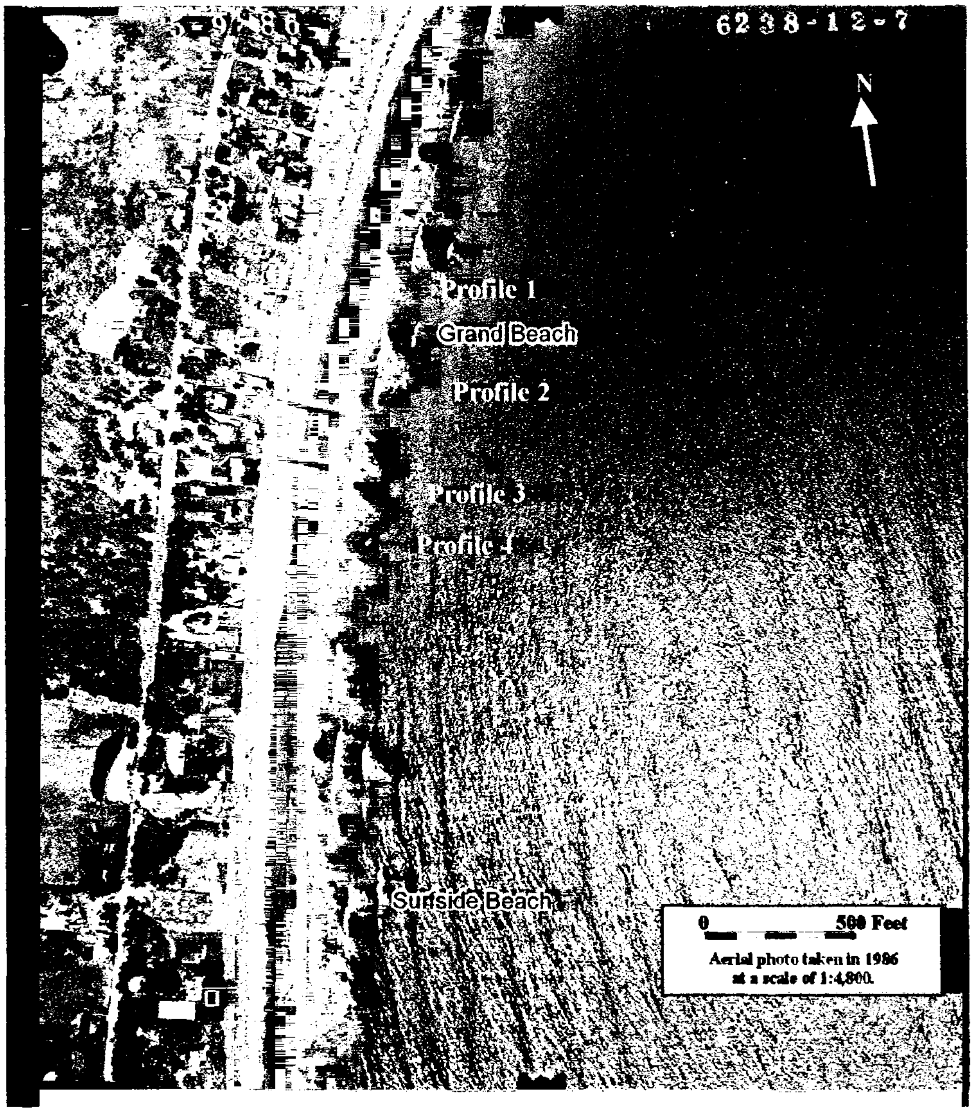


Figure A.4. 1986 aerial photograph of East Grand Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

Figure A.5. 1986 aerial photograph of Kinney Shores, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

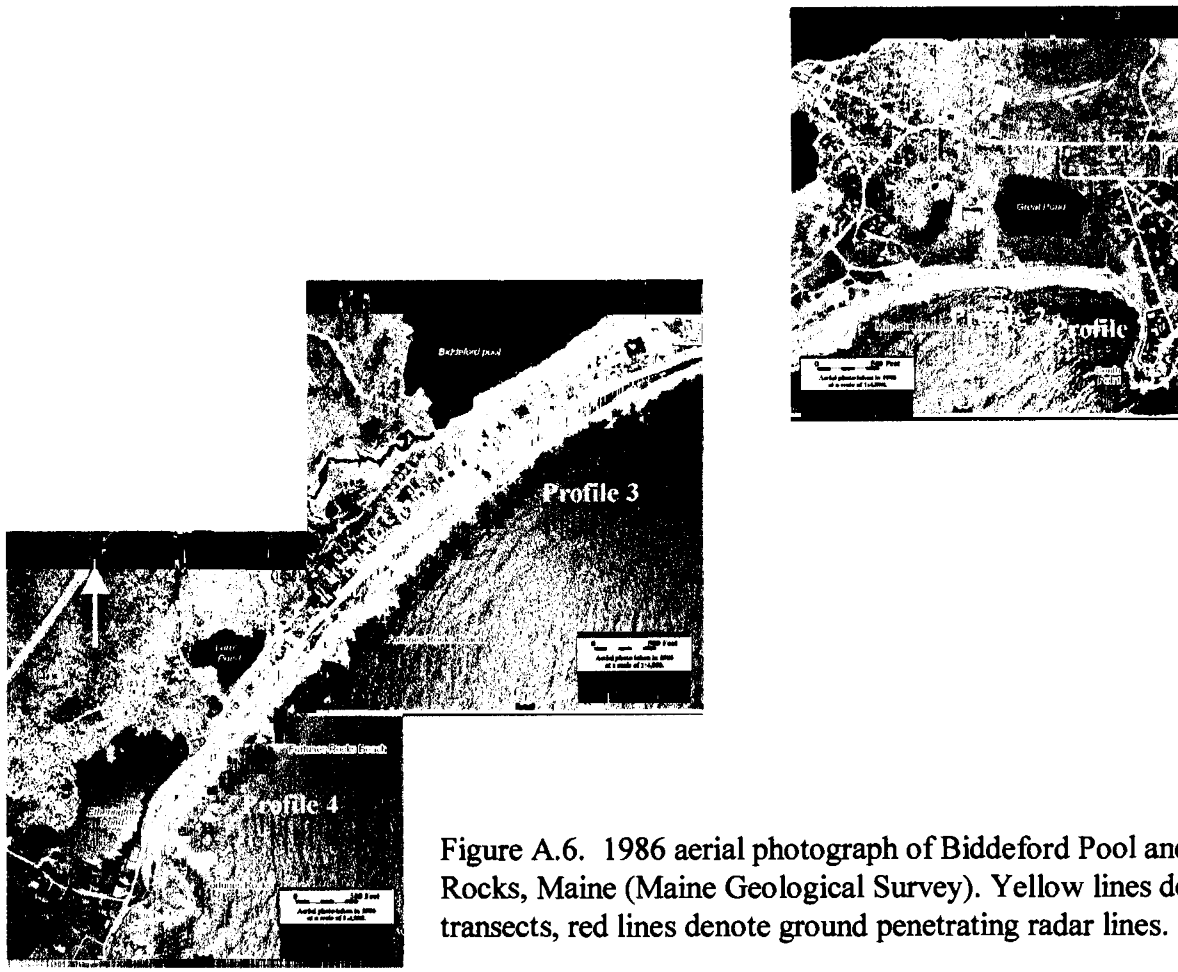


Figure A.6. 1986 aerial photograph of Biddeford Pool and Fortunes Rocks, Maine (Maine Geological Survey). Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

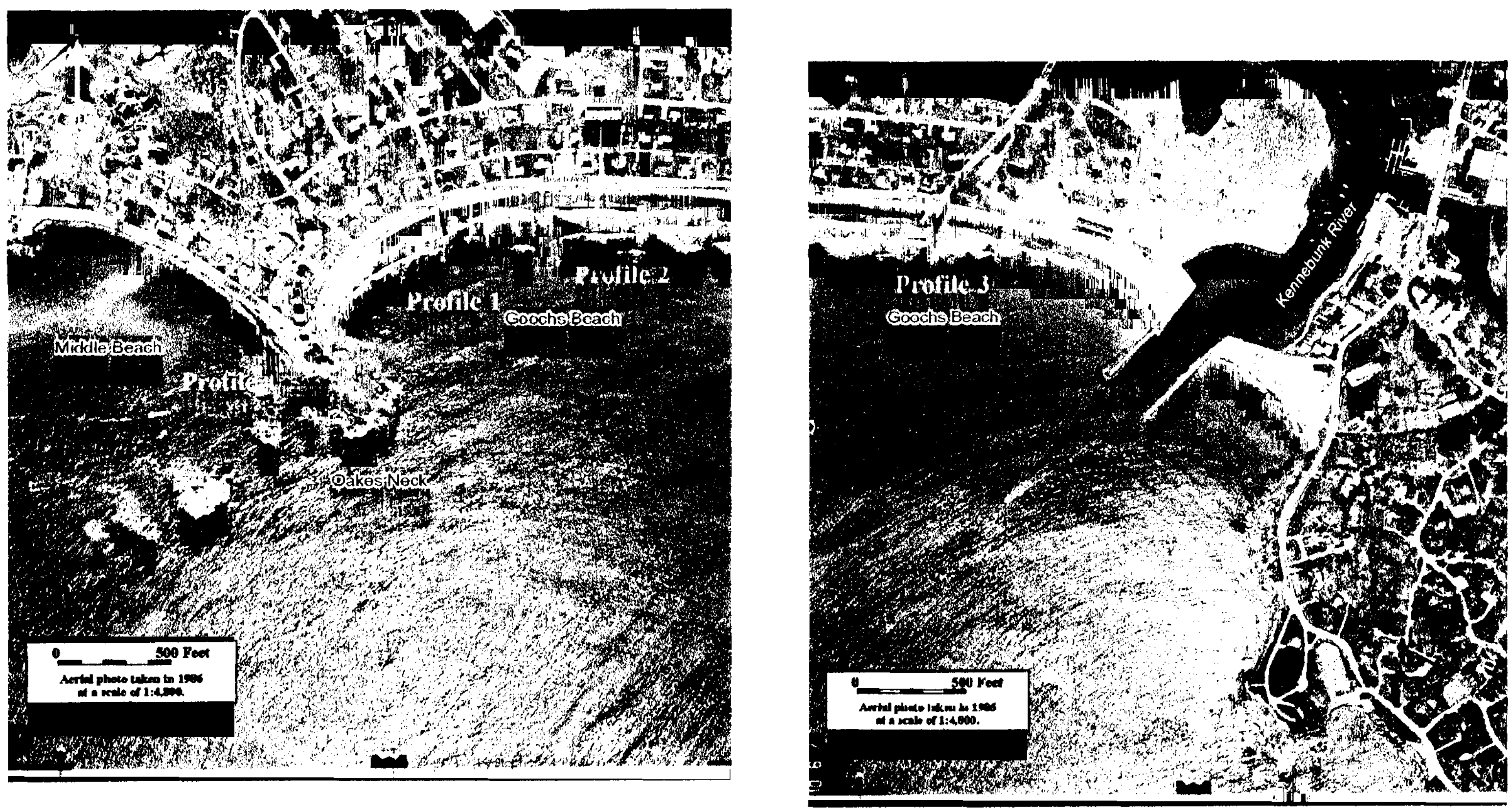


Figure A.7. 1986 aerial photograph of Goochs and Middle Beach, Maine (Maine Geological Survey). Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

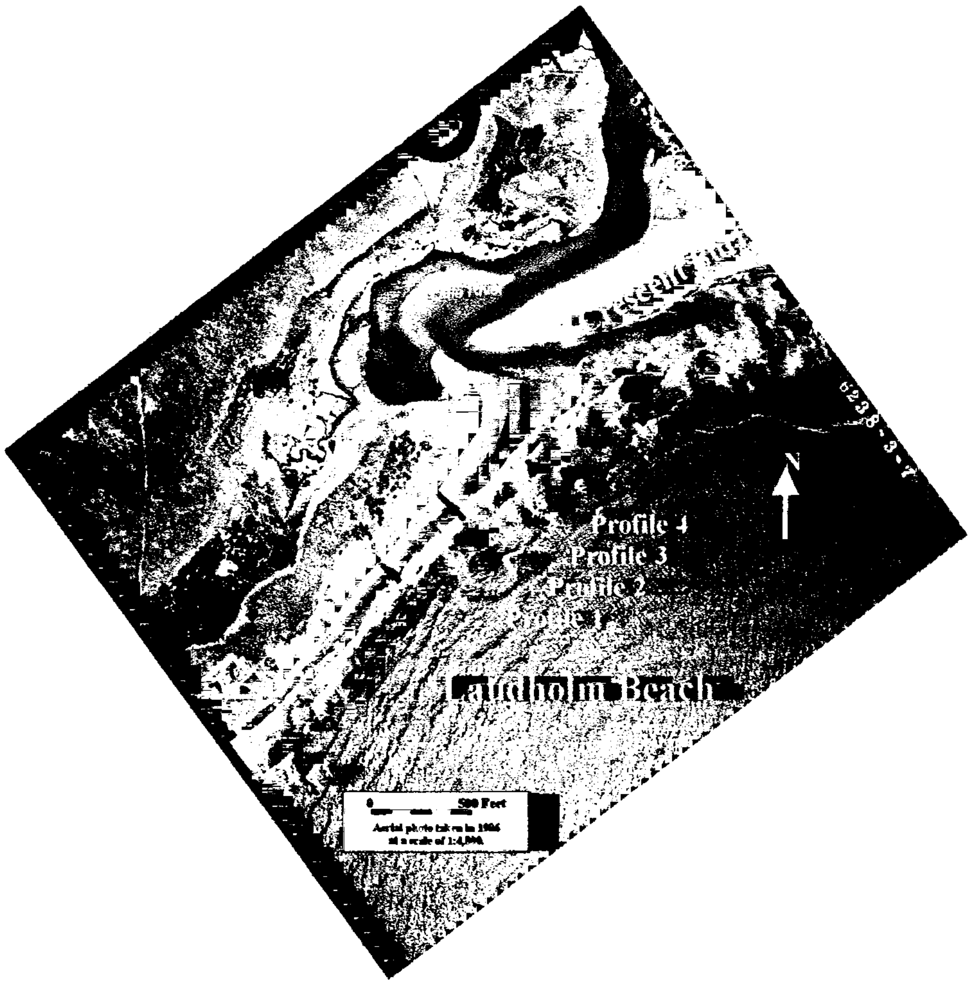


Figure A.8. 1986 aerial photograph of Laudholm Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

Figure A.9. 1986 aerial photograph of Ogunquit Beach, Maine (Maine Geological Survey). See Figure 1.1 for beach location. Yellow lines denote profile transects, red lines denote ground penetrating radar lines.

Appendix B

TOPOGRAPHIC PROFILES

Original monthly topographic measurements of each beach profile, compared to one another.

Original monthly topographic measurements of each beach profile, displayed sequentially in time and space.

Monthly measurements of each beach profile altered to the same length. Some profiles were shortened, while others were extended to a common distance.

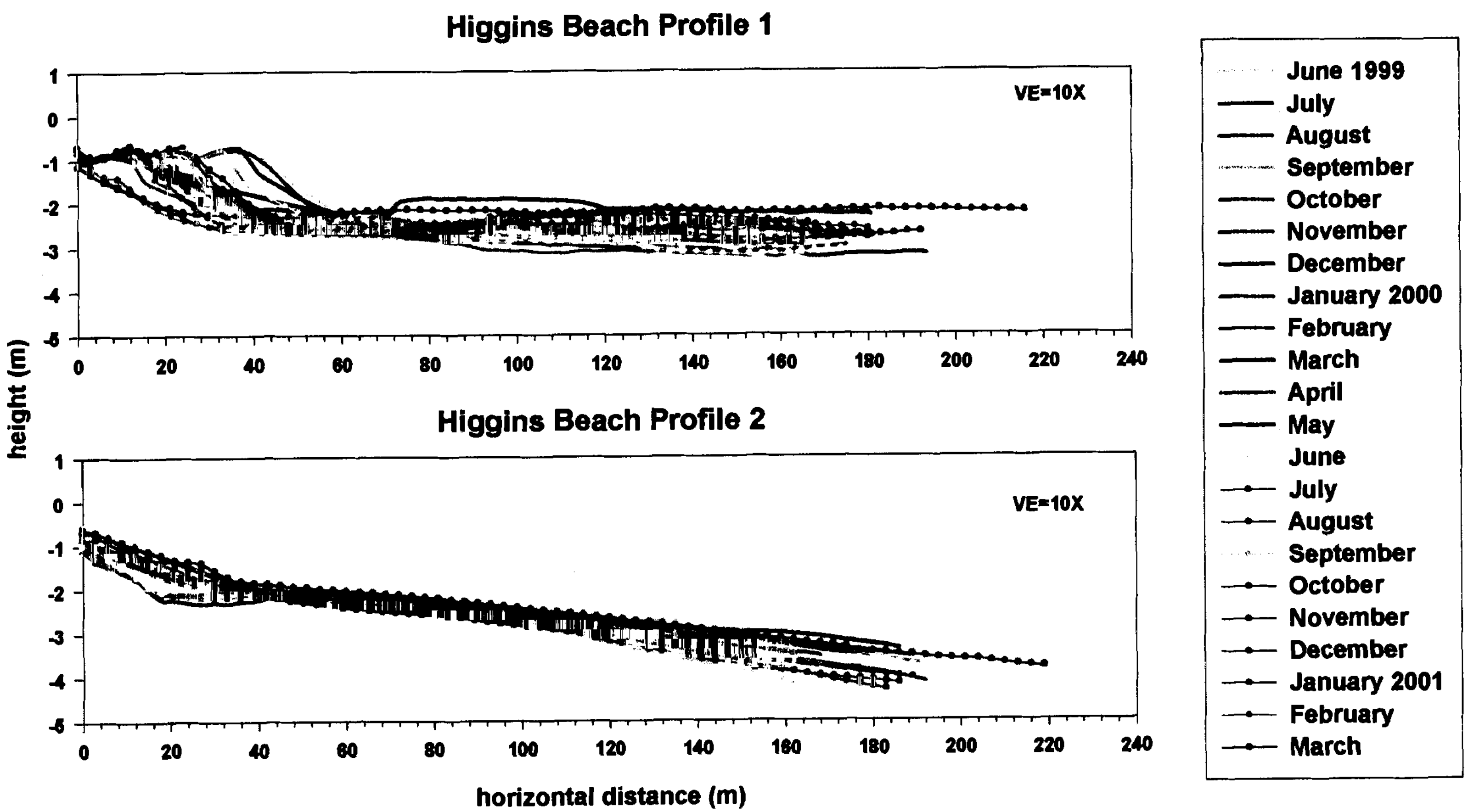


Figure B.1. Higgins Beach Topographic Profiles 1 and 2 original measurements.

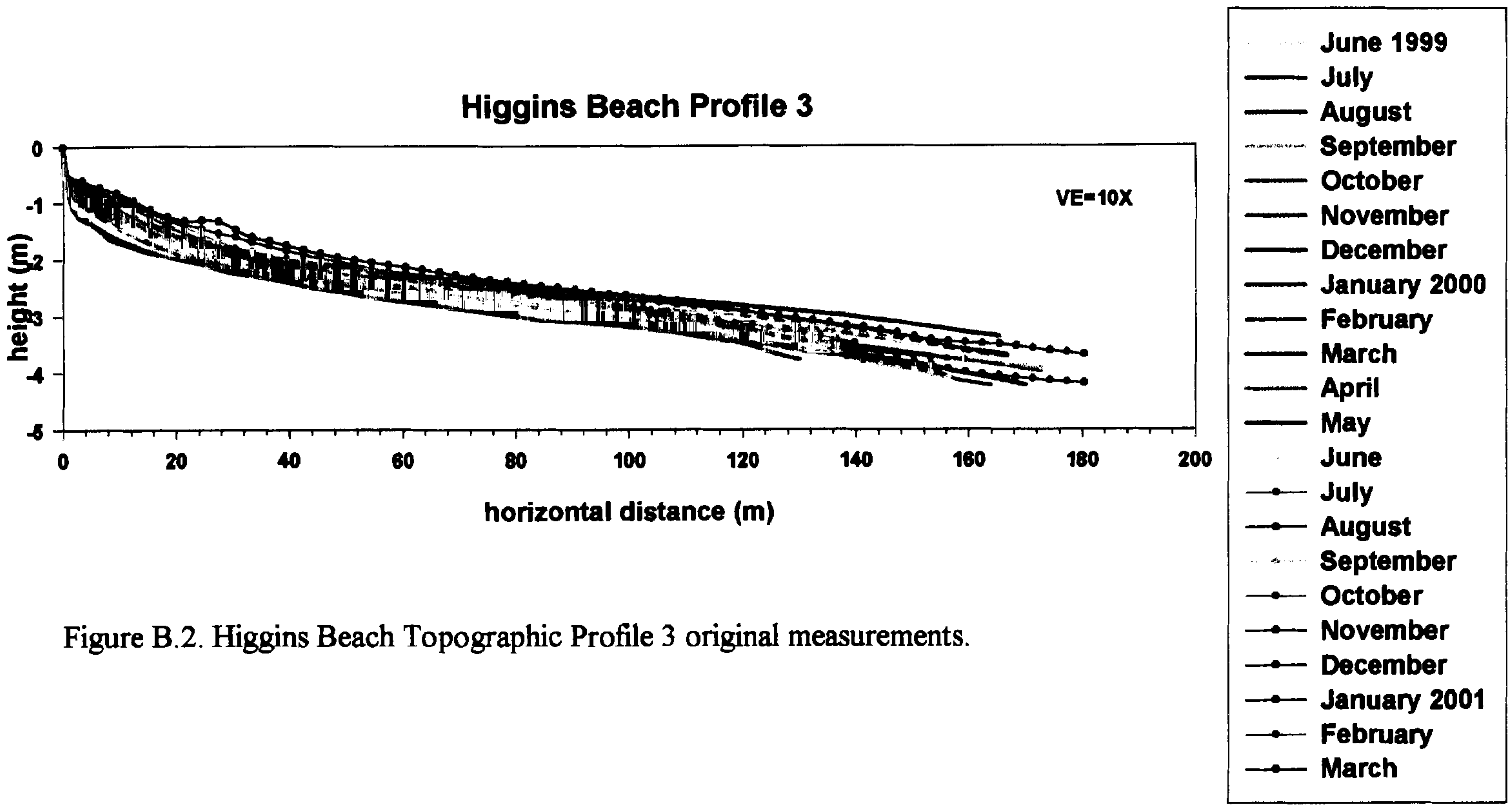


Figure B.2. Higgins Beach Topographic Profile 3 original measurements.

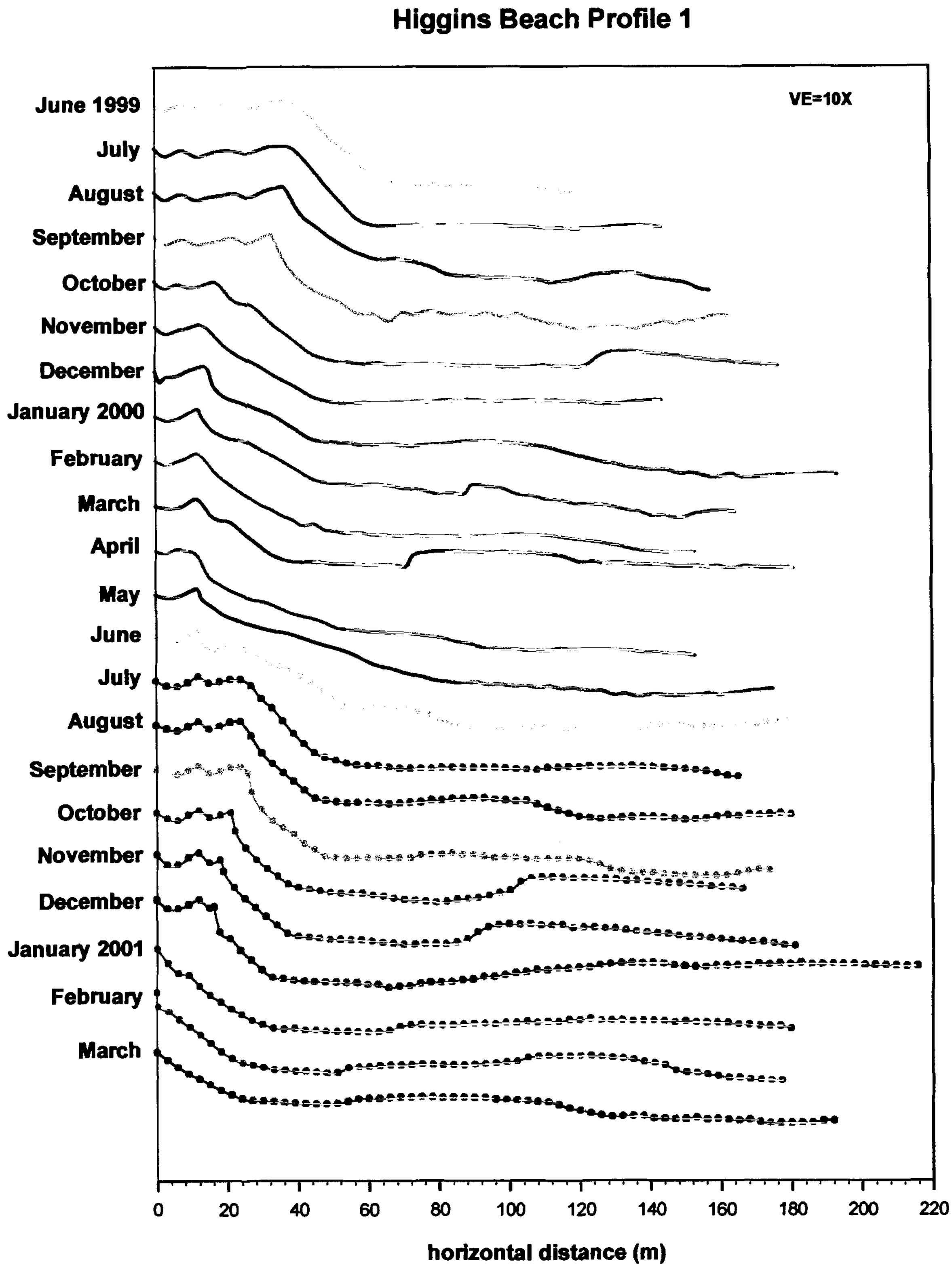


Figure B.3. Higgins Beach Profile 1 monthly topographic changes.

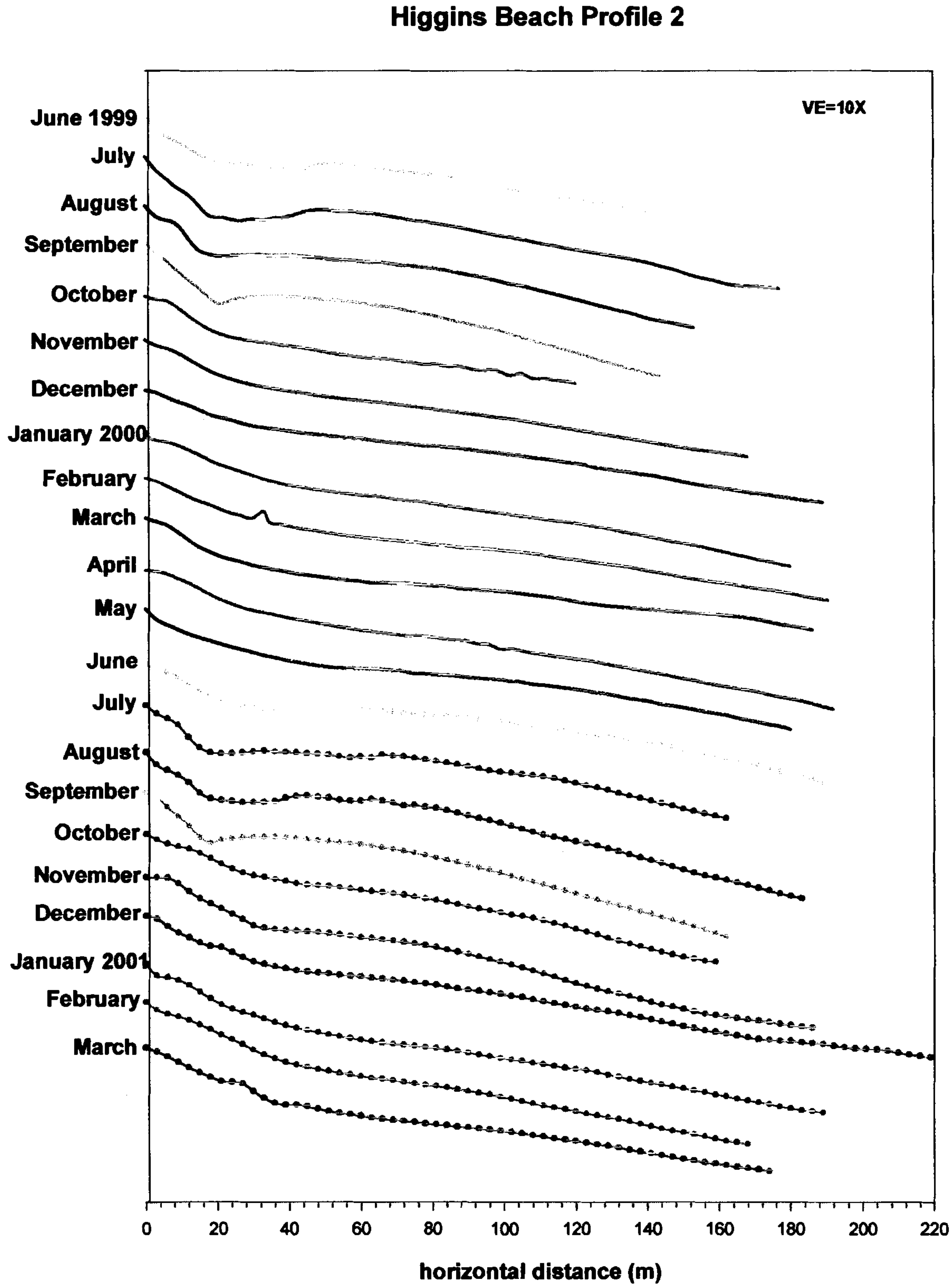


Figure B.4. Higgins Beach Profile 2 monthly topographic changes.

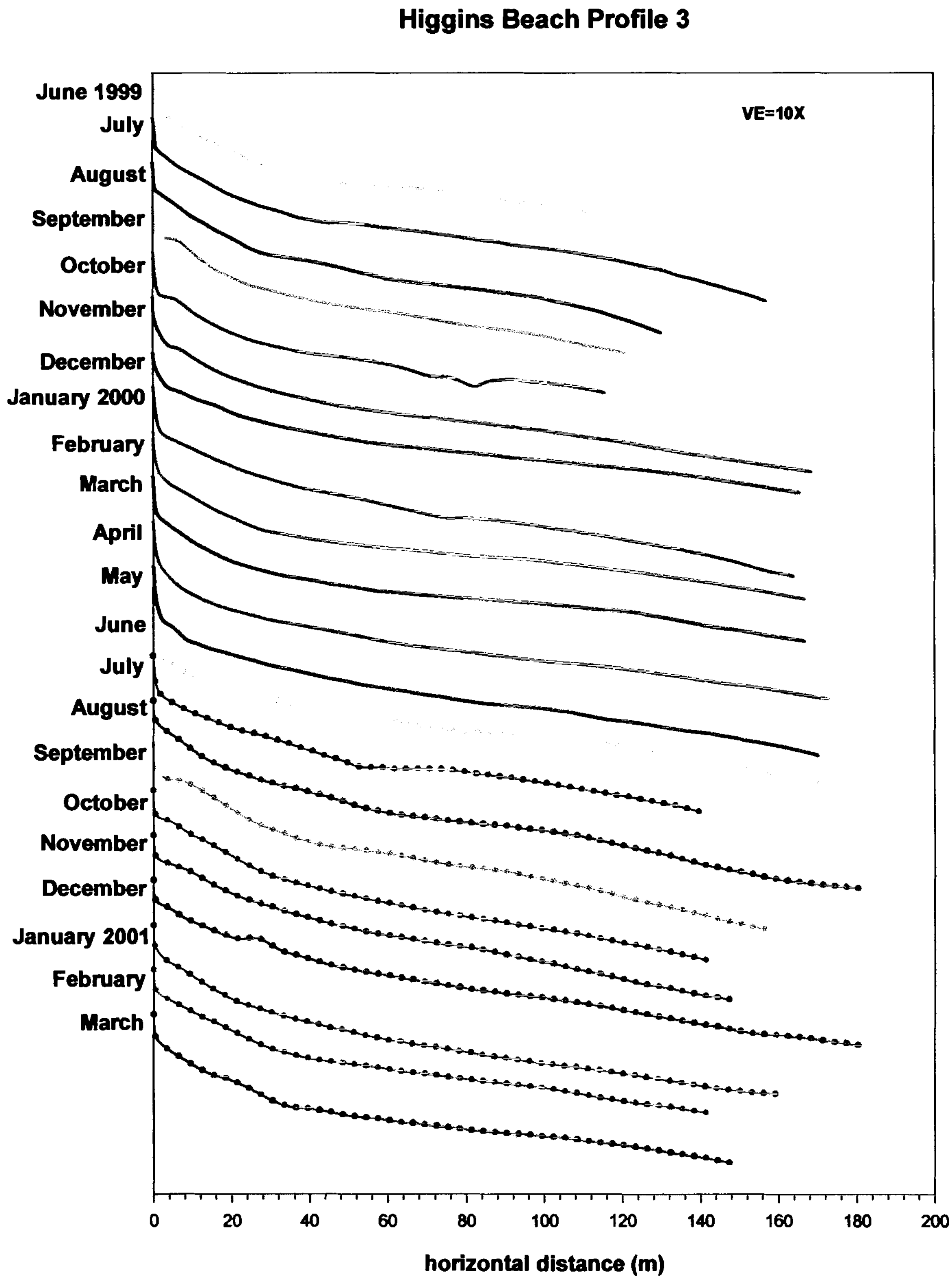


Figure B.5. Higgins Beach Profile 3 monthly topographic changes.

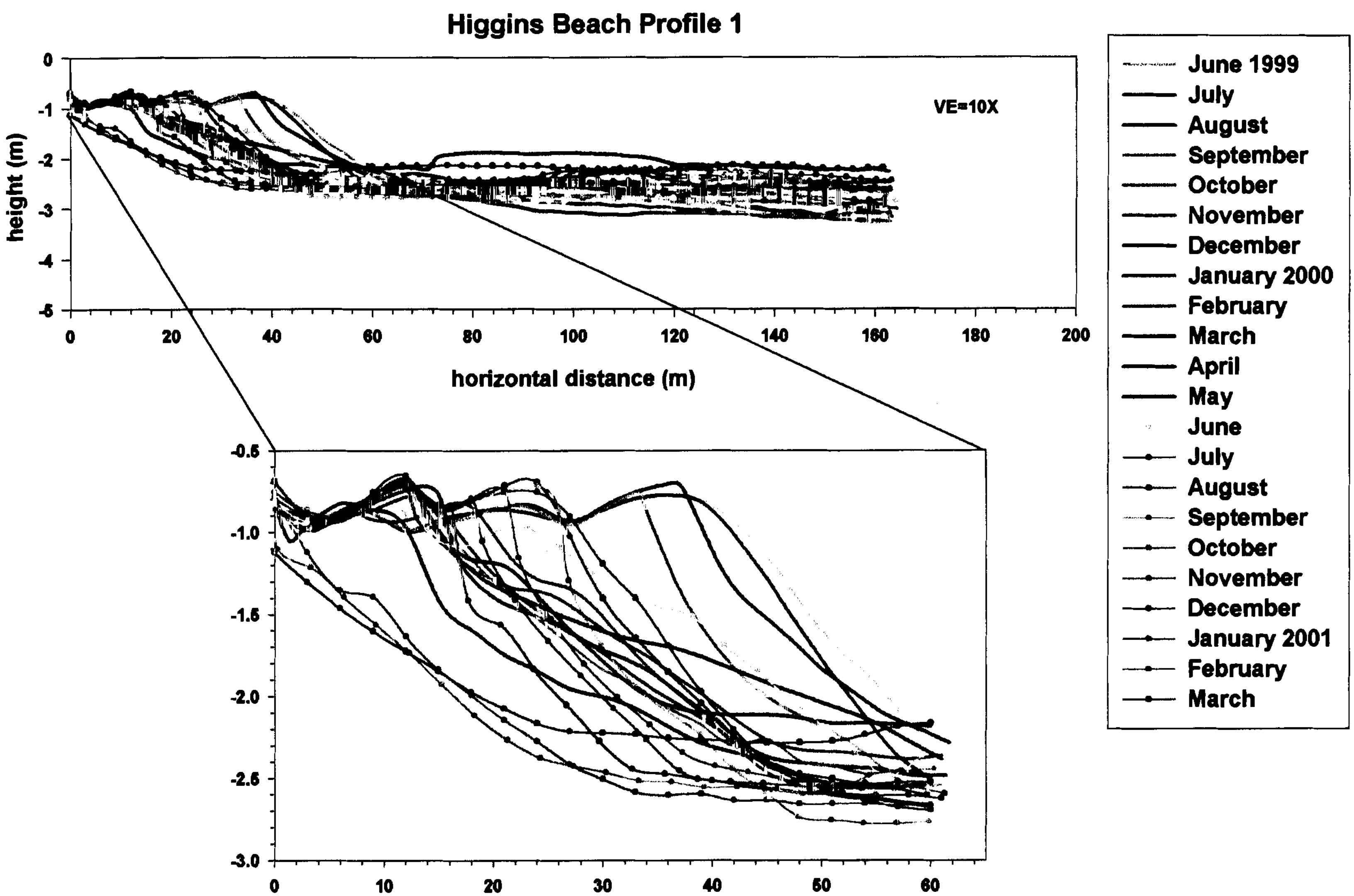


Figure B.6. Higgins Beach Profile 1 monthly topographic changes altered to same length.

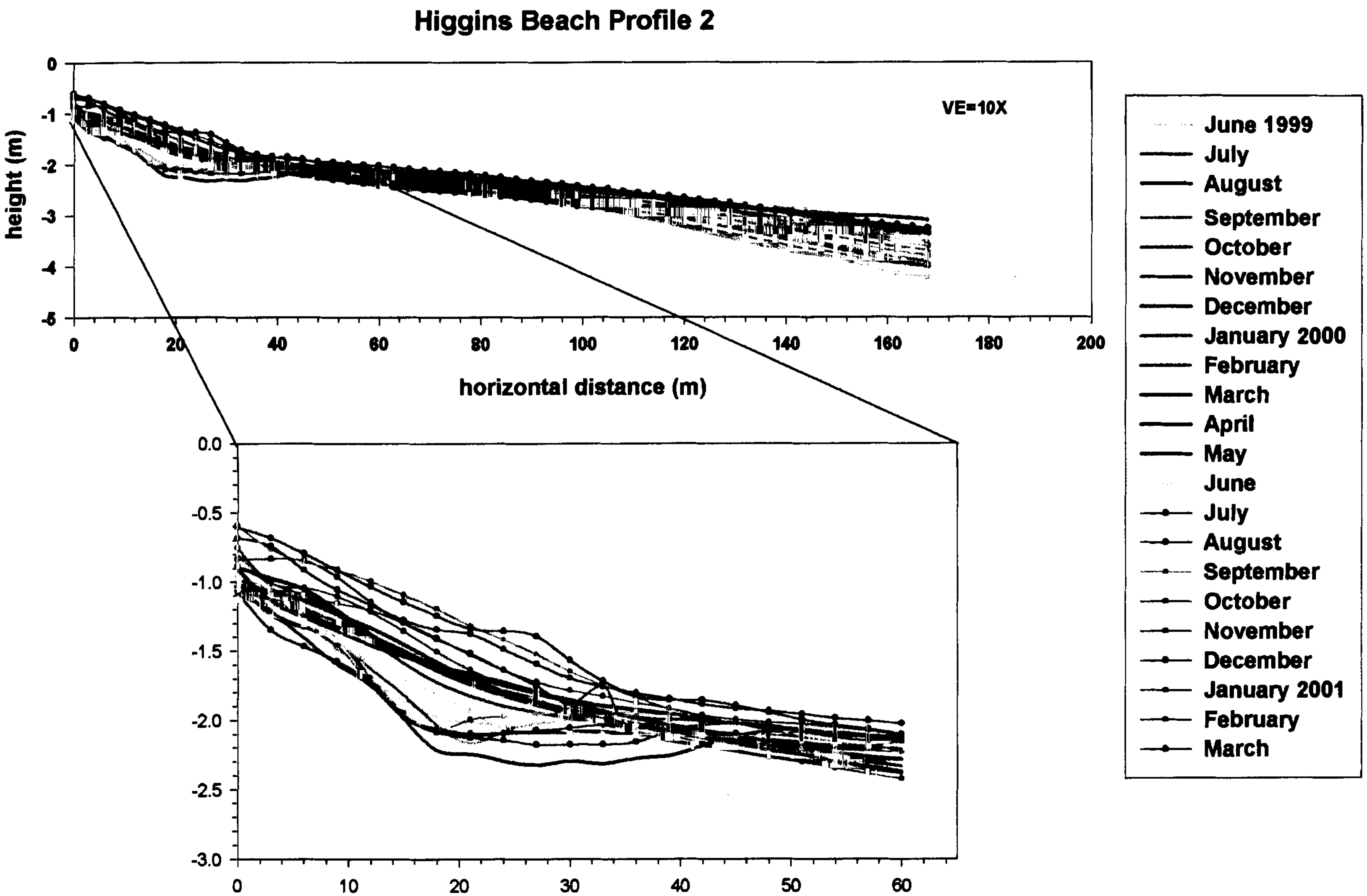


Figure B.7. Higgins Beach Profile 2 monthly topographic changes altered to same length.

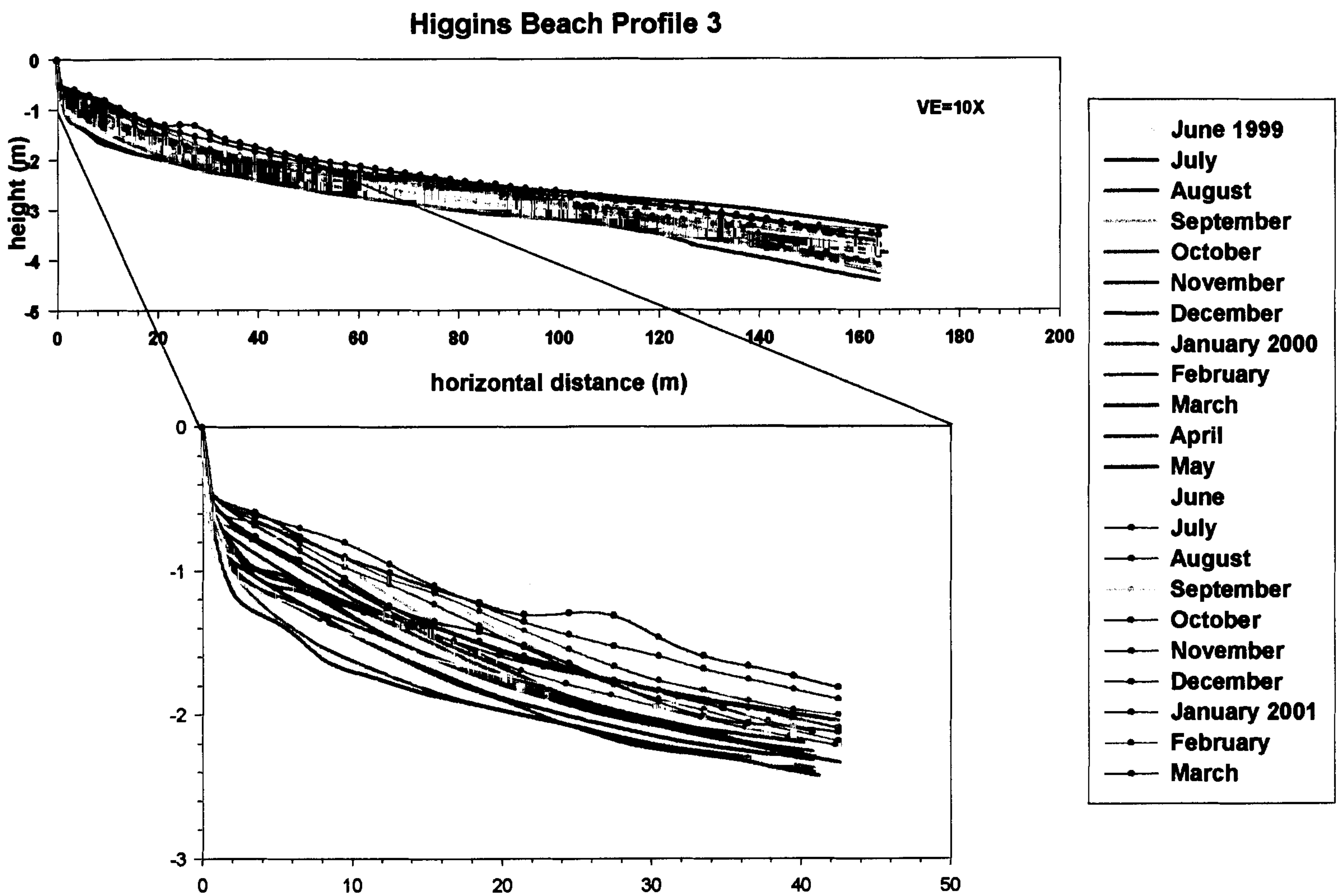


Figure B.8. Higgins Beach Profile 3 monthly topographic changes altered to same length.

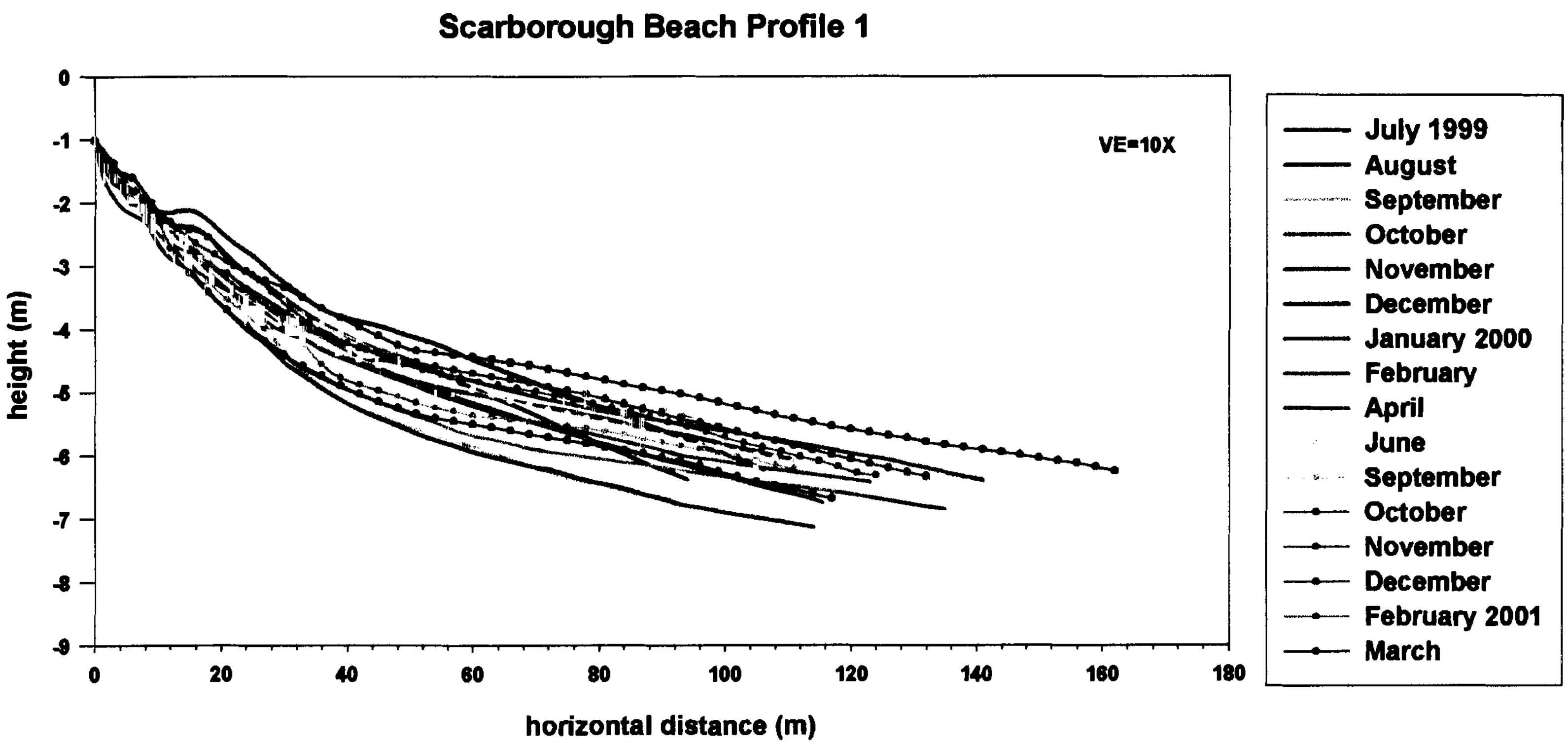


Figure B.9. Scarborough Beach Topographic Profile 1 original measurements.

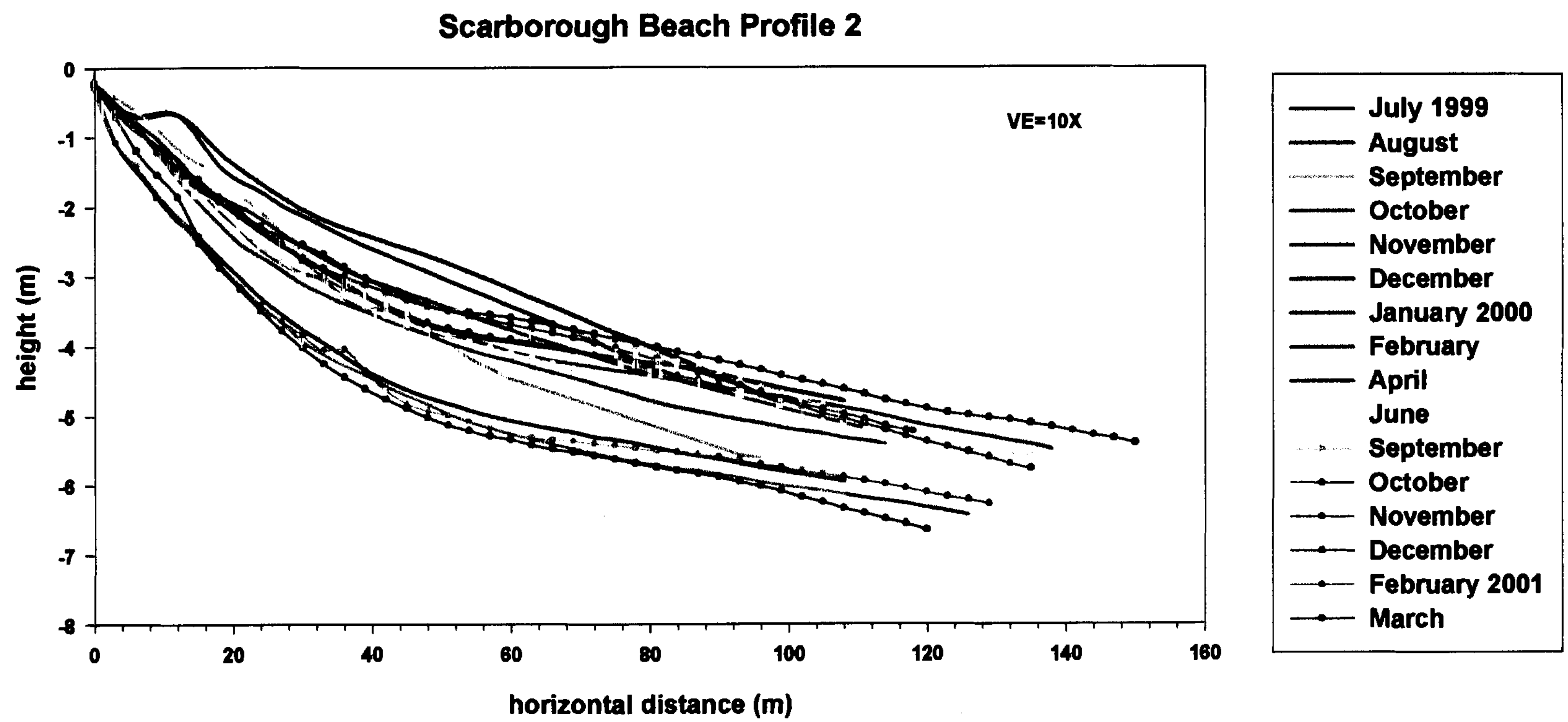


Figure B.10. Scarborough Beach Topographic Profile 2 original measurements.

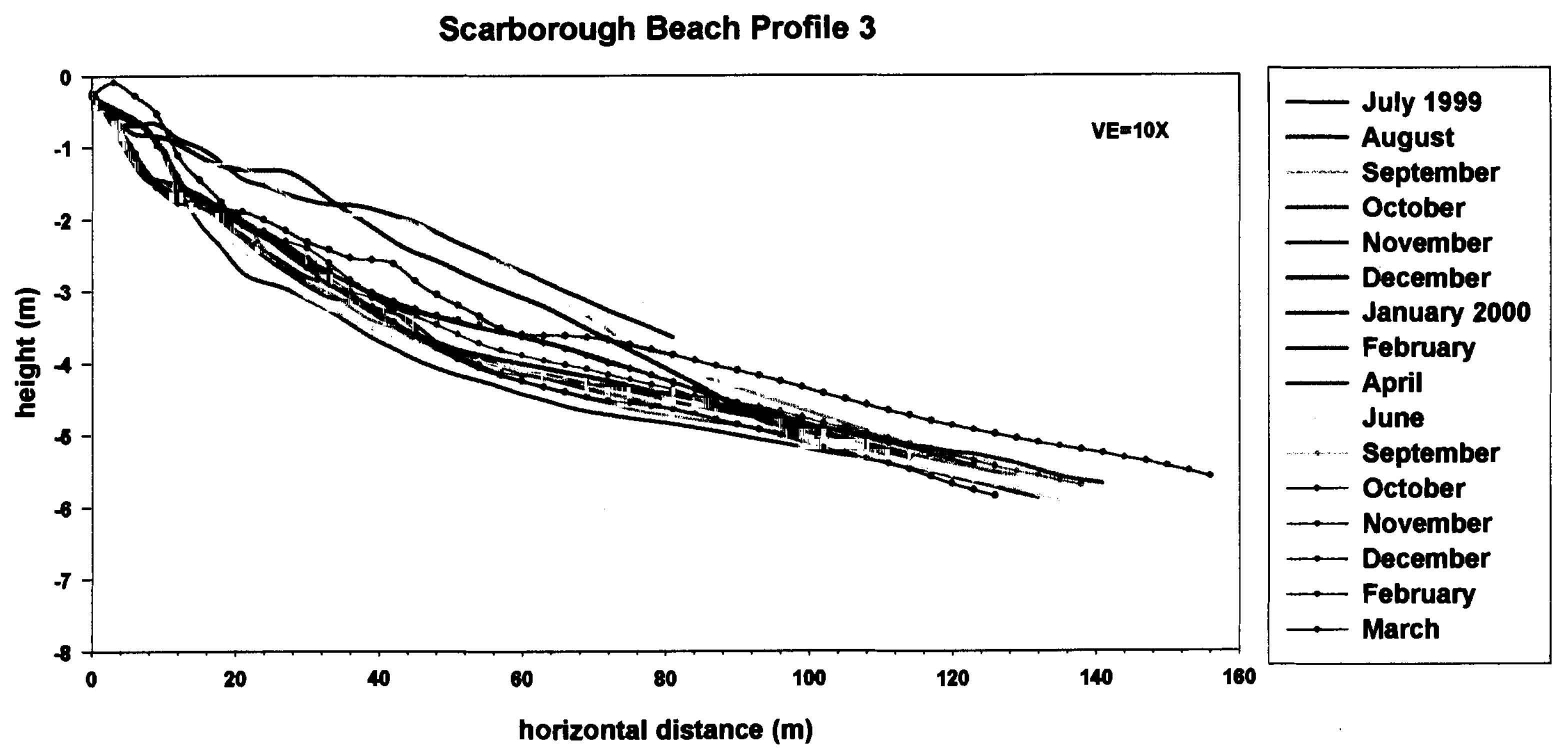


Figure B.11. Scarborough Beach Topographic Profile 3 original measurements.

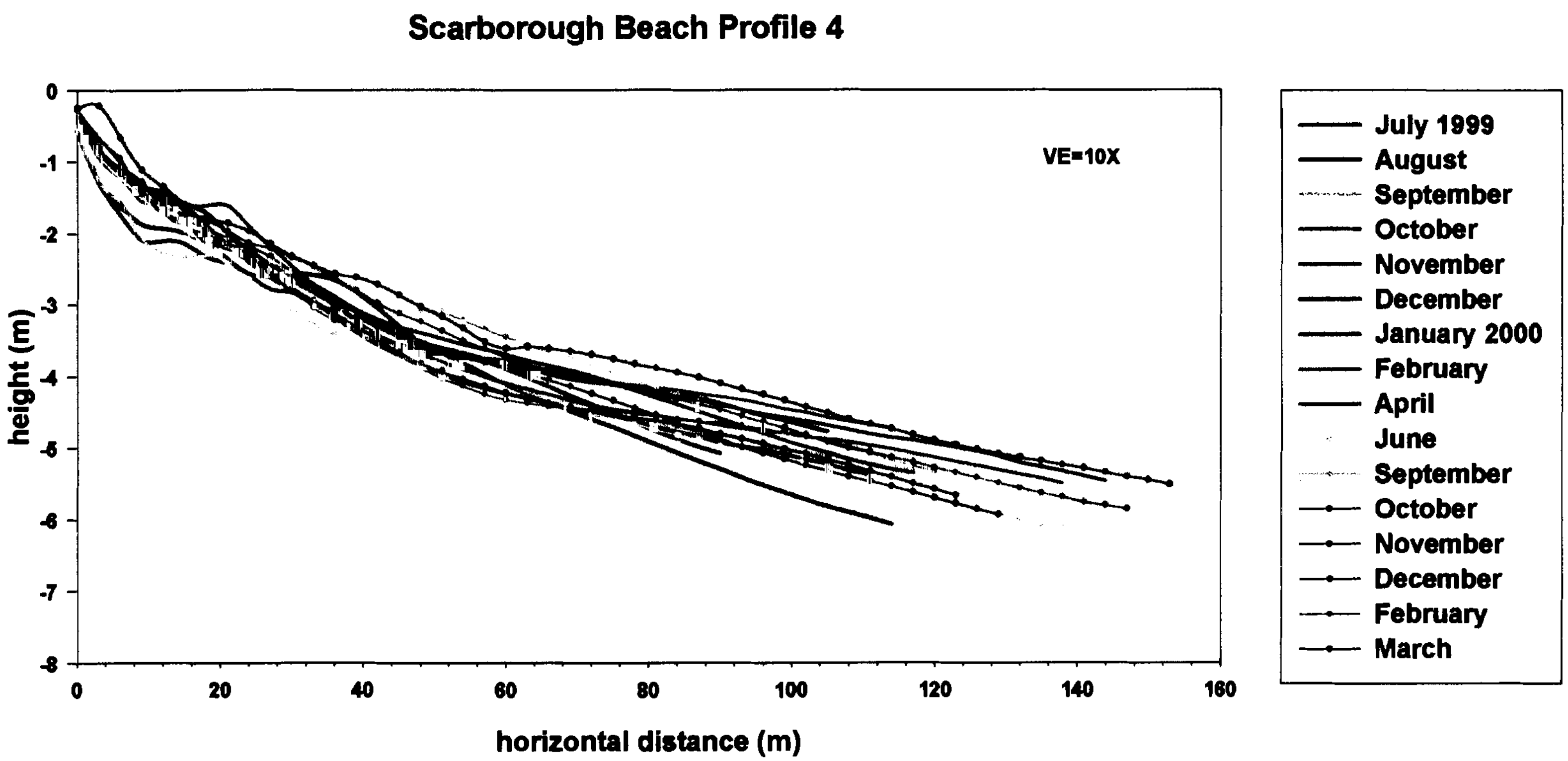


Figure B.12. Scarborough Beach Topographic Profile 4 original measurements.

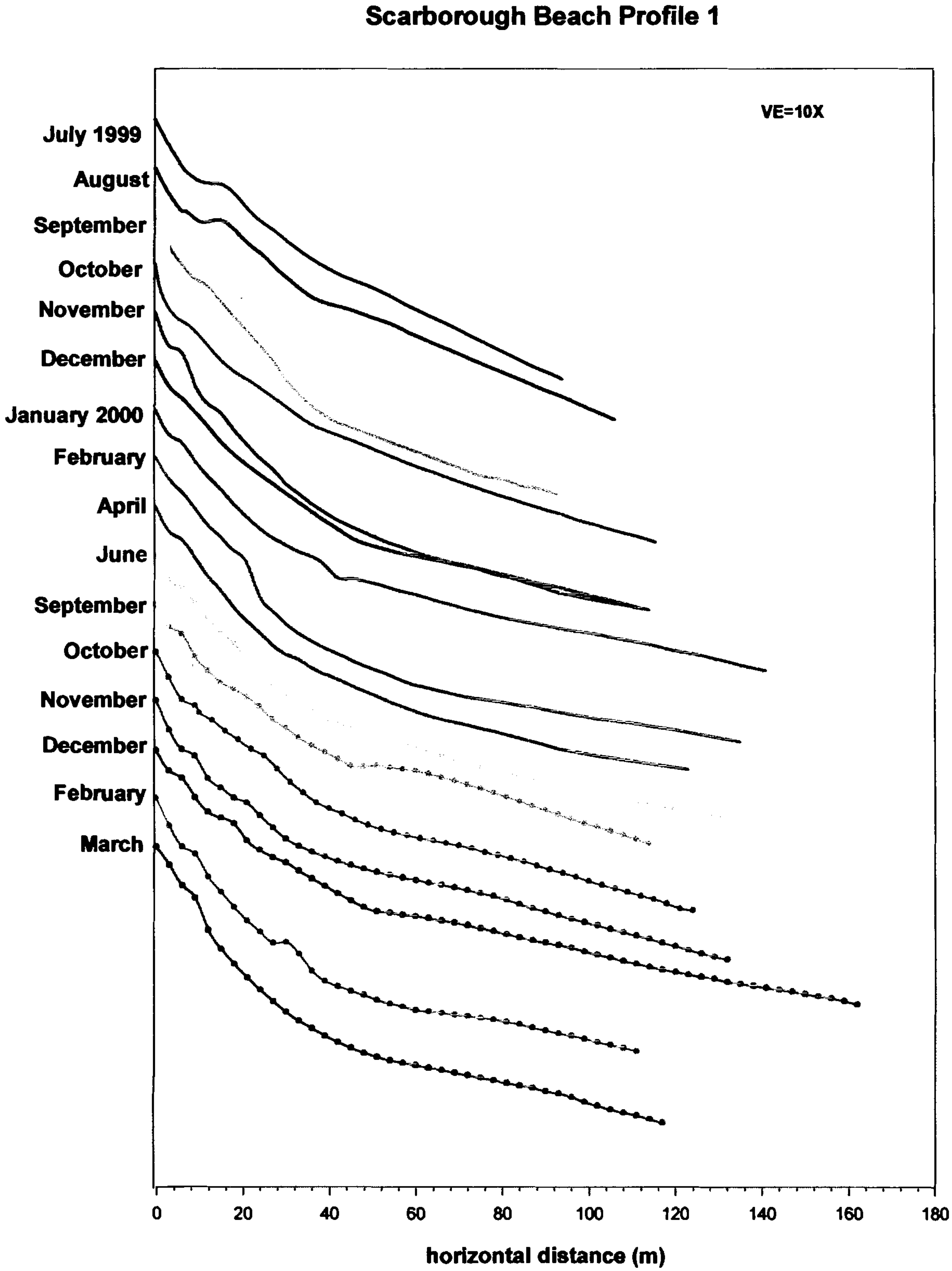


Figure B.13. Scarborough Beach Profile1 monthly topographic changes.

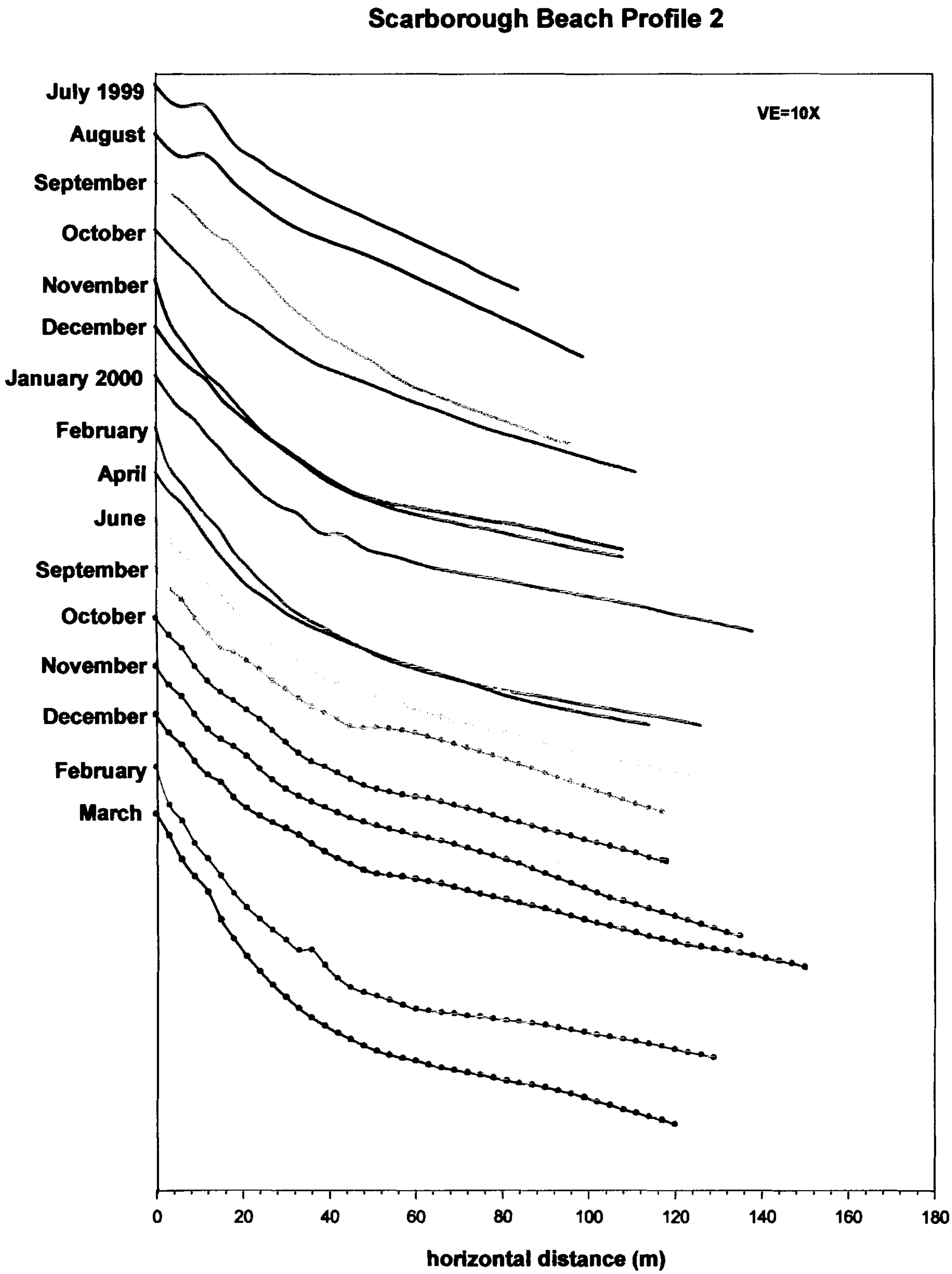


Figure B.14. Scarborough Beach Profile 2 monthly topographic changes.

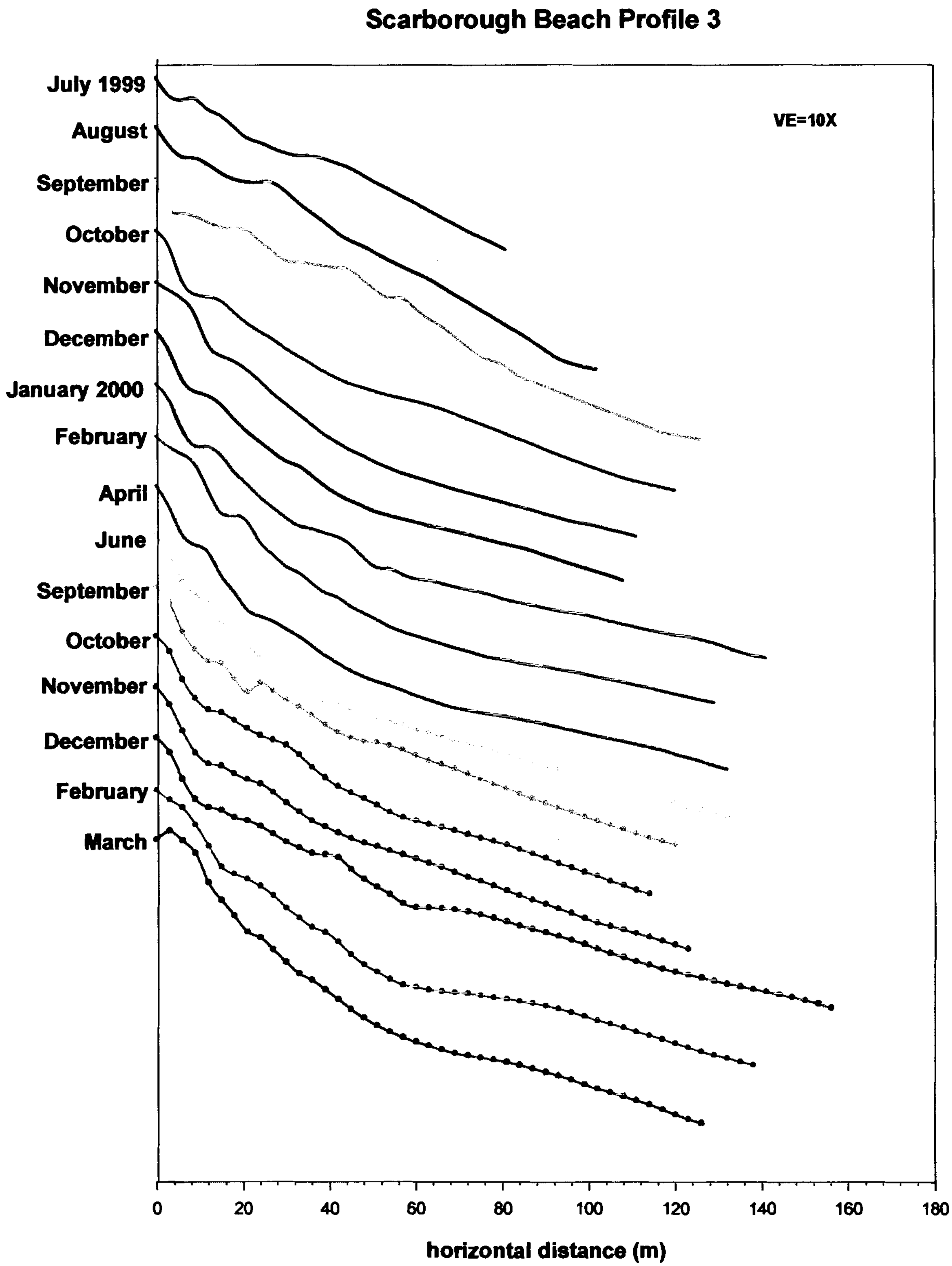


Figure B.15. Scarborough Beach Profile 3 monthly topographic changes.

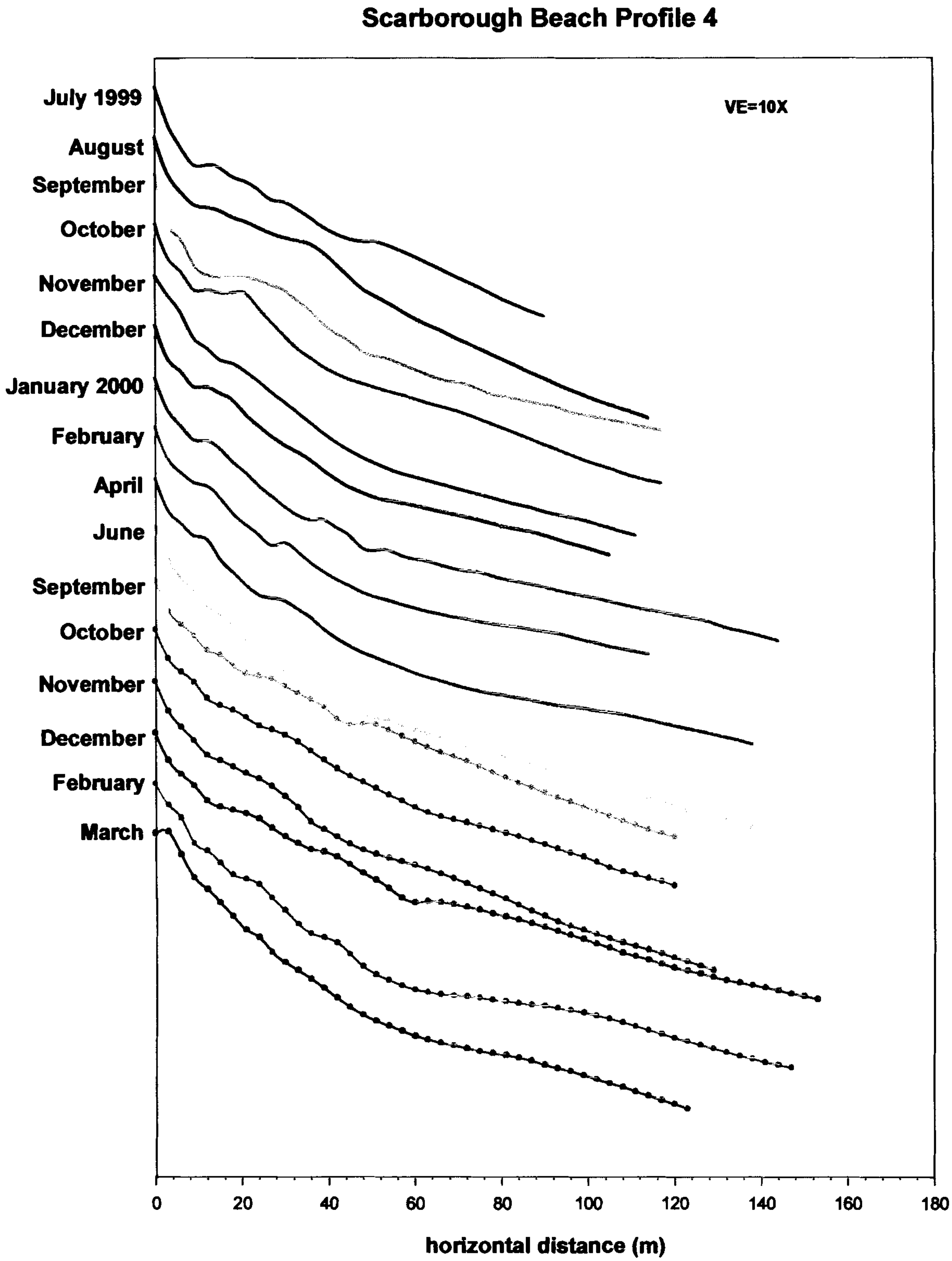


Figure B.16. Scarborough Beach Profile 4 monthly topographic changes.

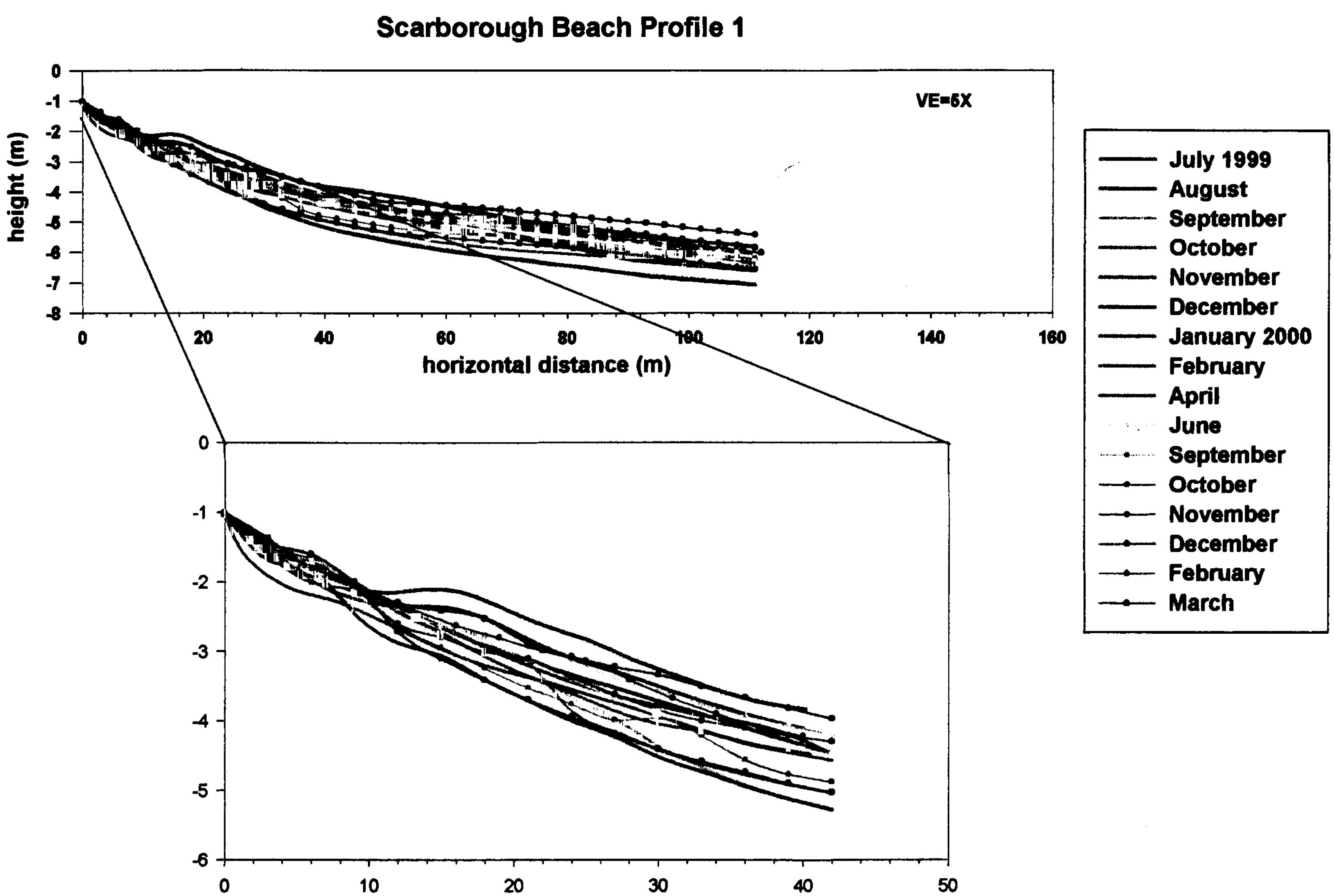


Figure B.17. Scarborough Beach Profile 1 monthly topographic changes altered to same length.

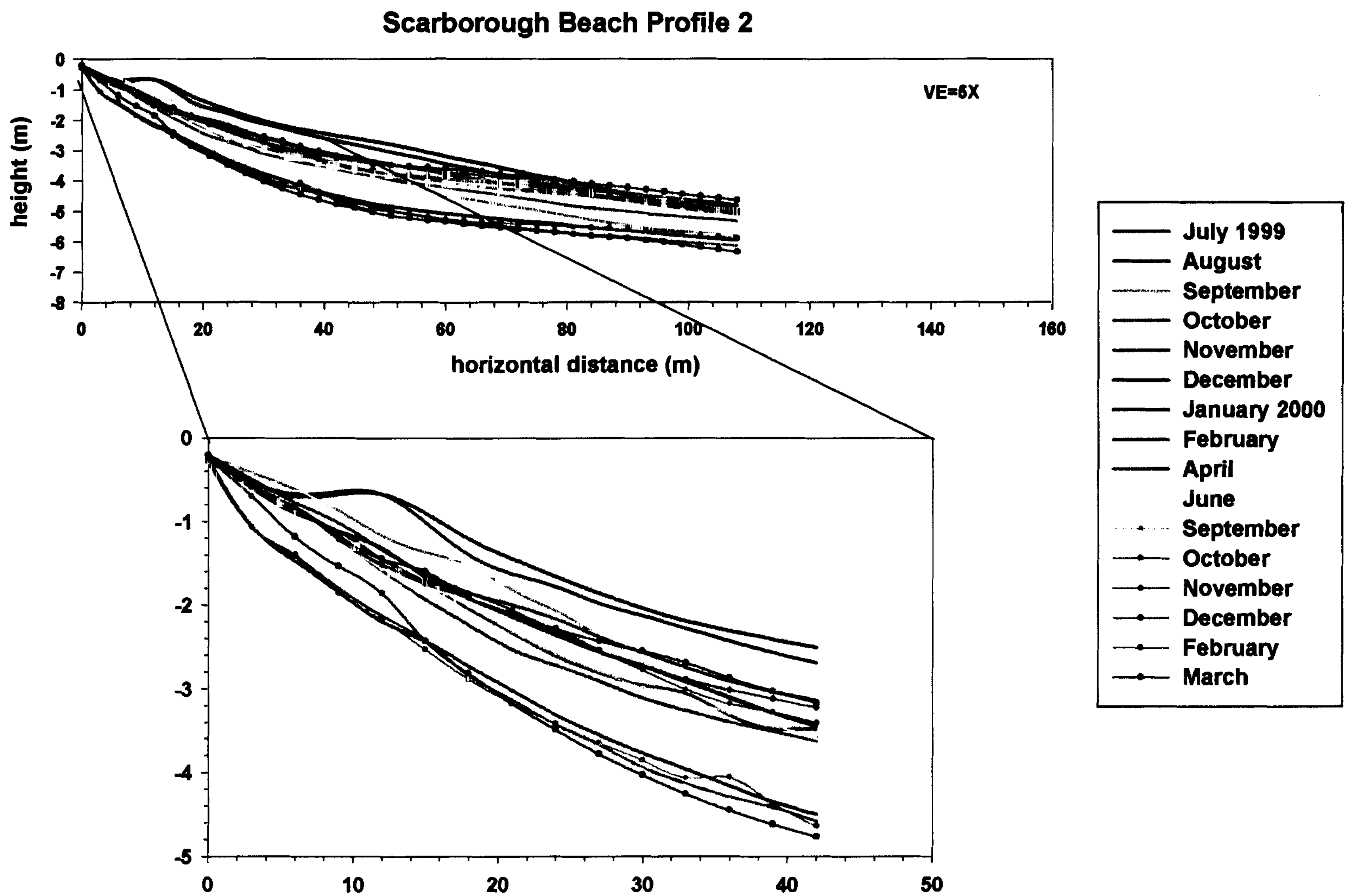


Figure B.18. Scarborough Beach Profile 2 monthly topographic changes altered to same length.

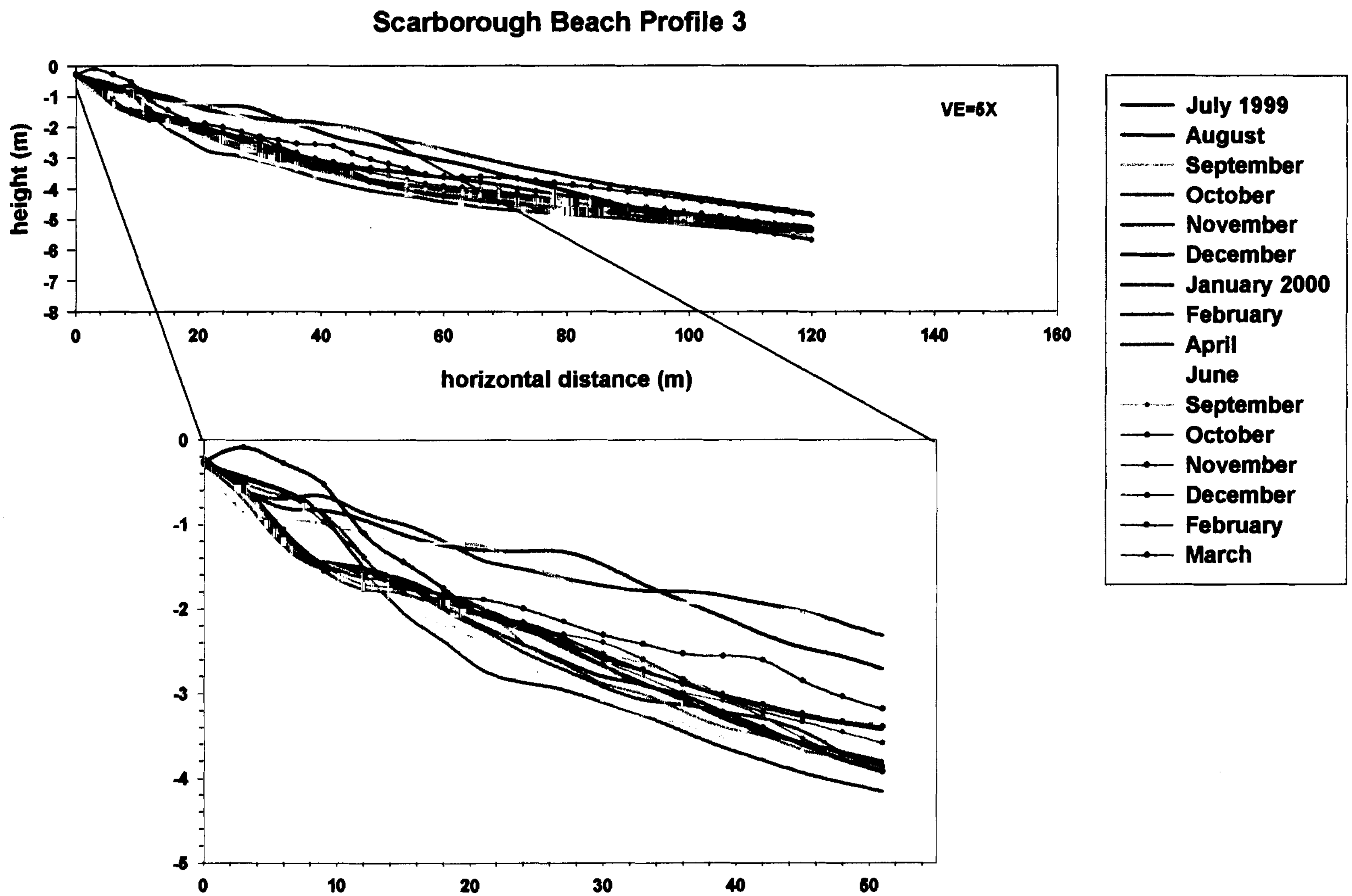


Figure B.19. Scarborough Beach Profile 3 monthly topographic changes altered to same length.

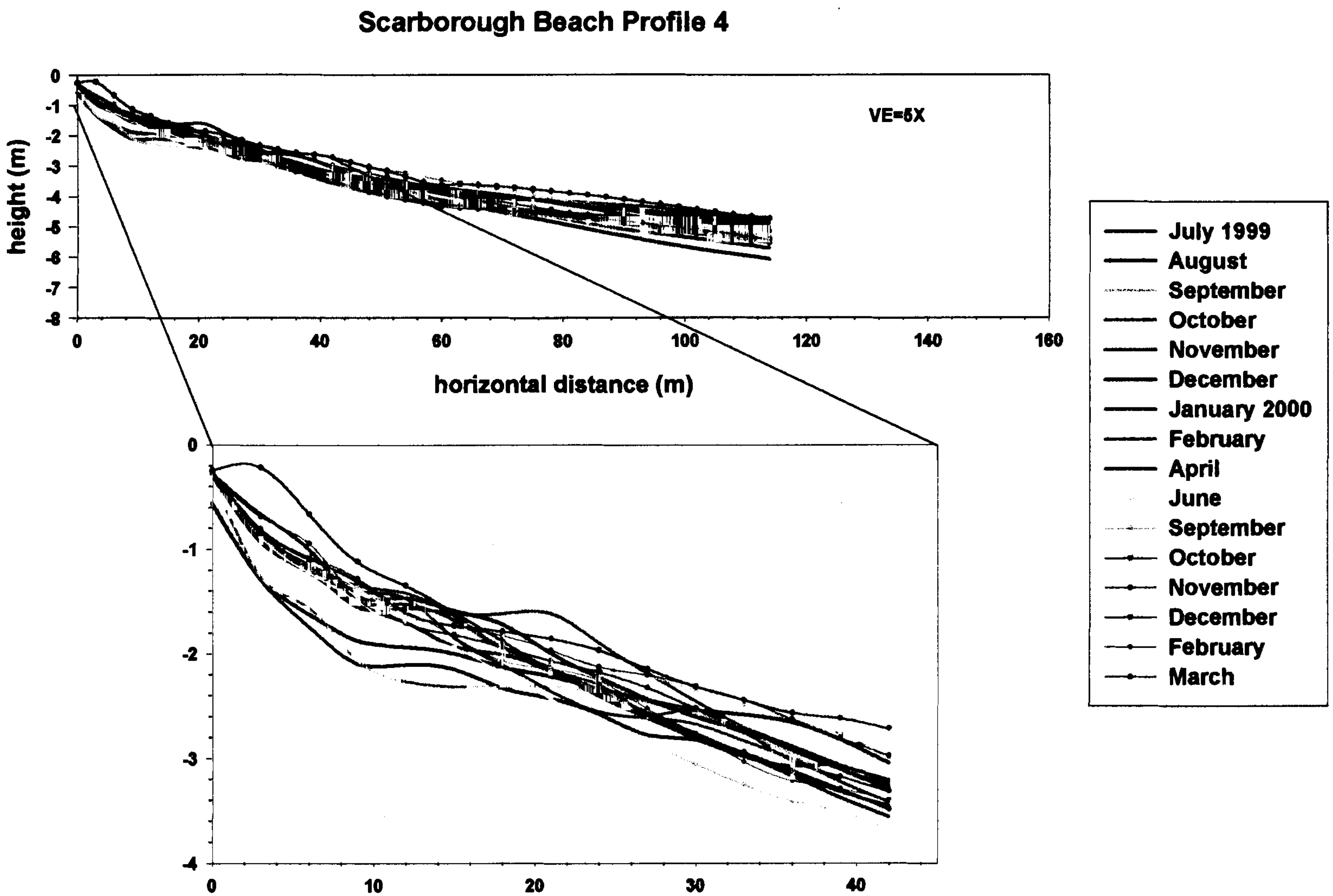


Figure B.20. Scarborough Beach Profile 4 monthly topographic change altered to same length.

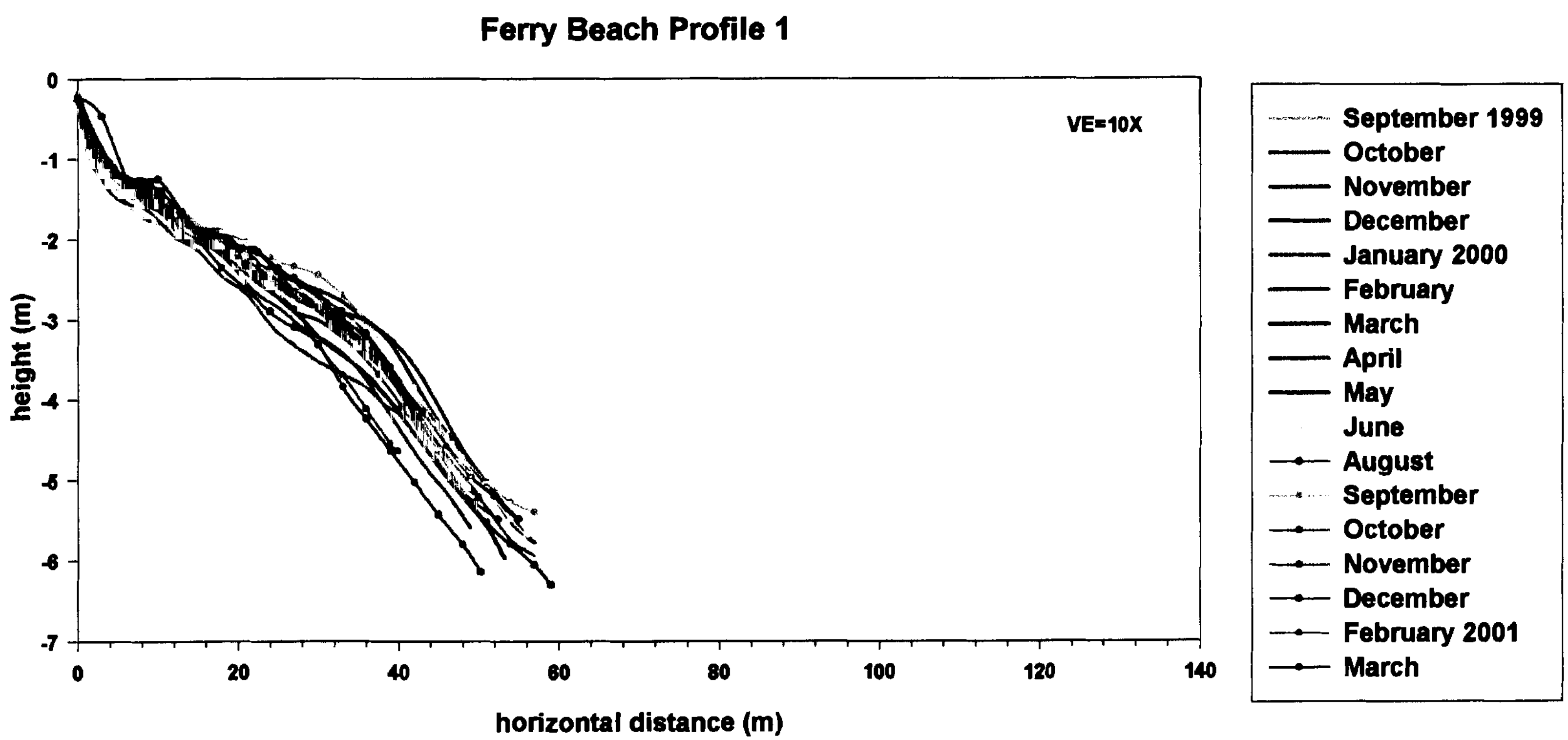


Figure B.21. Ferry Beach Topographic Profile 1 original measurements.

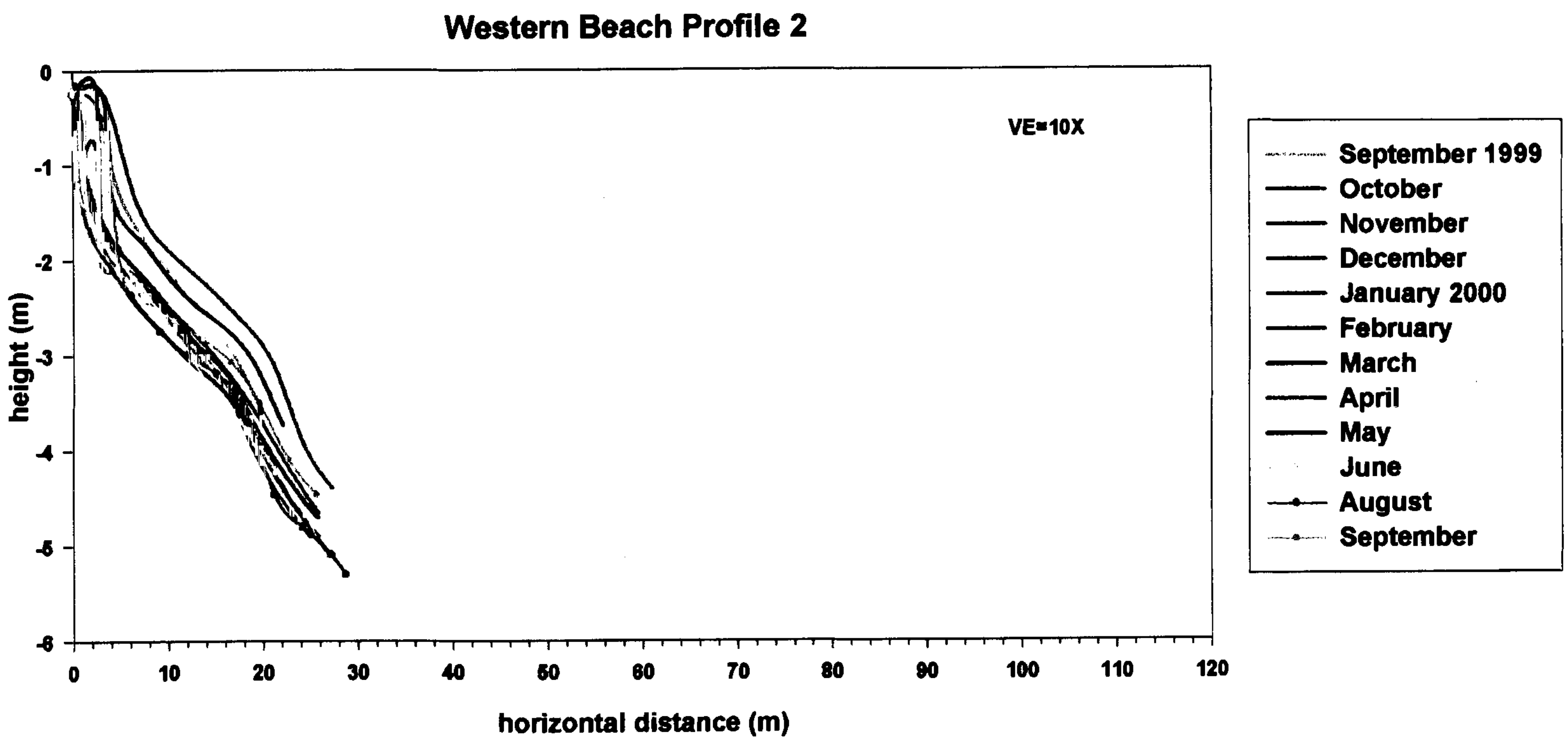


Figure B.22. Ferry Beach Topographic Profile 2 original measurements.

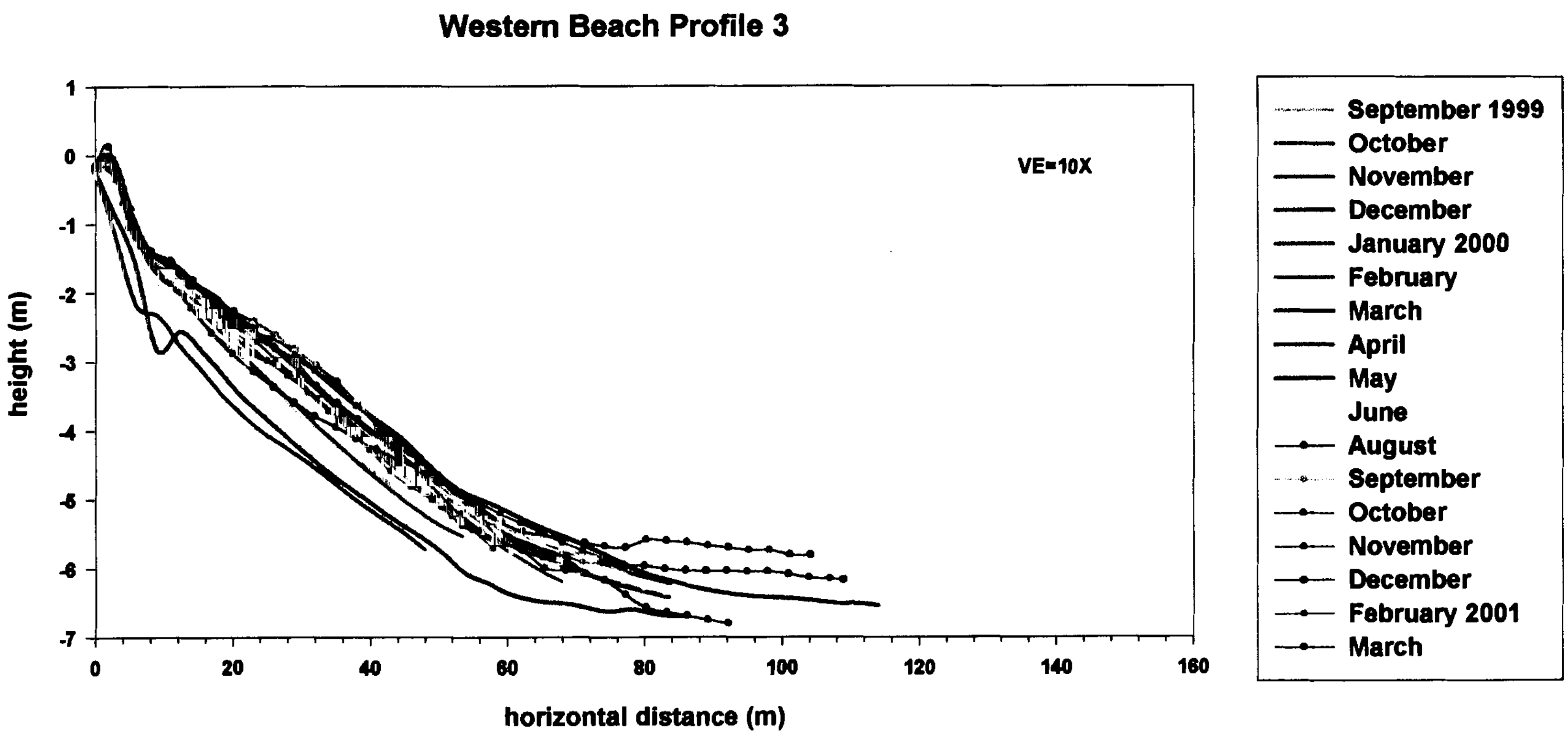


Figure B.23. Western Beach Topographic Profile 3 original measurements.

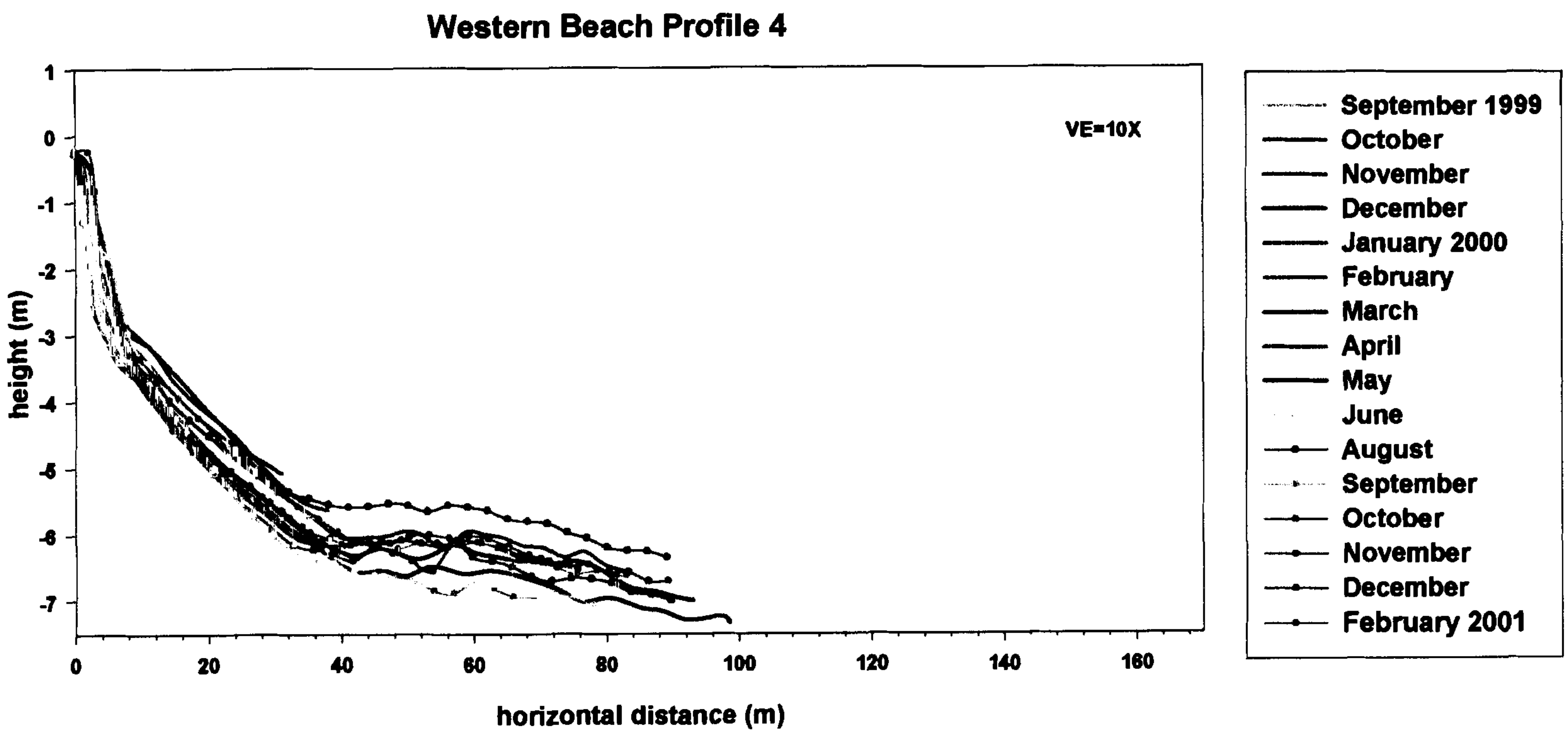


Figure B.24. Western Beach Topographic Profile 4 original measurements.

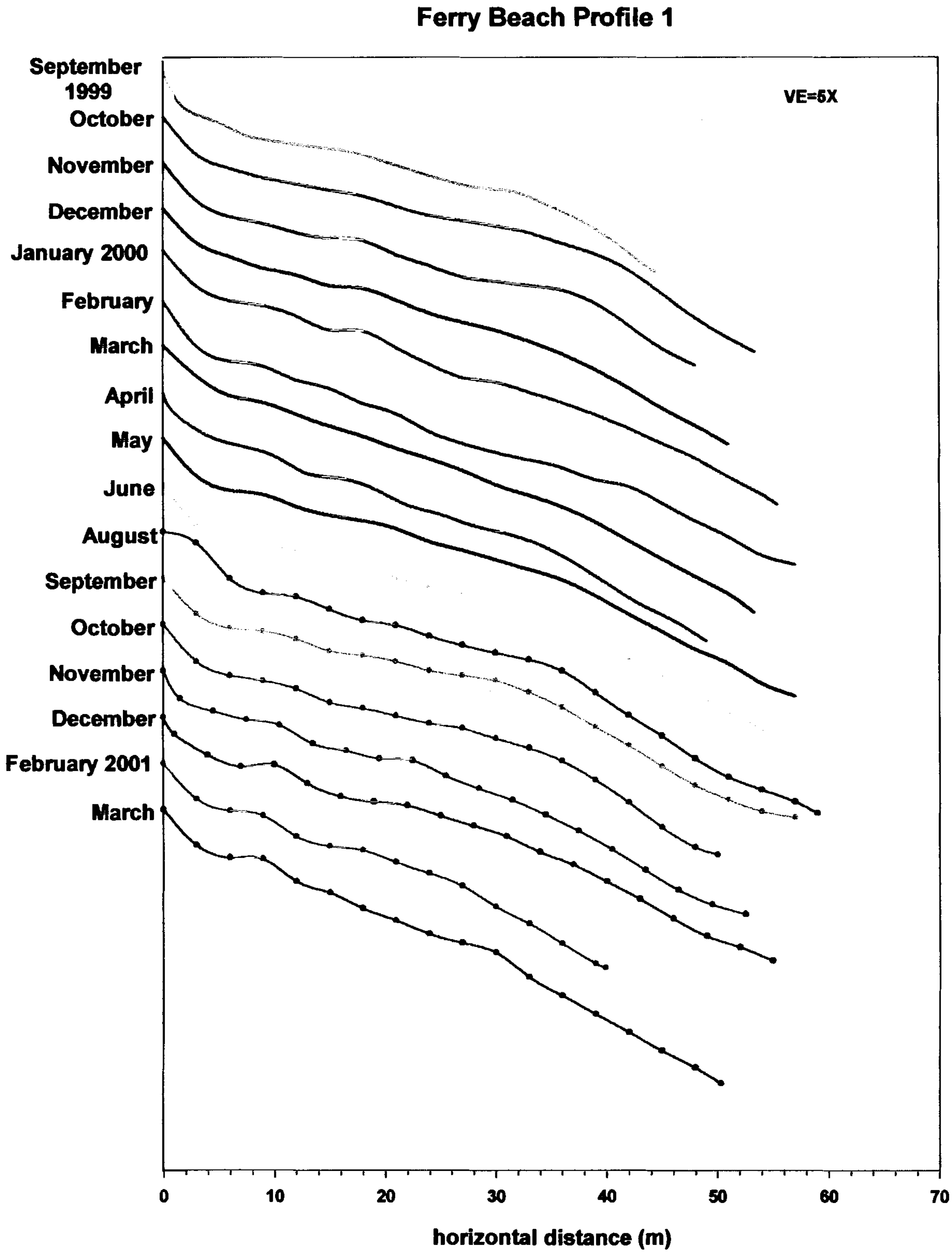


Figure B.25. Ferry Beach Profile 1 monthly topographic changes.

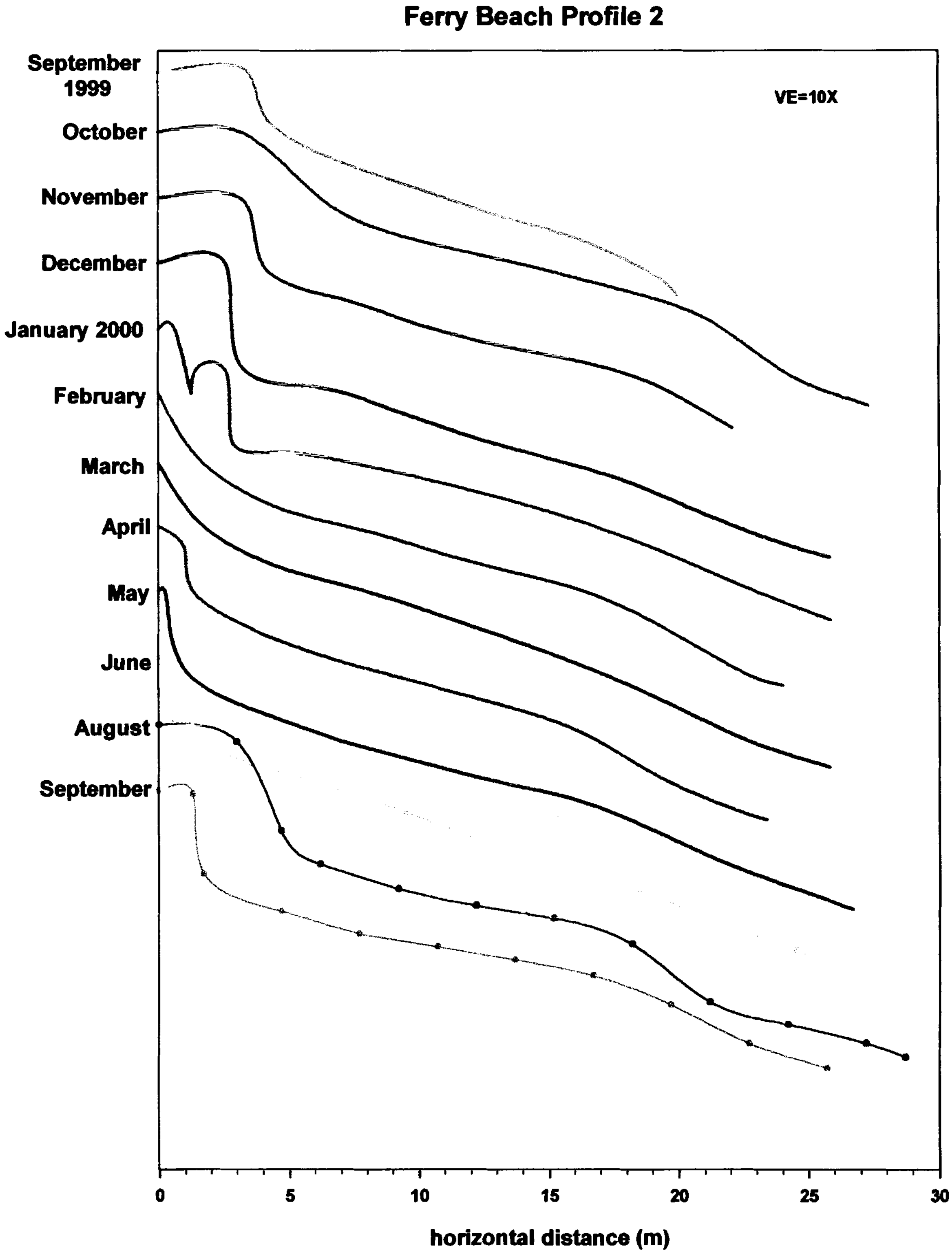


Figure B.26. Ferry Beach Profile 2 monthly topographic changes.

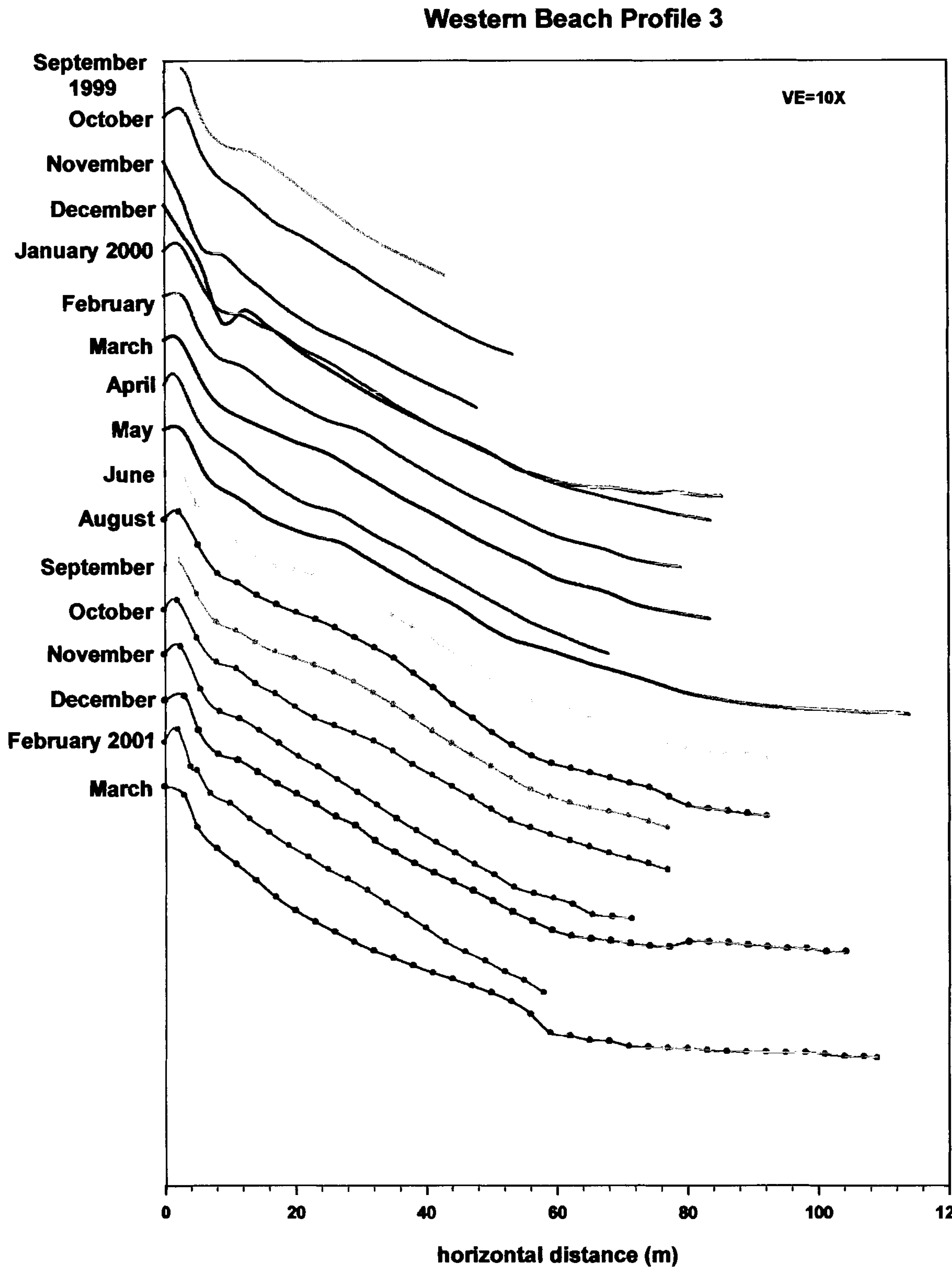


Figure B.27. Western Beach Profile 3 monthly topographic changes.

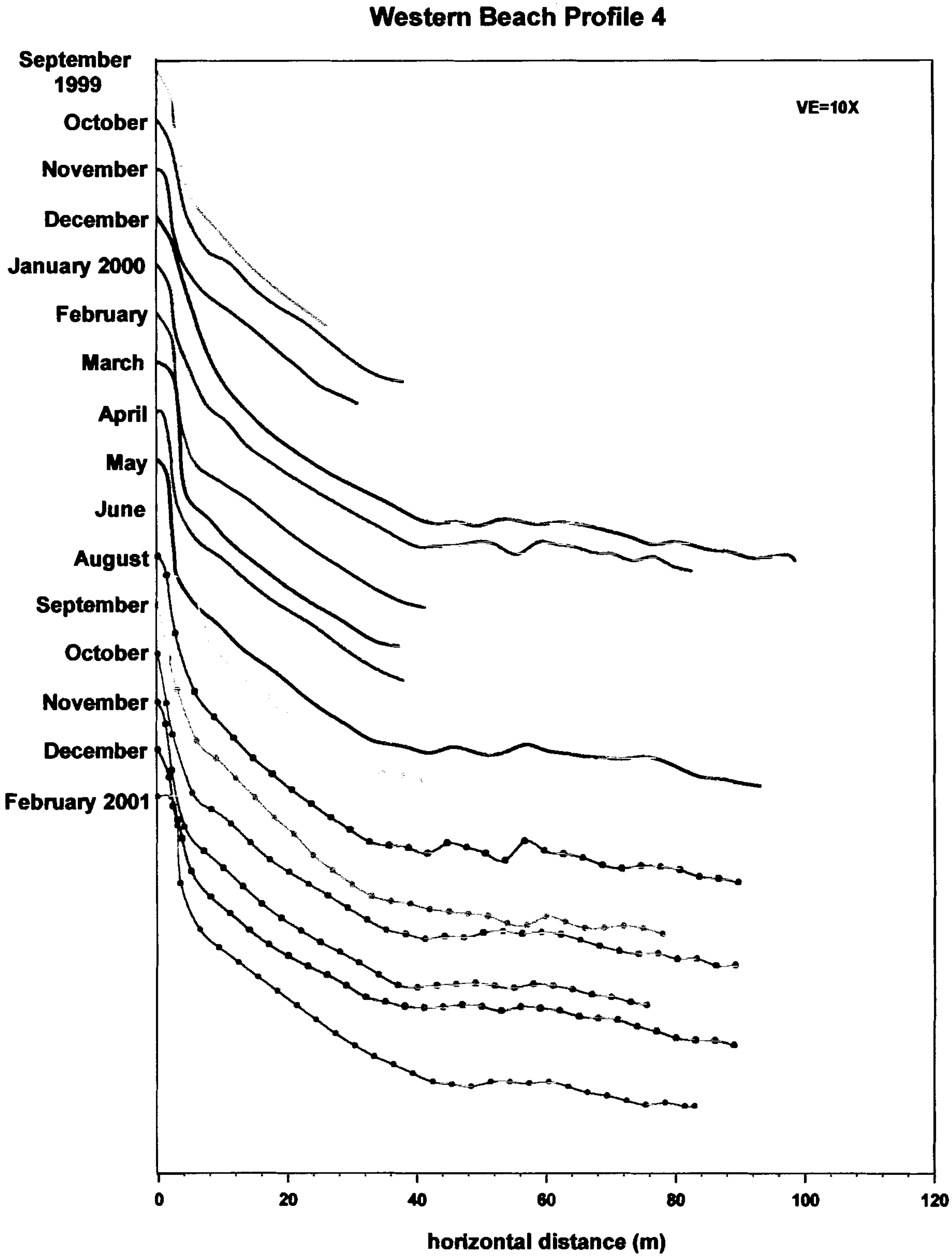


Figure B.28. Western Beach Profile 4 monthly topographic changes.

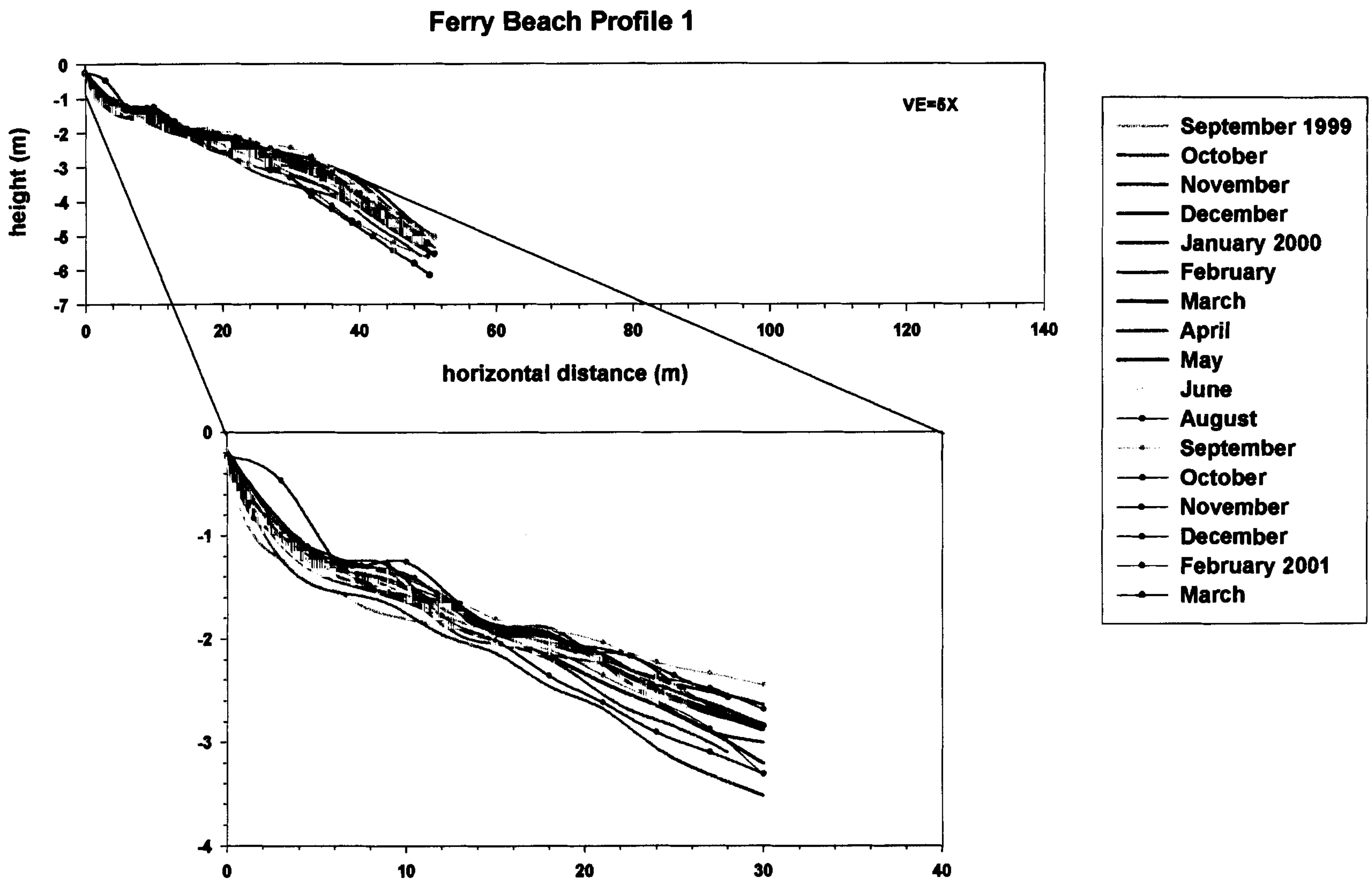


Figure B.29. Ferry Beach Profile 1 monthly topographic changes altered to same length.

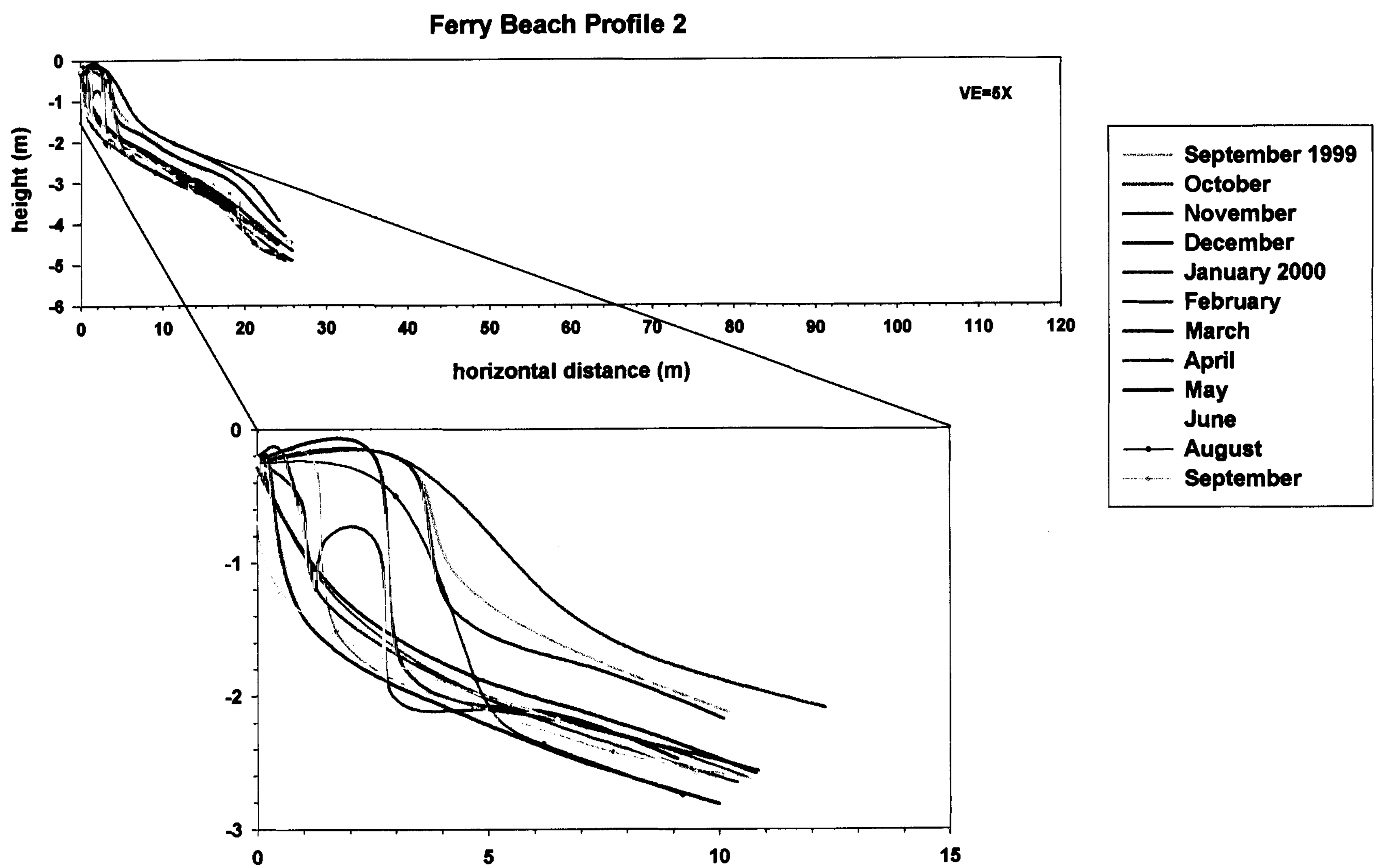


Figure B.30. Ferry Beach Profile 2 monthly topographic changes altered to same length.

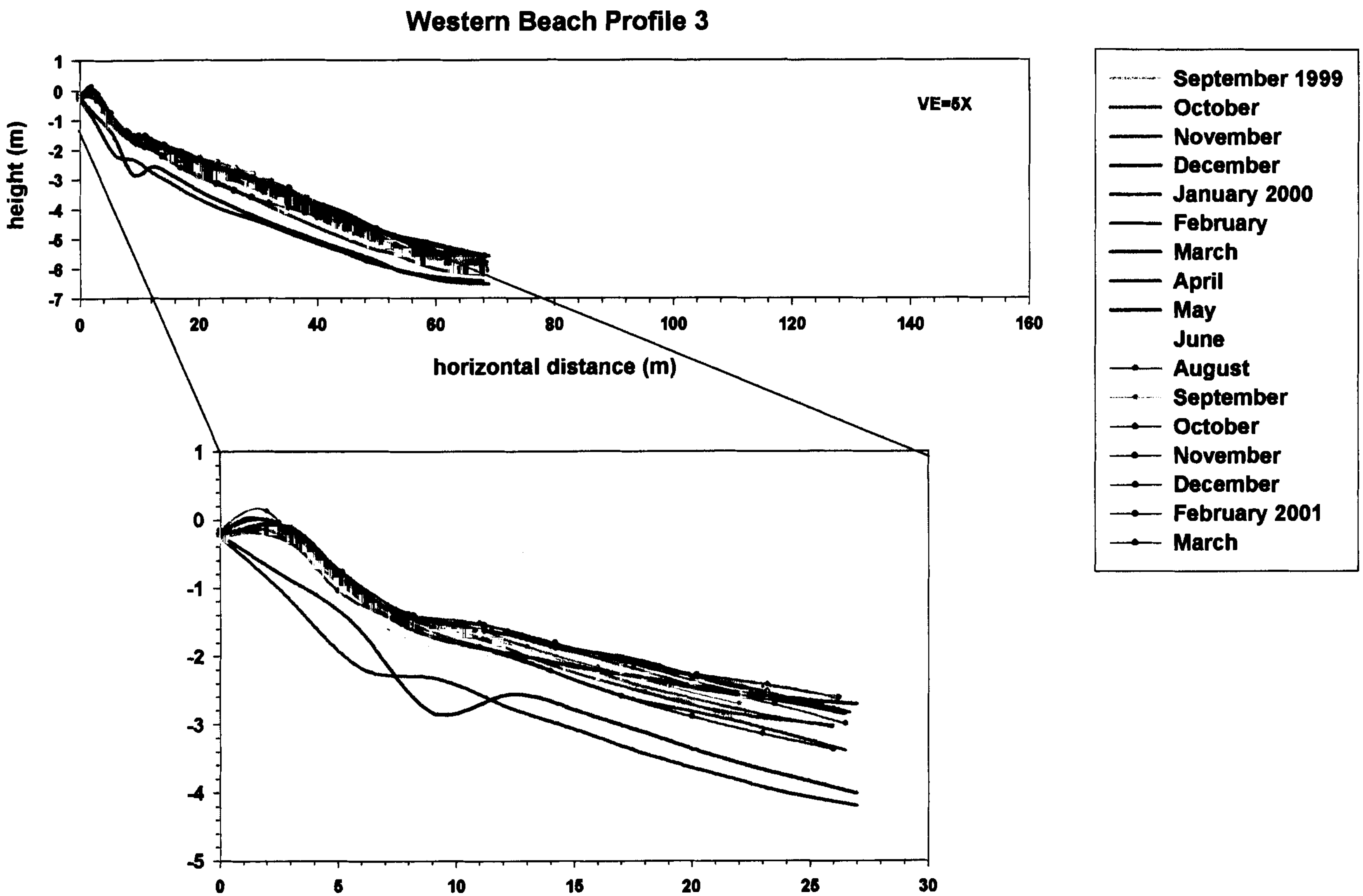


Figure B.31. Western Beach Profile 3 monthly topographic changes altered to same length.

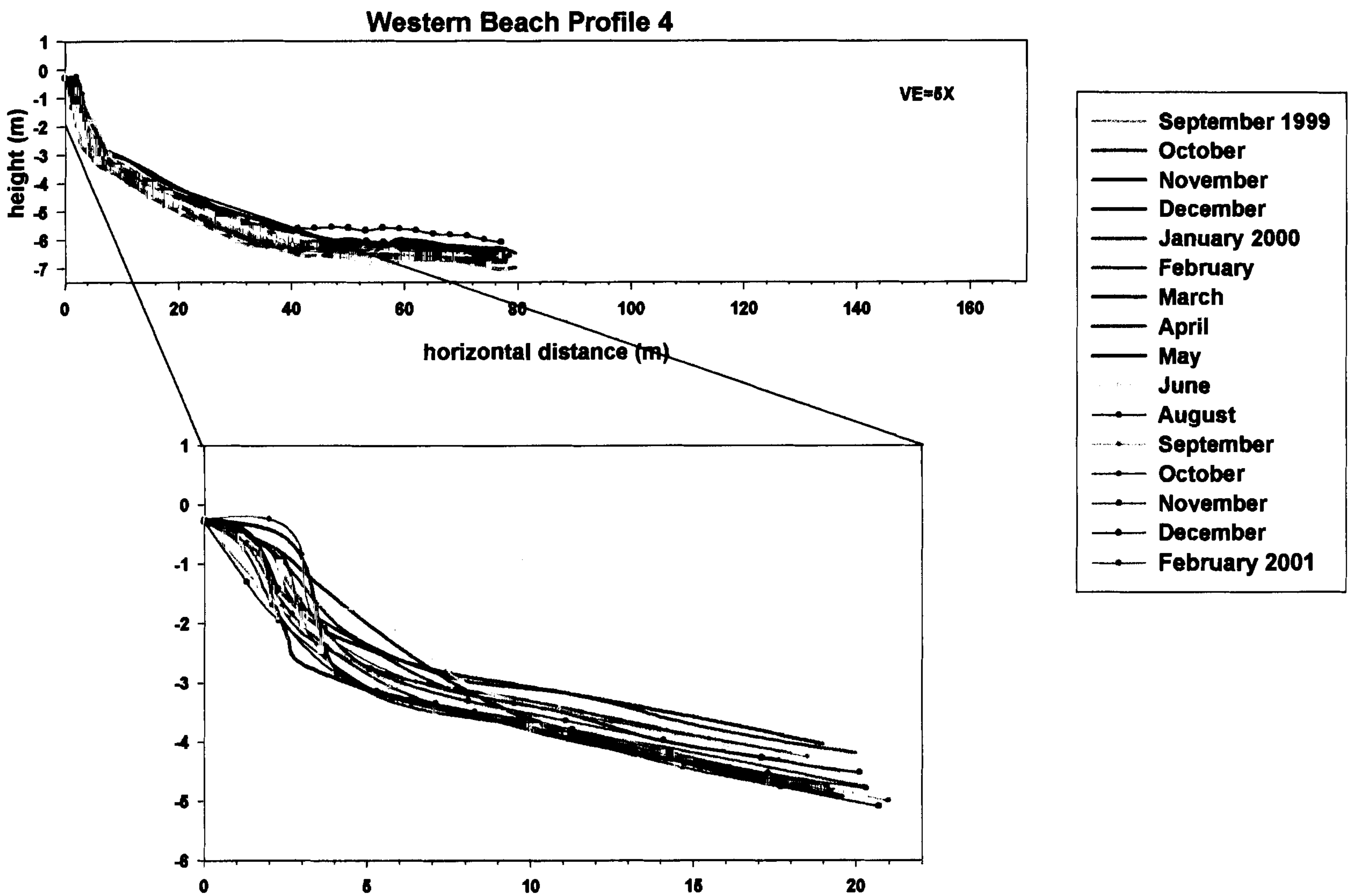
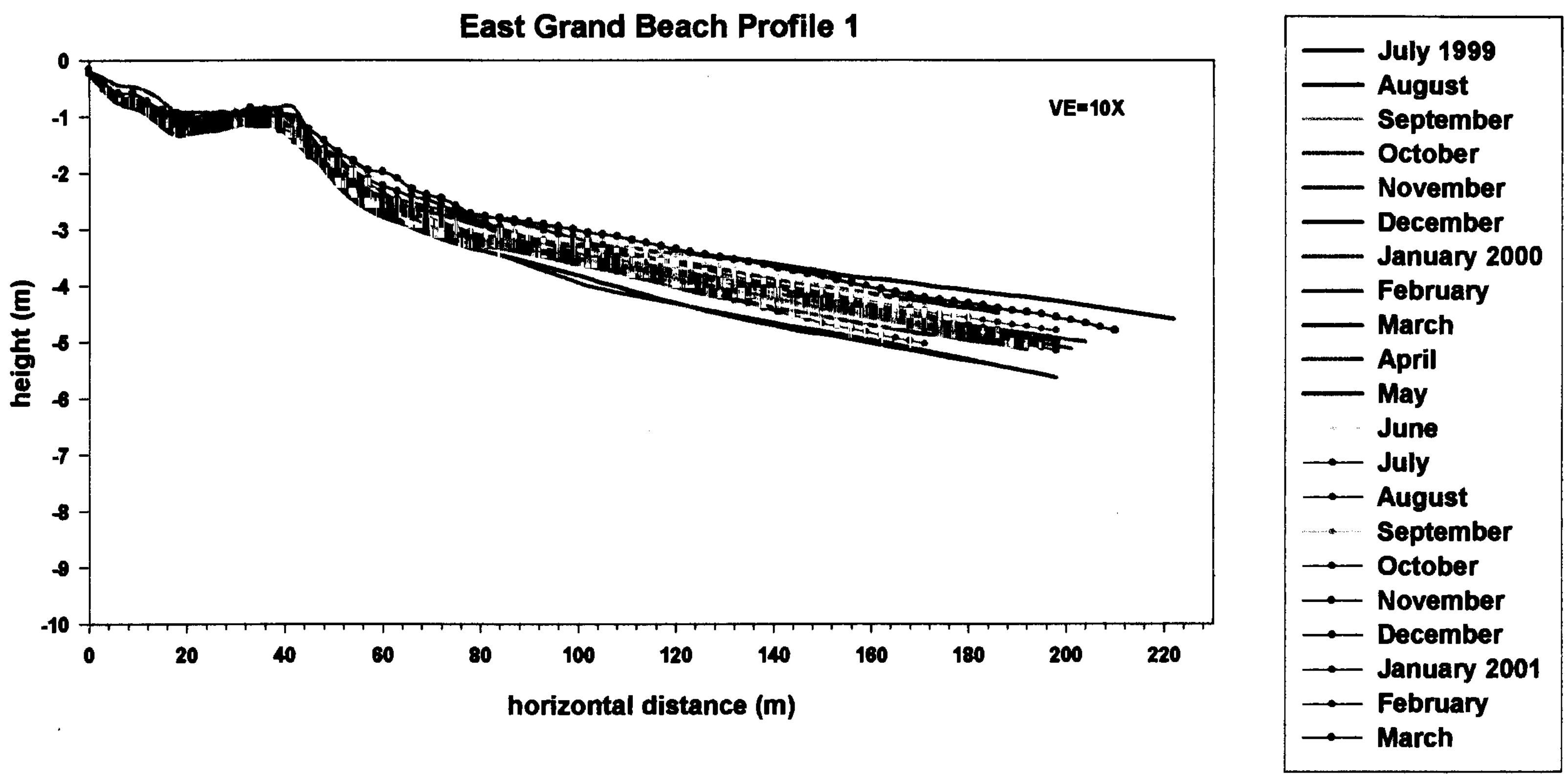
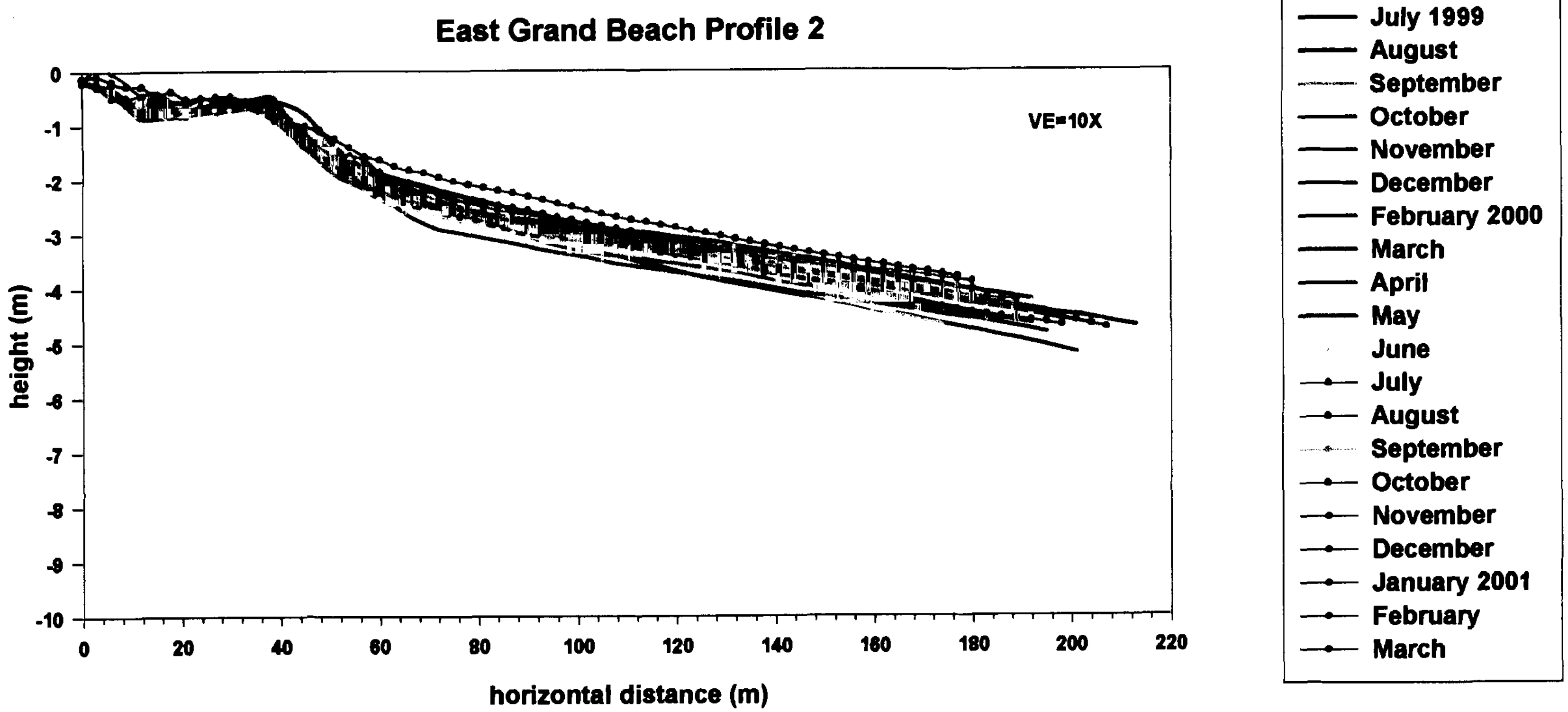


Figure B.32. Western Beach Profile 4 monthly topographic changes altered to same length.



B.33. East Grand Beach Topographic Profile 1 original measurements.



B.34. East Grand Beach Topographic Profile 2 original measurements.

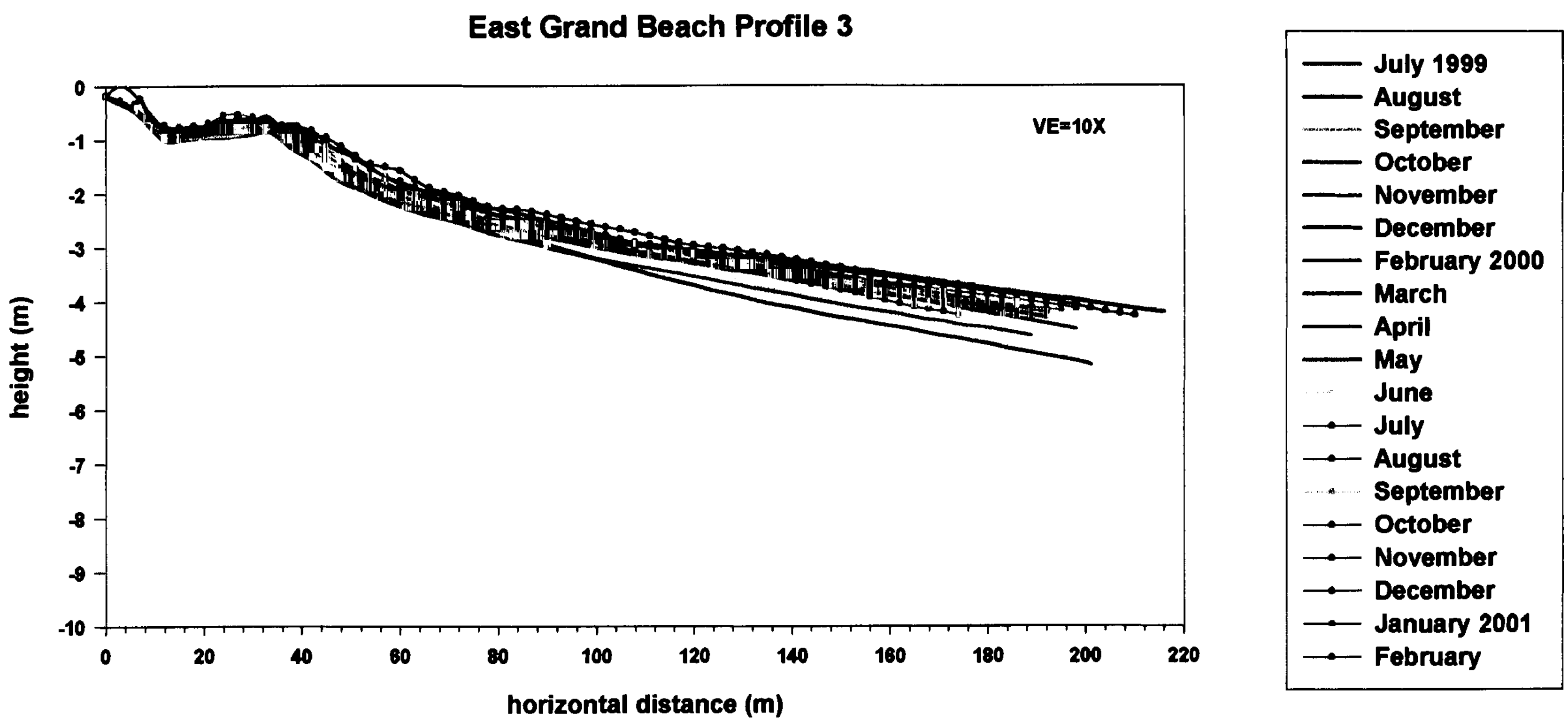


Figure B.35. East Grand Beach Topographic Profile 3 original measurements.

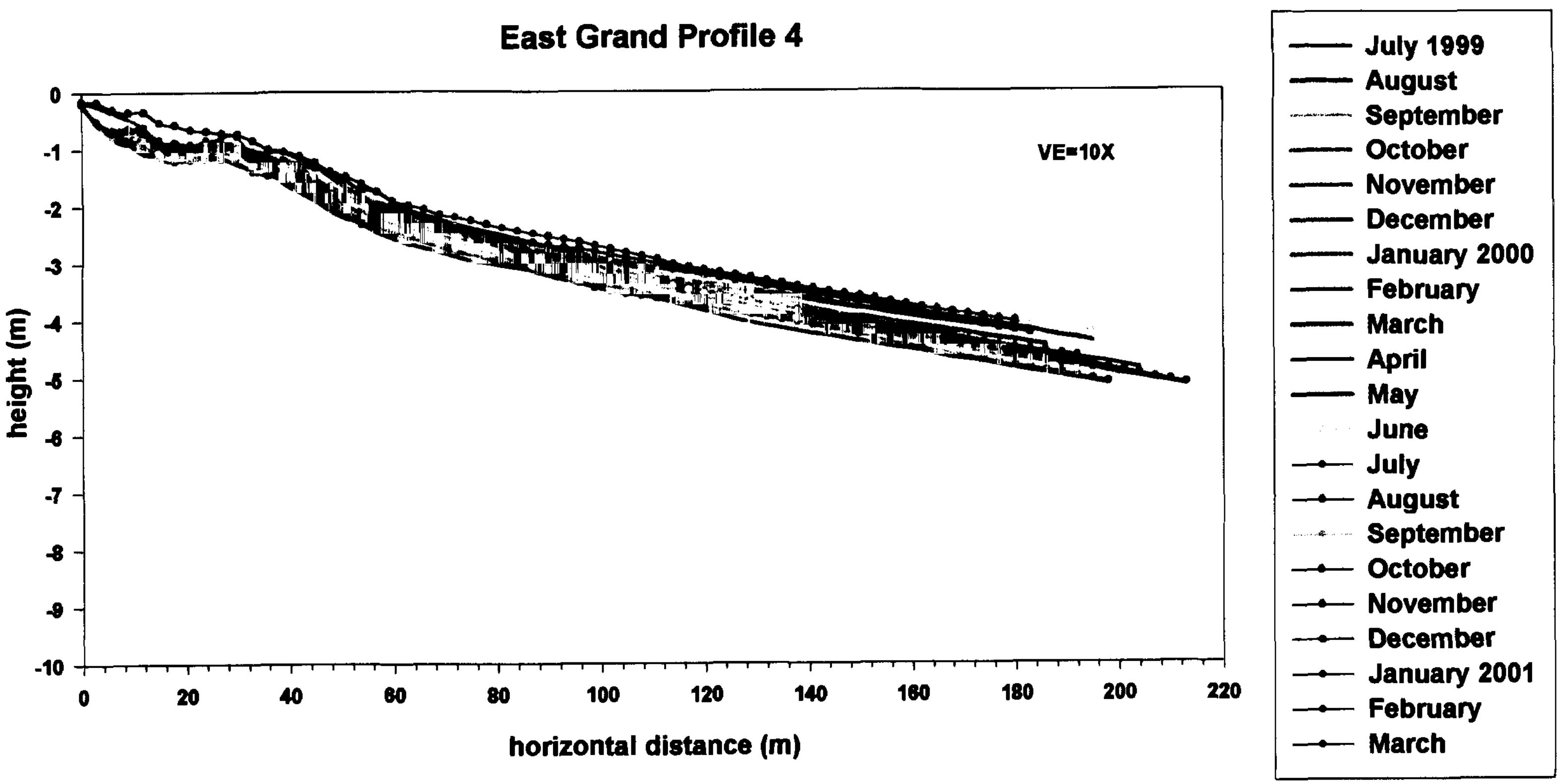


Figure B.36. East Grand Beach Topographic Profile 4 original measurements.

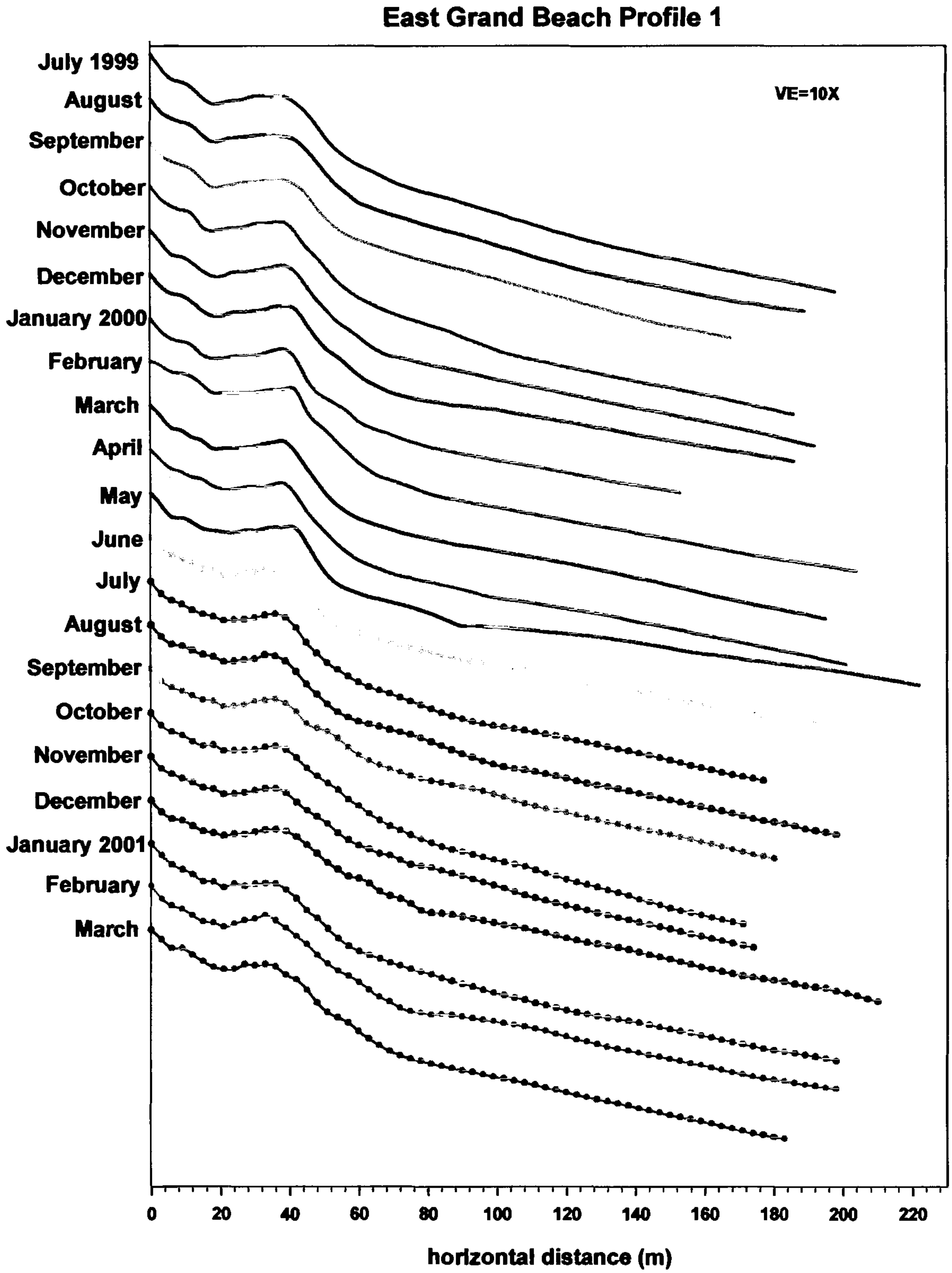


Figure B.37. East Grand Beach Profile 1 monthly topographic changes.

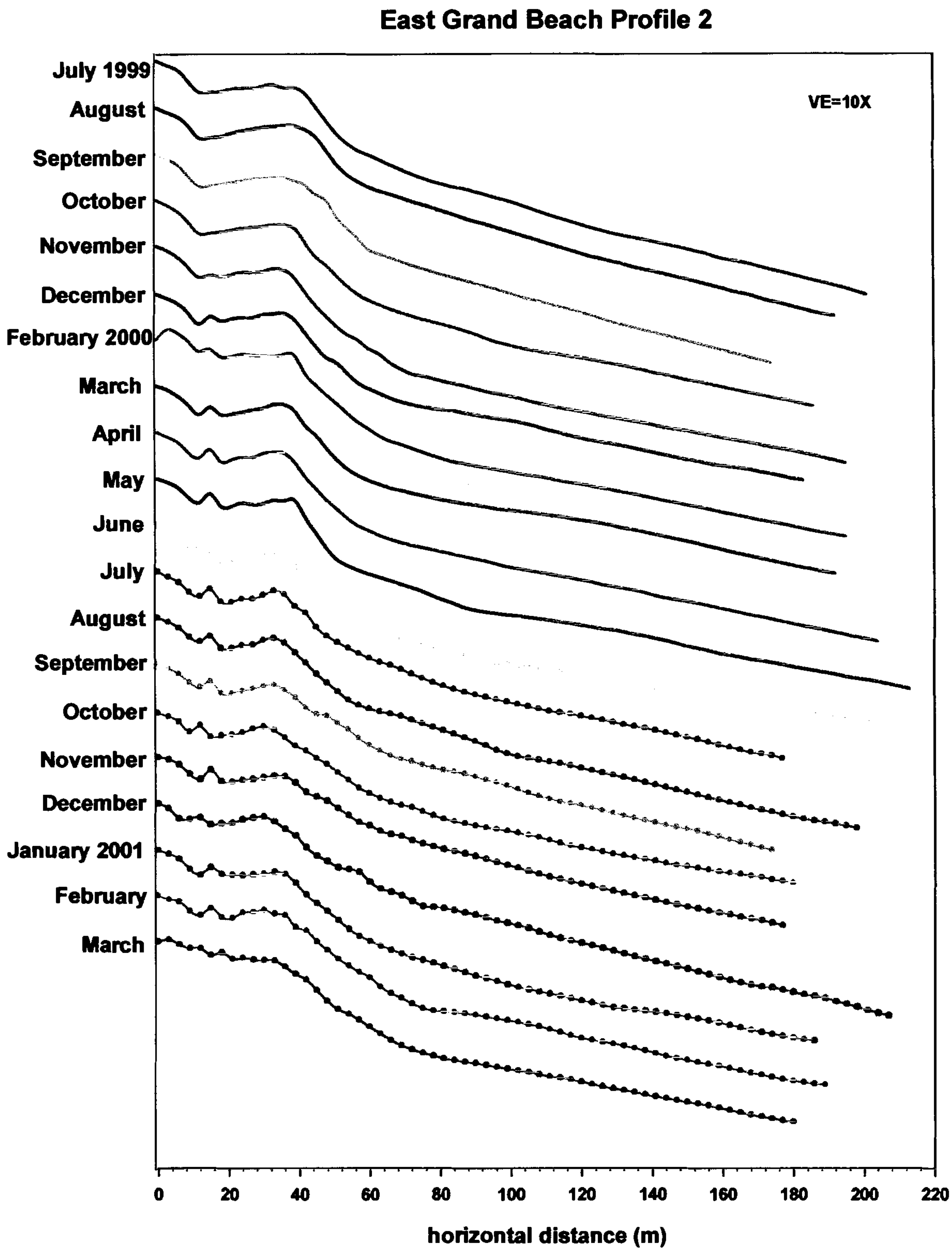


Figure B.38. East Grand Beach Profile 2 monthly topographic changes.

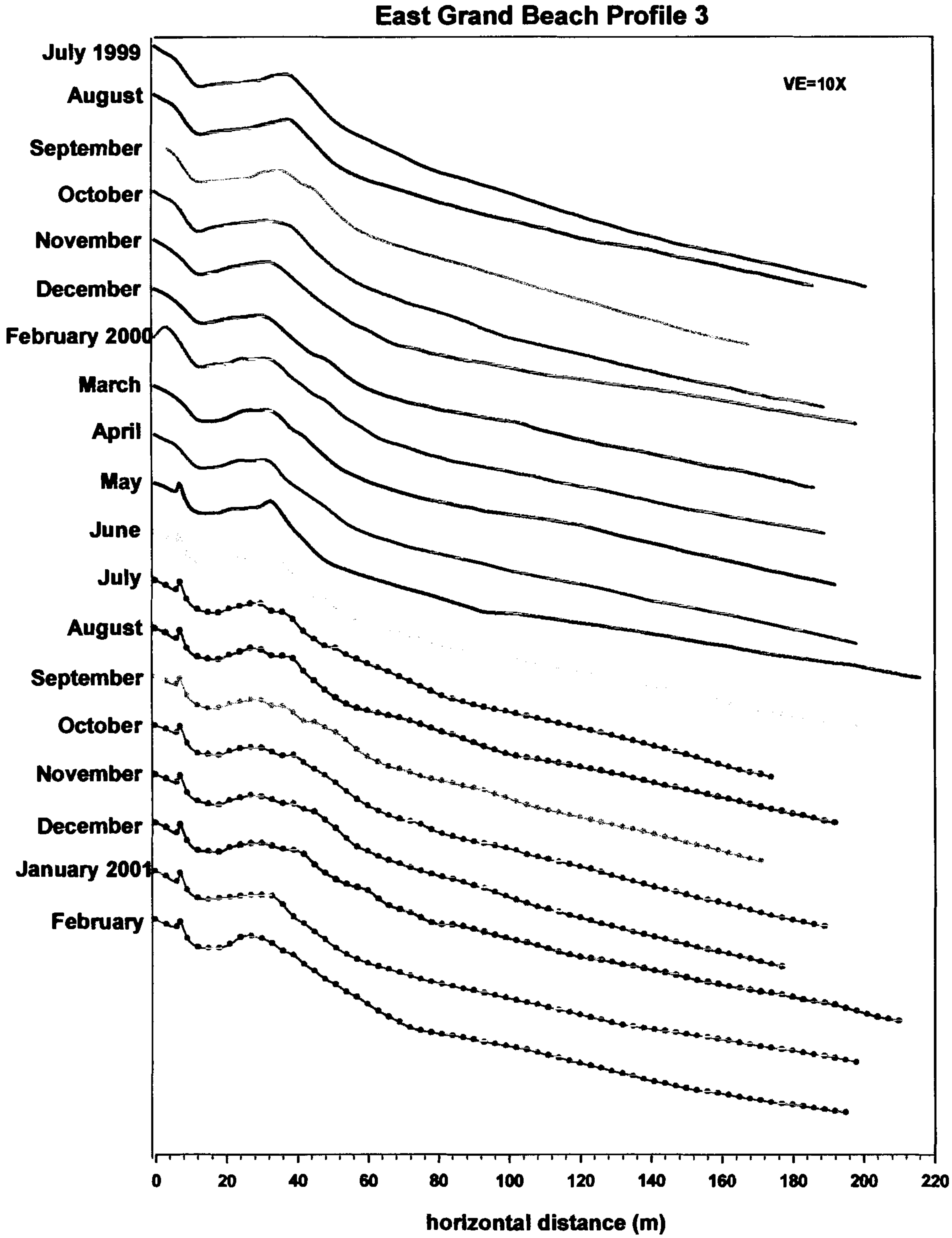


Figure B.39. East Grand Beach Profile 3 monthly topographic changes.

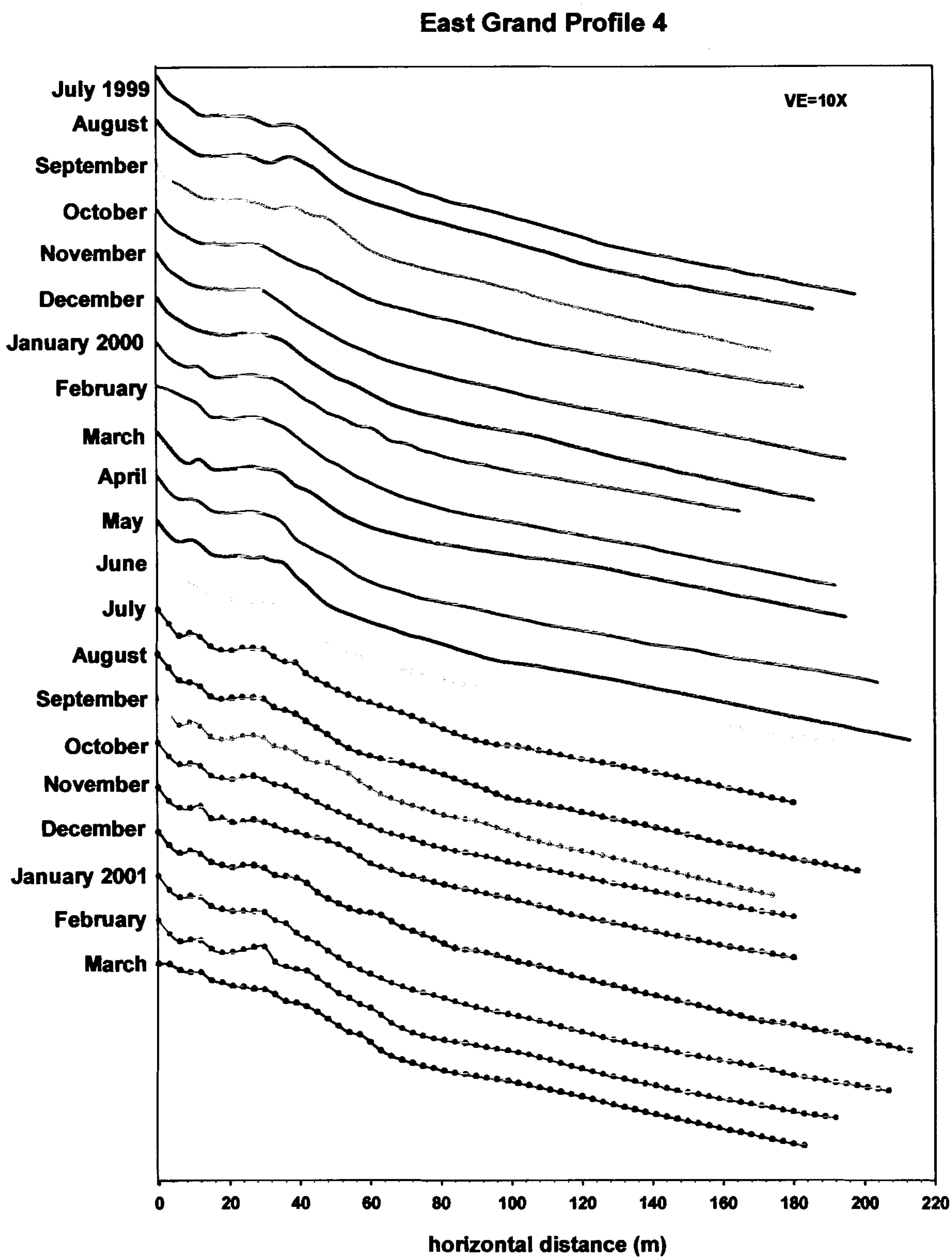


Figure B.40. East Grand Beach Profile 4 monthly topographic changes.

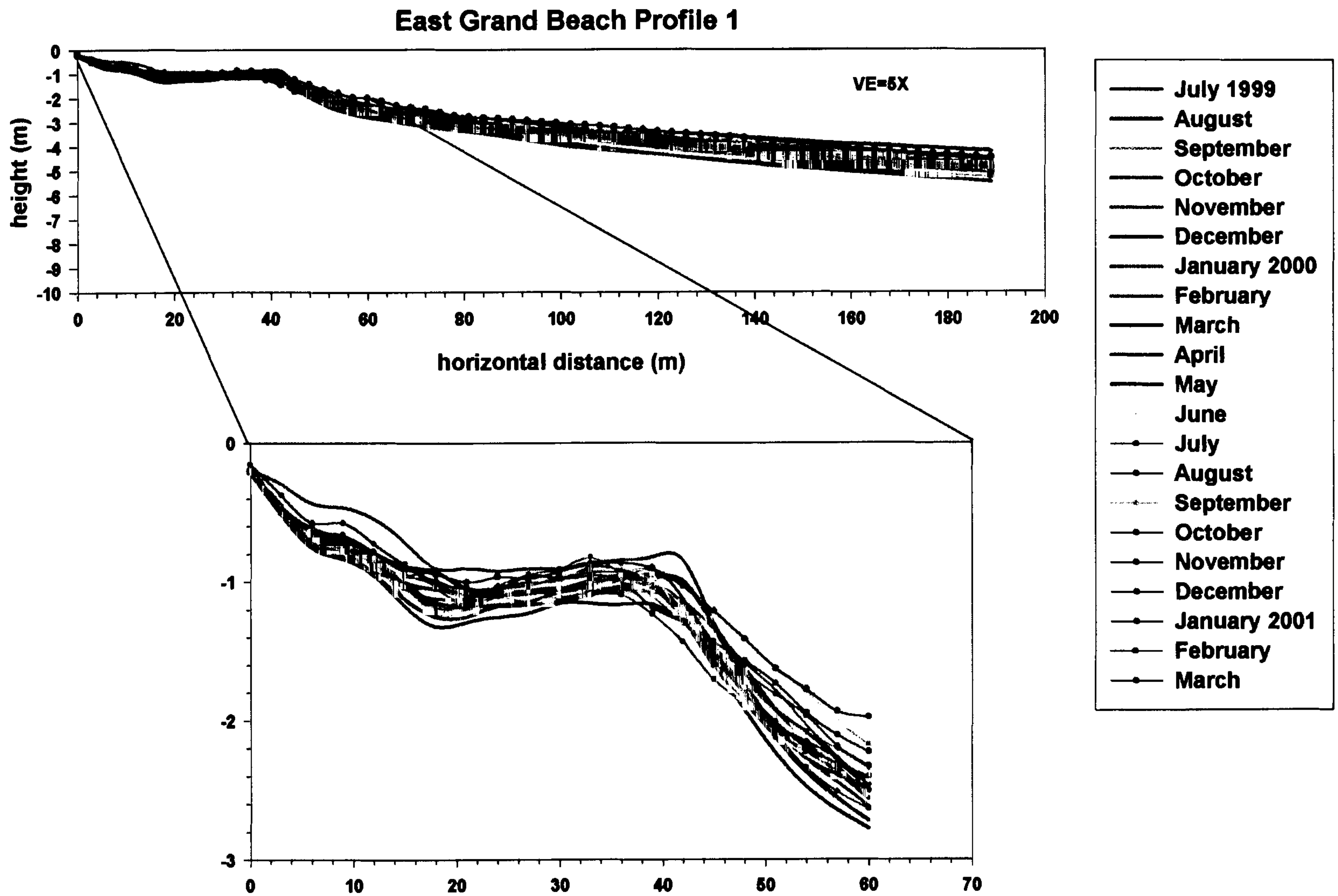
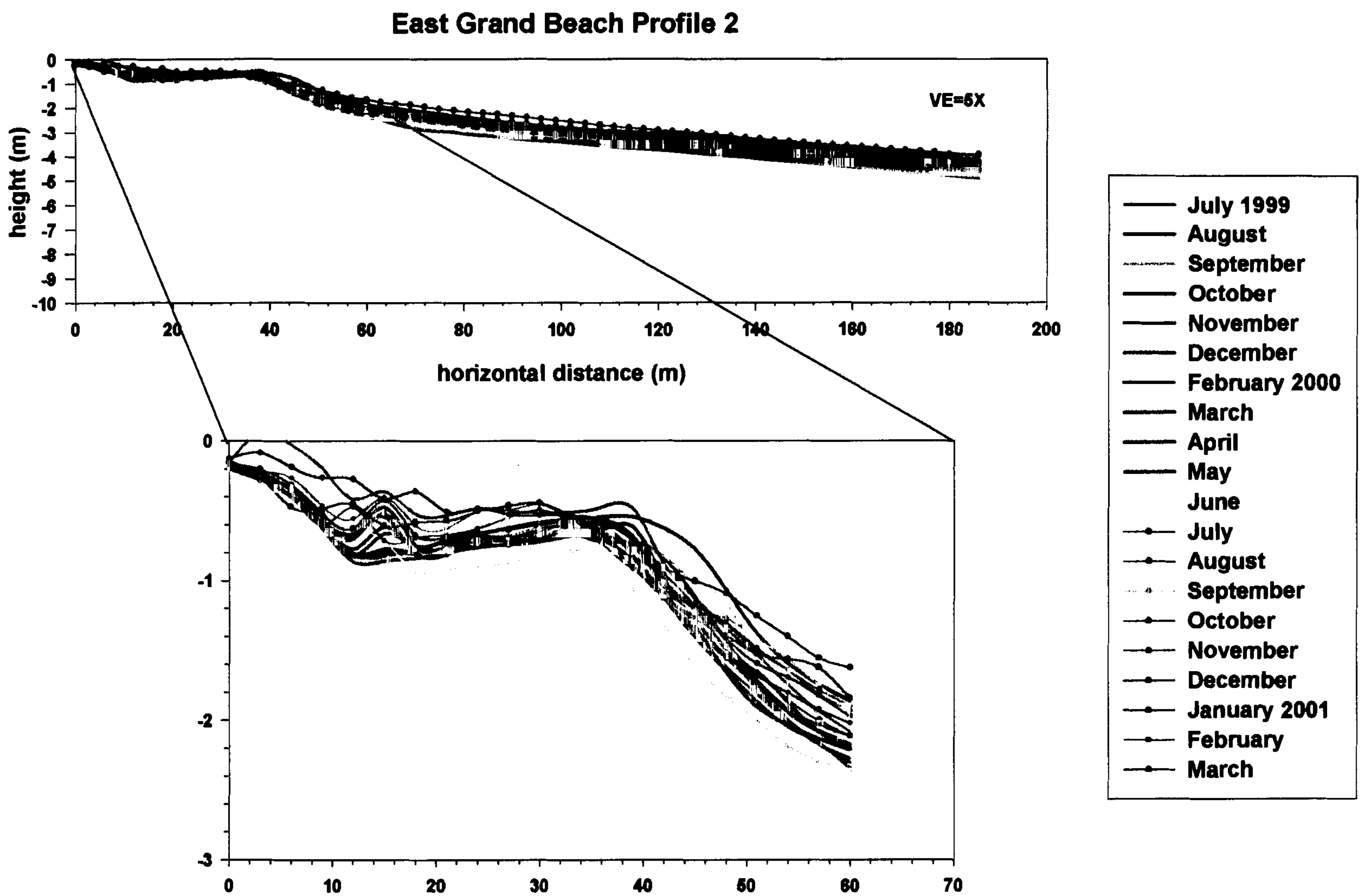
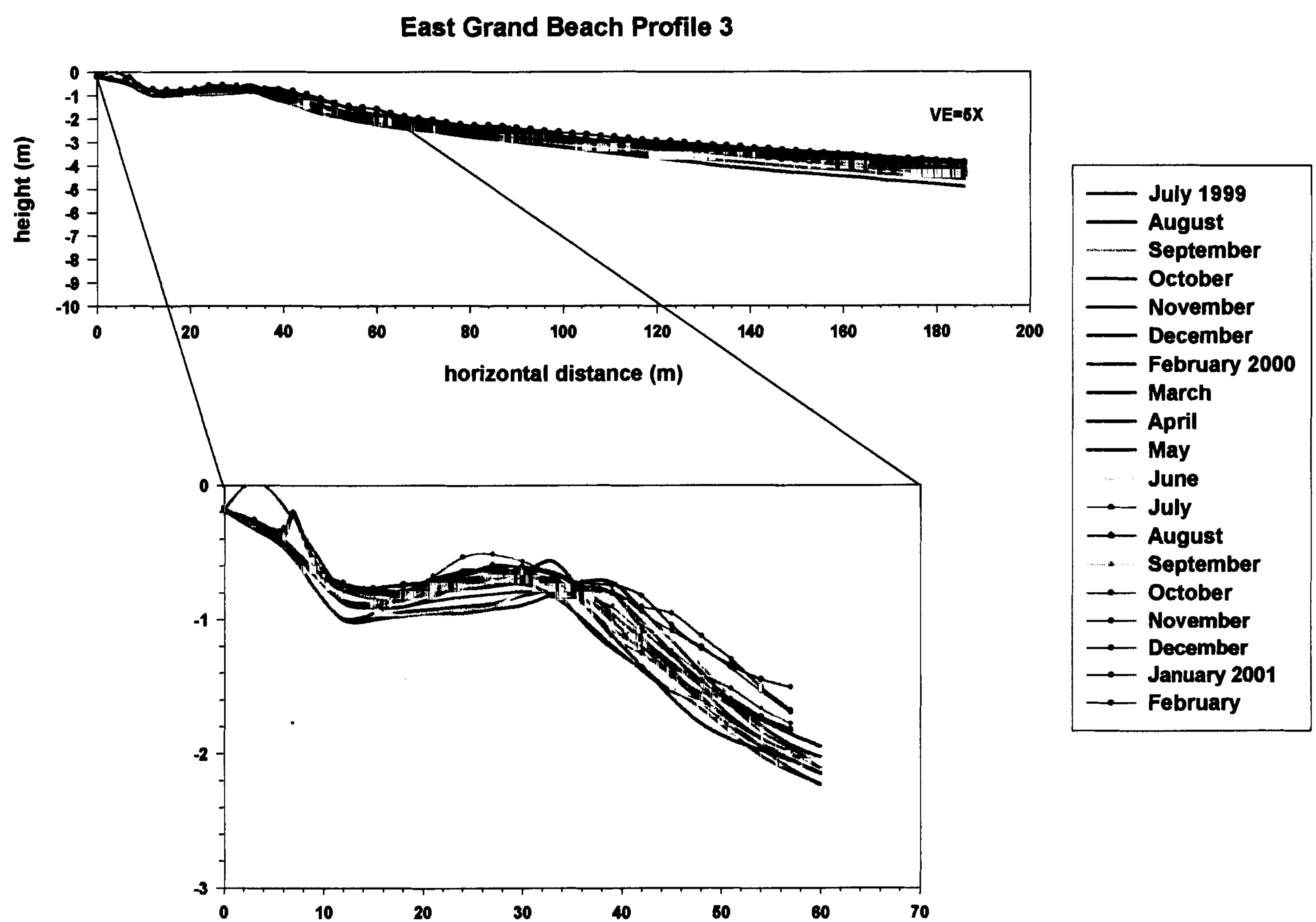


Figure B.41. East Grand Beach Profile 1 monthly topographic changes altered to same length.



B.42. East Grand Beach Profile 2 monthly topographic changes altered to same length.



B.43. East Grand Beach Profile 3 monthly topographic changes altered to same length.

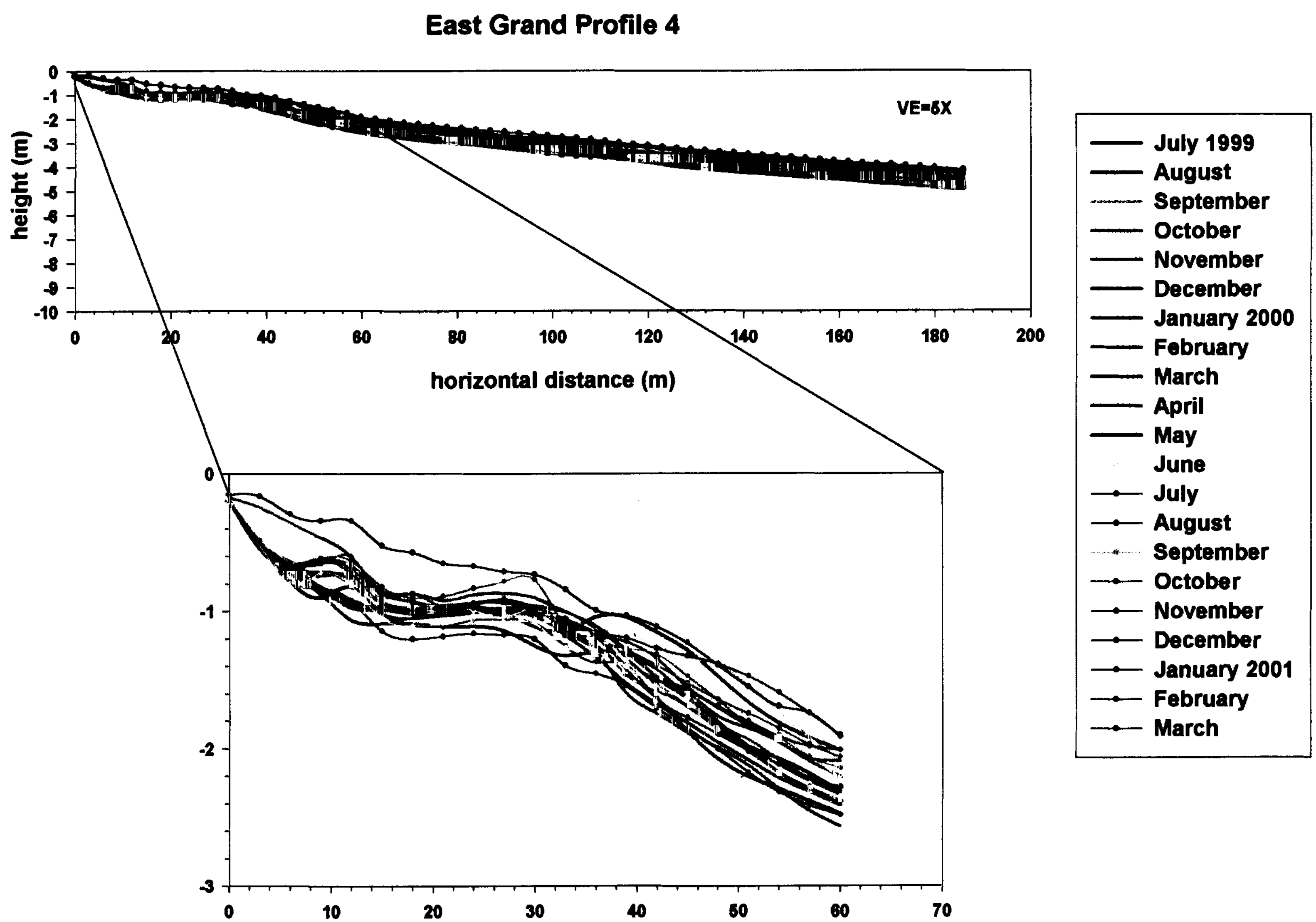


Figure B.44. East Grand Beach 4 monthly topographic changes altered to same length.

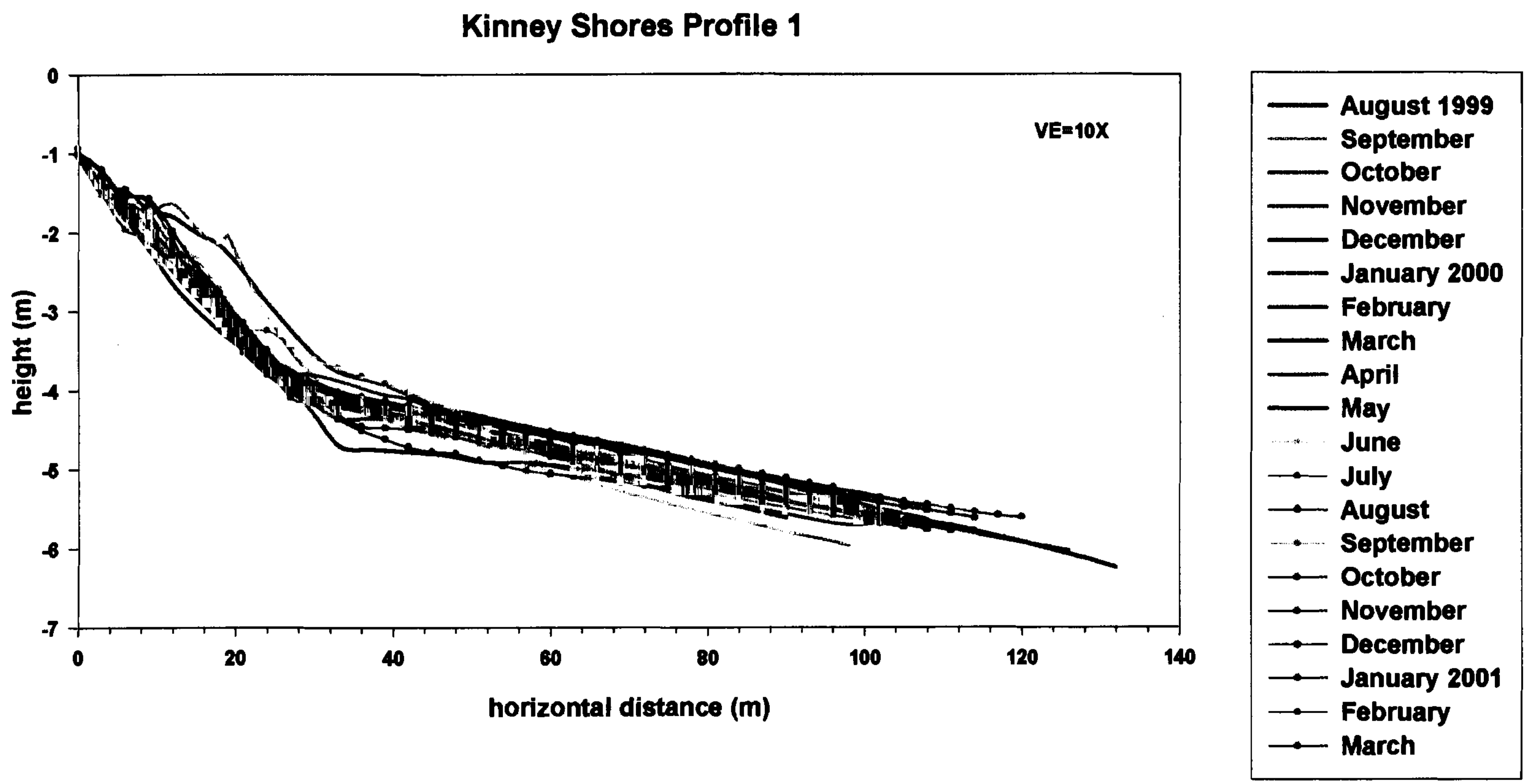


Figure B.45. Kinney Shores Topographic Profile 1 original measurements.

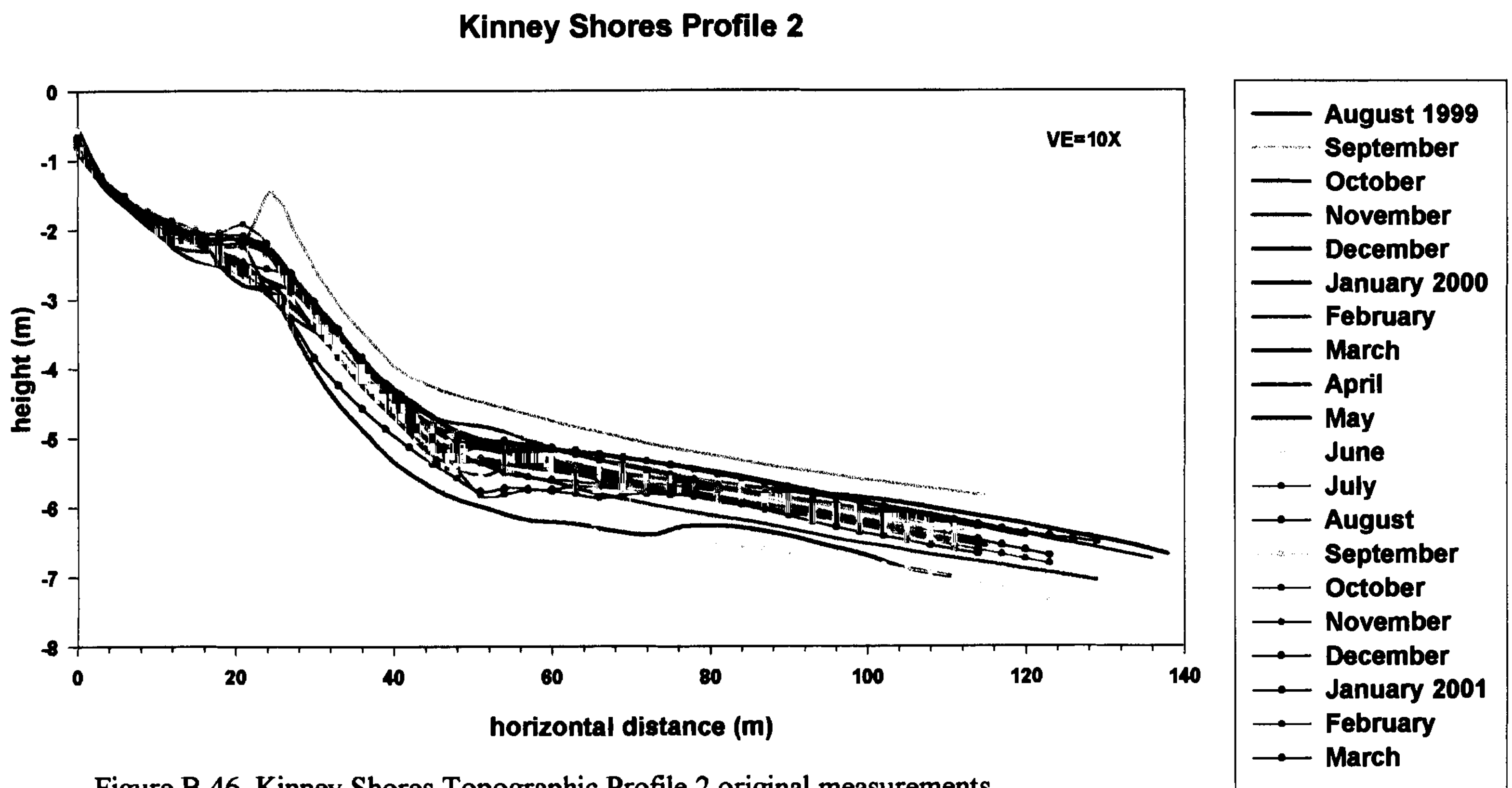


Figure B.46. Kinney Shores Topographic Profile 2 original measurements.

Kinney Shores Profile 1

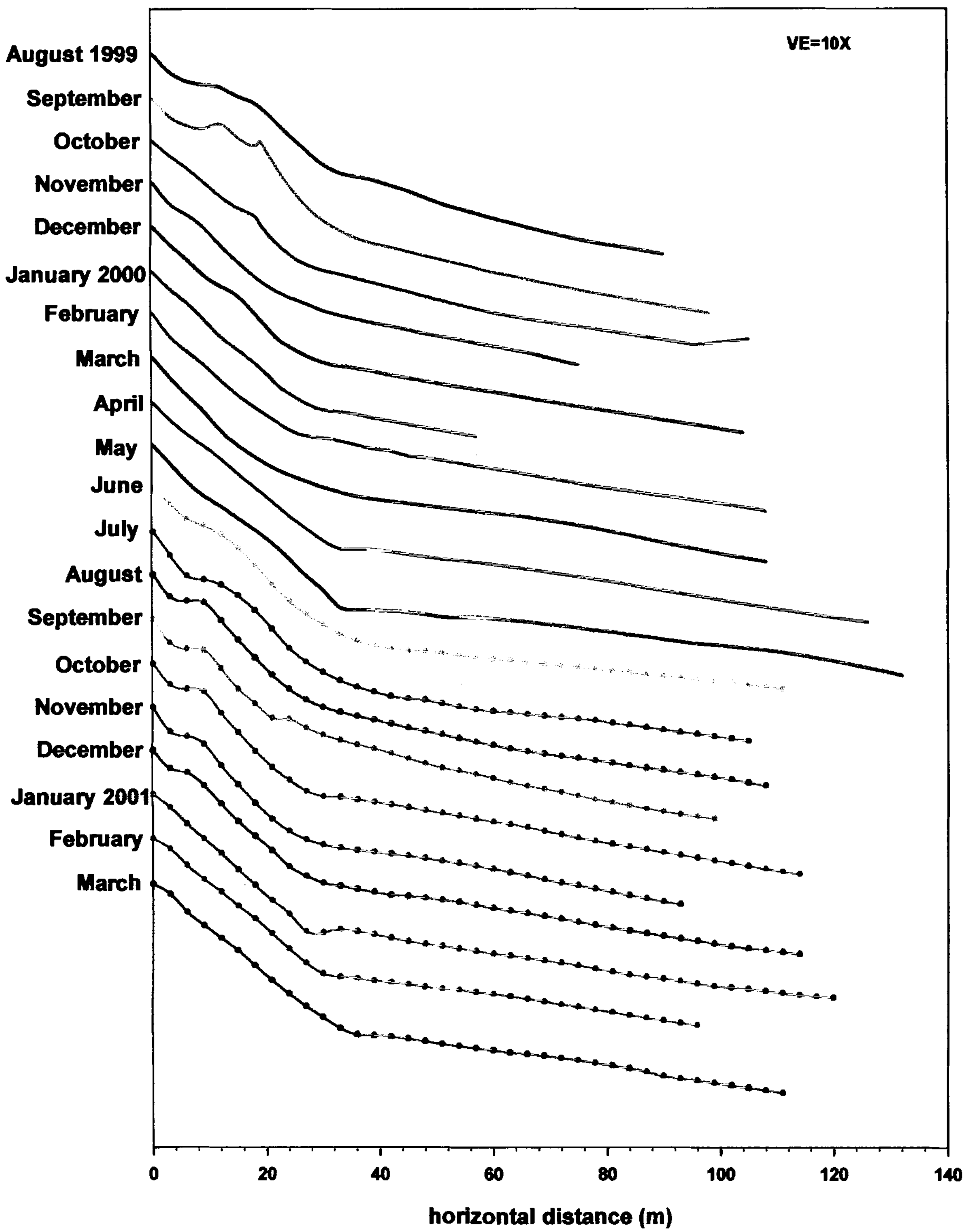


Figure B.47. Kinney Shores Profile 1 monthly topographic changes.

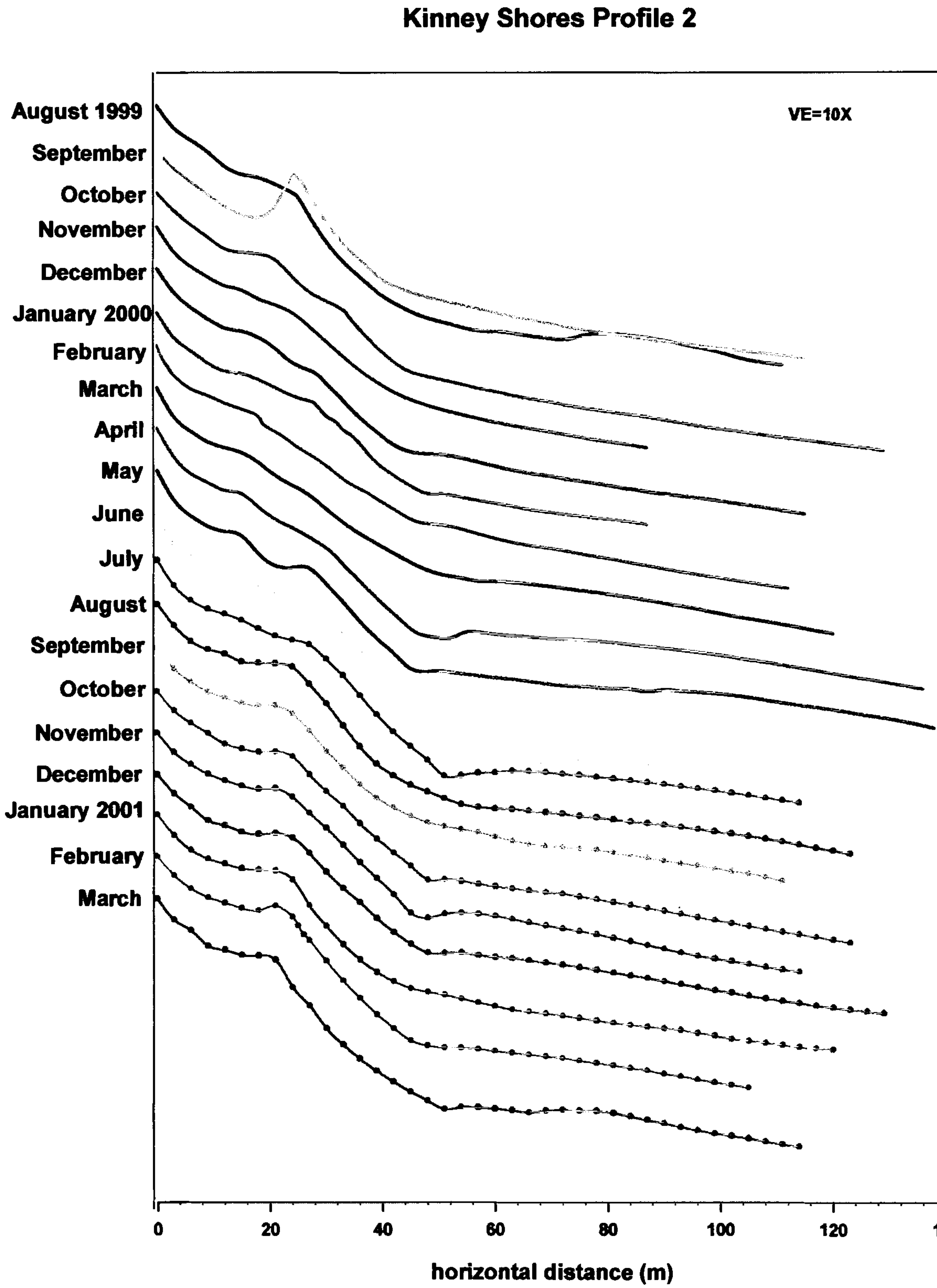


Figure B.48. Kinney Shores monthly topographic changes.

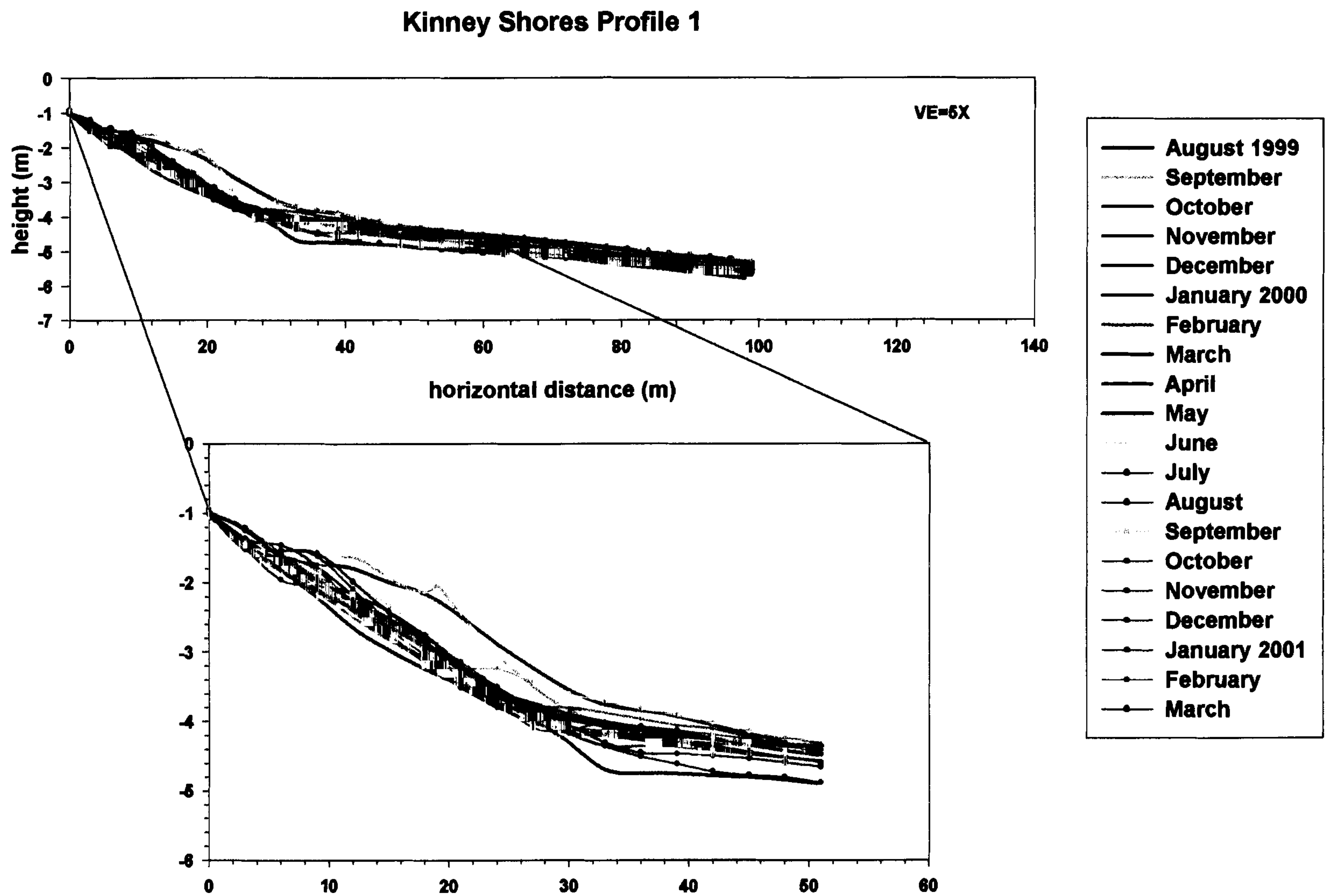


Figure B.49. Kinney Shores Profile 1 monthly topographic changes altered to same length.

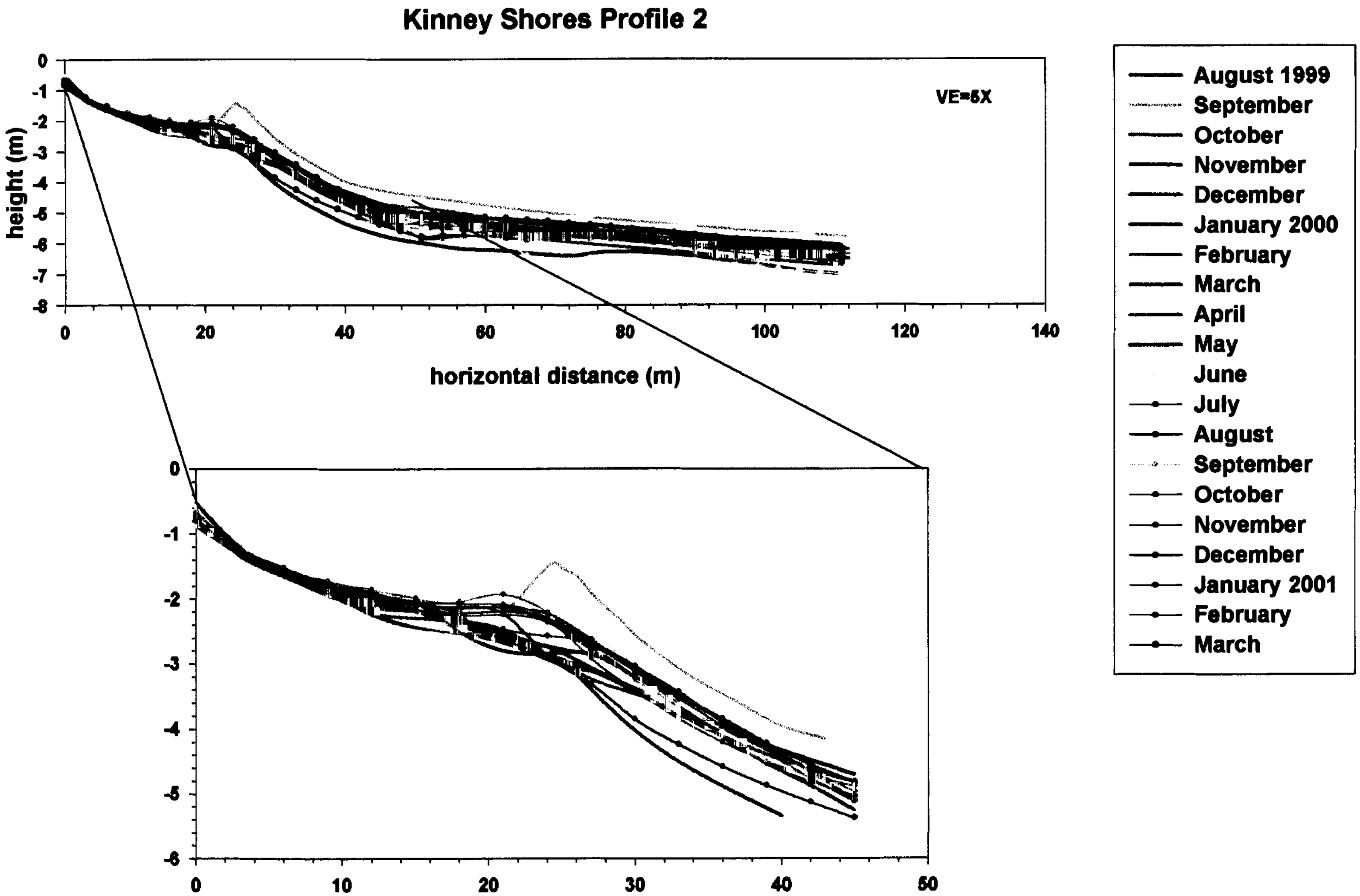


Figure B.50. Kinney Shores Profile 2 monthly topographic changes altered to same length.

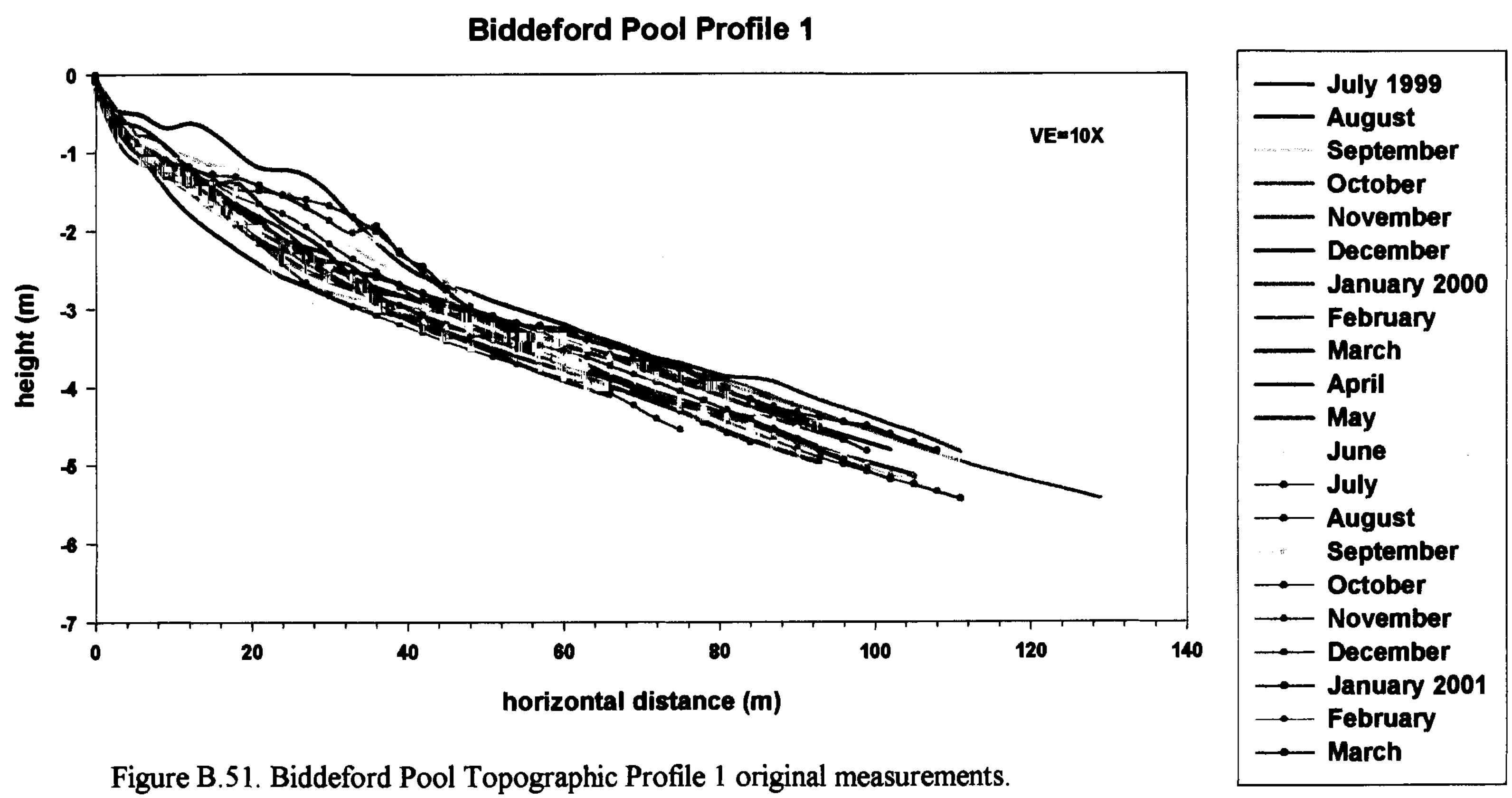


Figure B.51. Biddeford Pool Topographic Profile 1 original measurements.

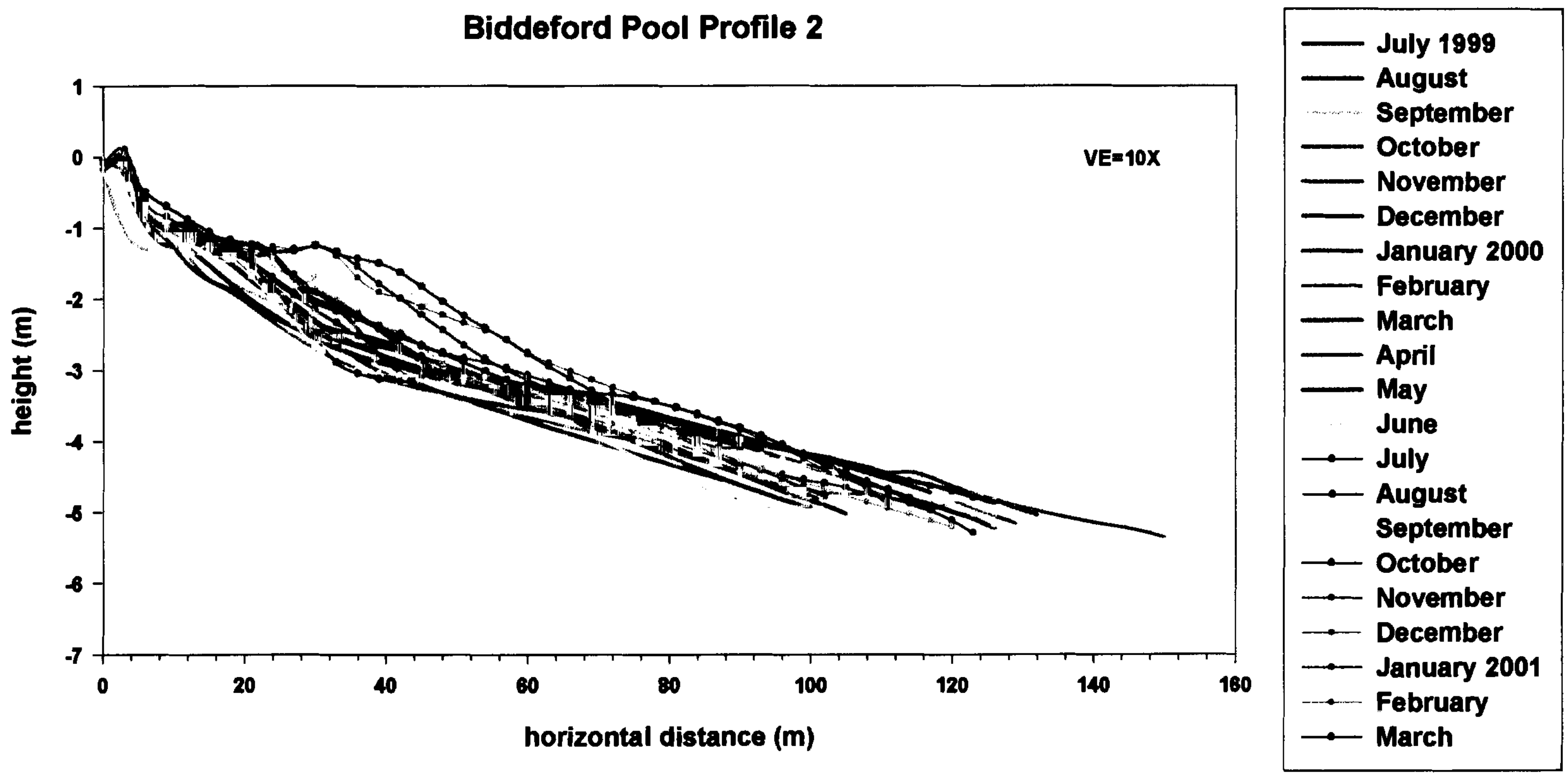


Figure B.52. Biddeford Pool Topographic Profile 2 original measurements.

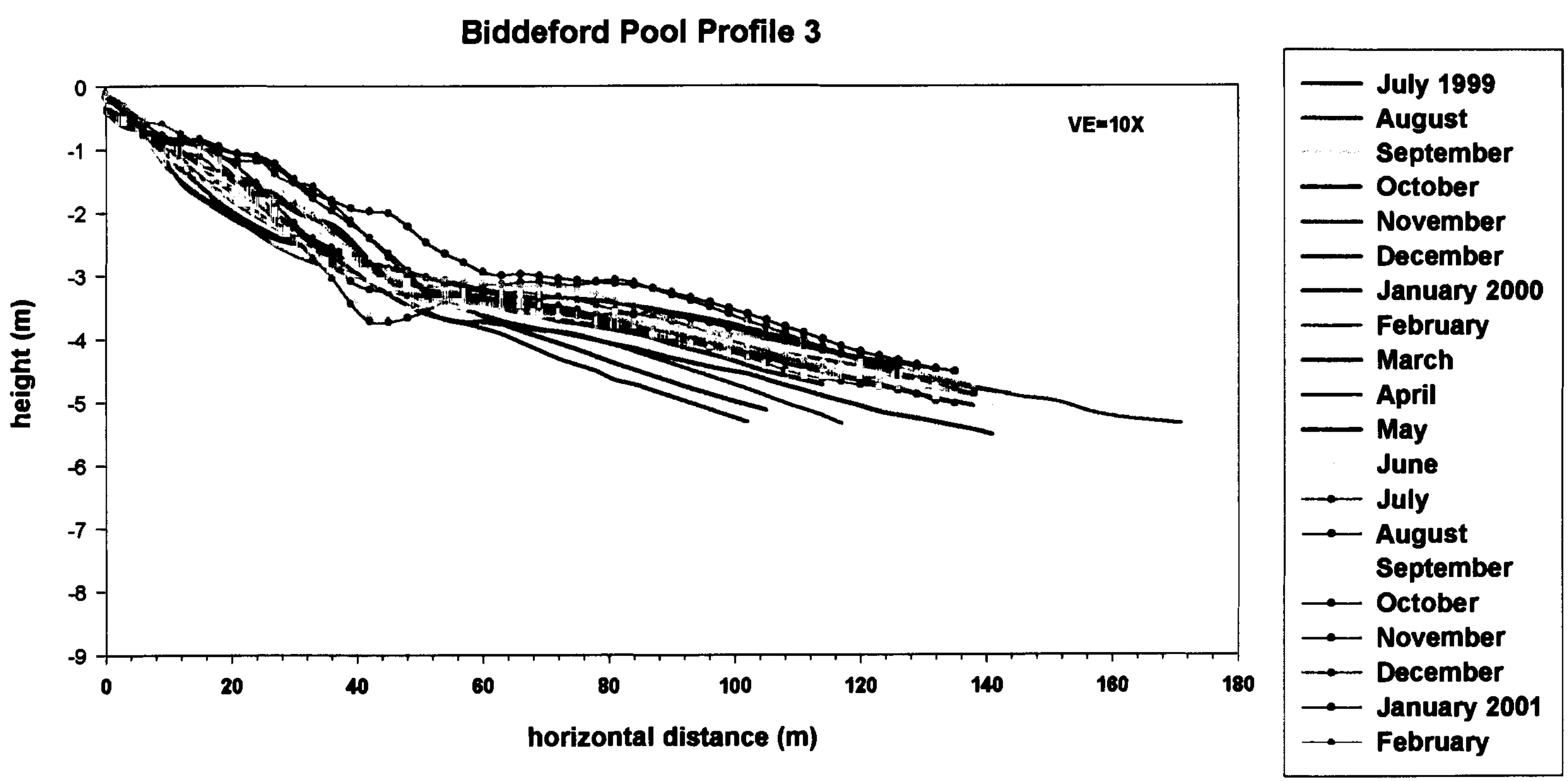


Figure B.53. Biddeford Pool Topographic Profile 3 original measurements.

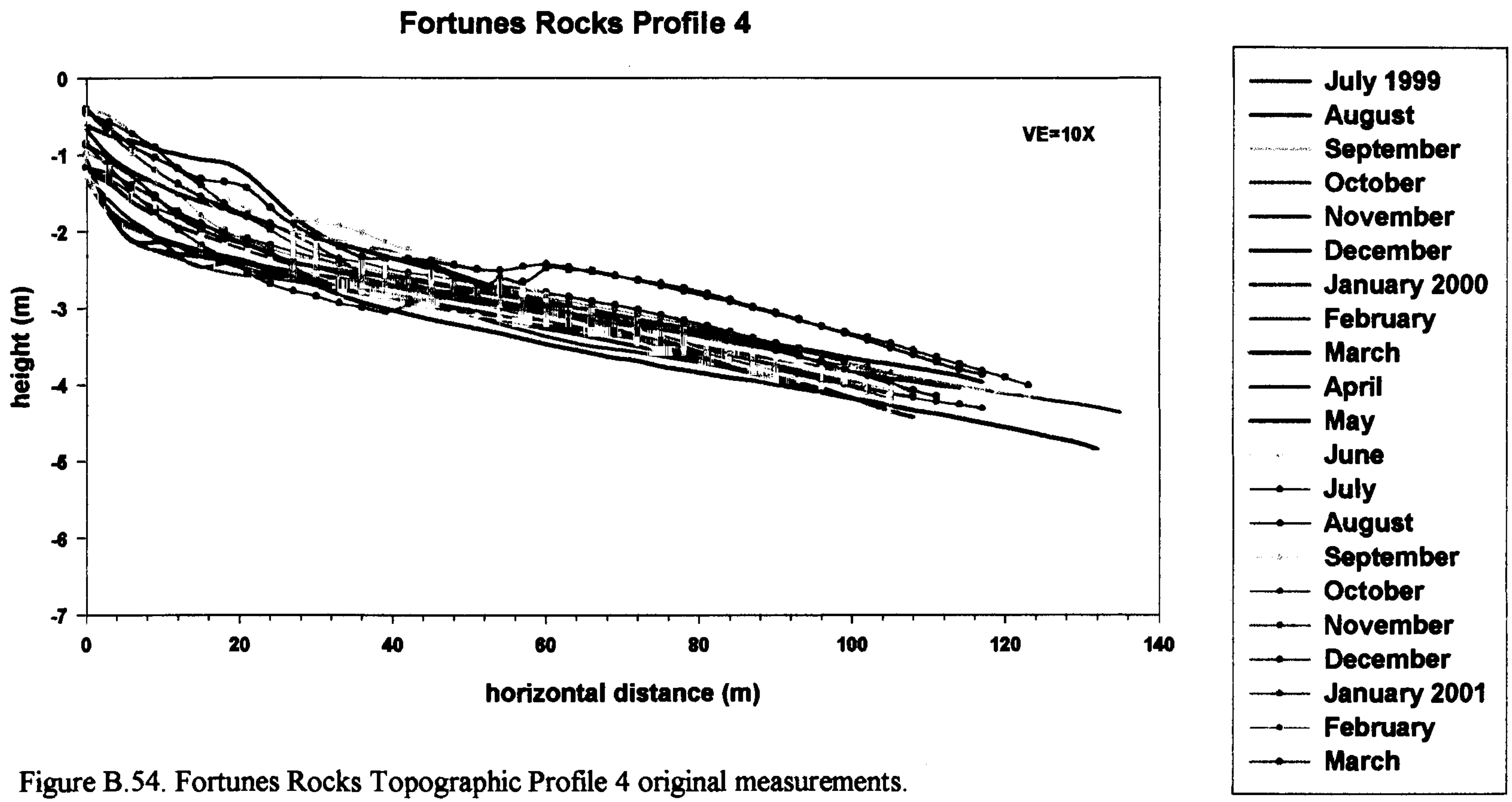


Figure B.54. Fortunes Rocks Topographic Profile 4 original measurements.

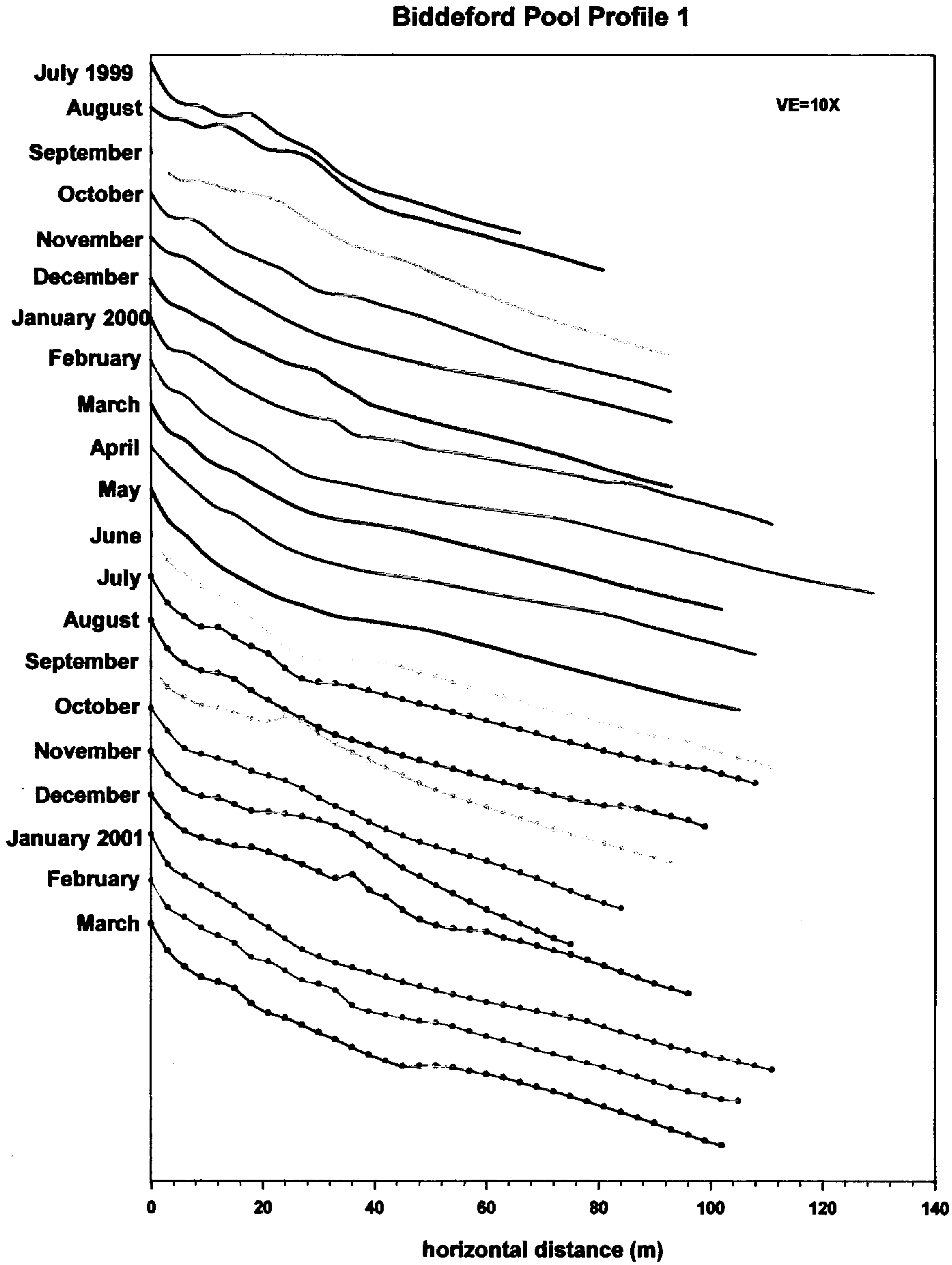


Figure B.55. Biddeford Pool Profile 1 monthly topographic changes.

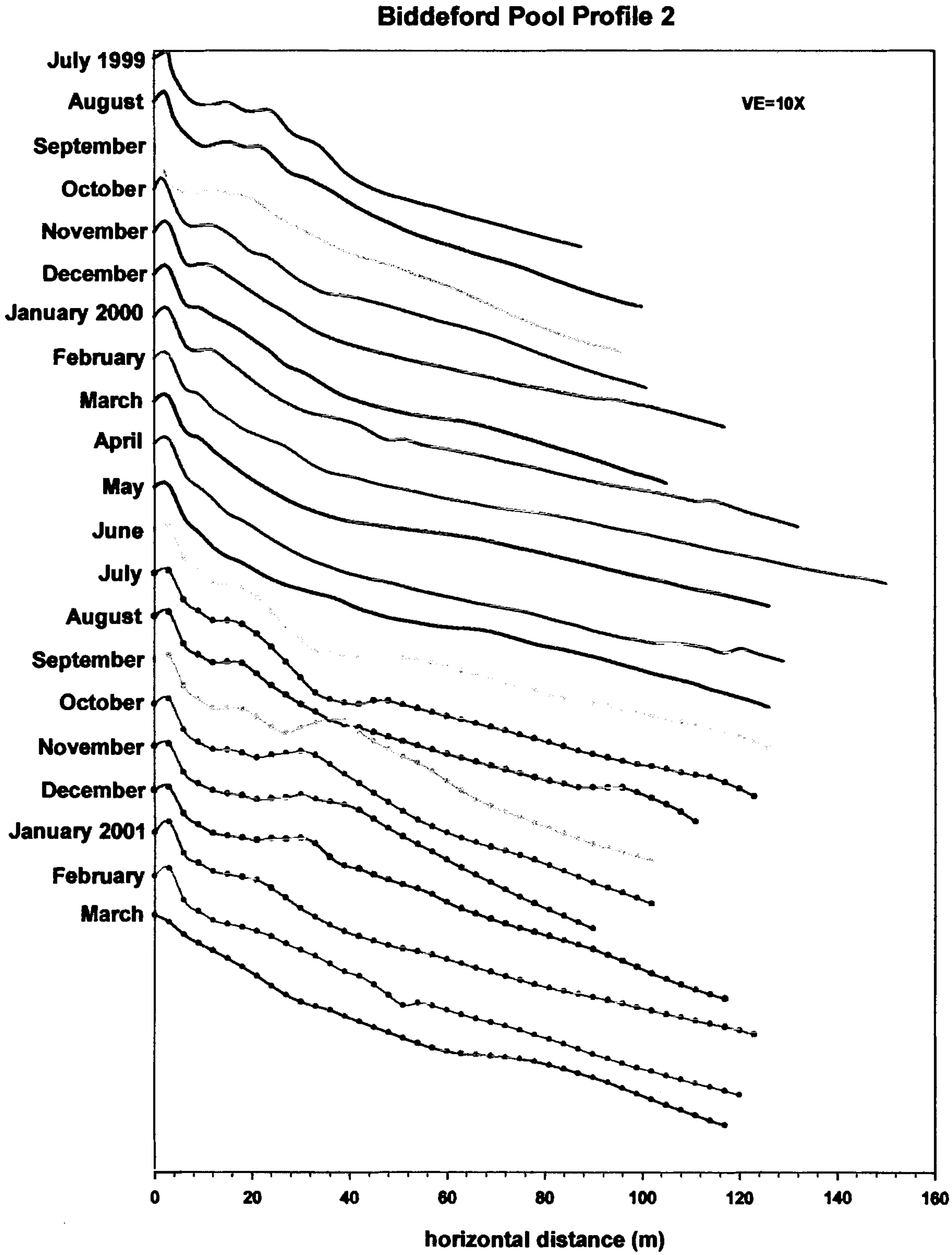


Figure B.56. Biddeford Pool Profile 2 monthly topograhic changes.

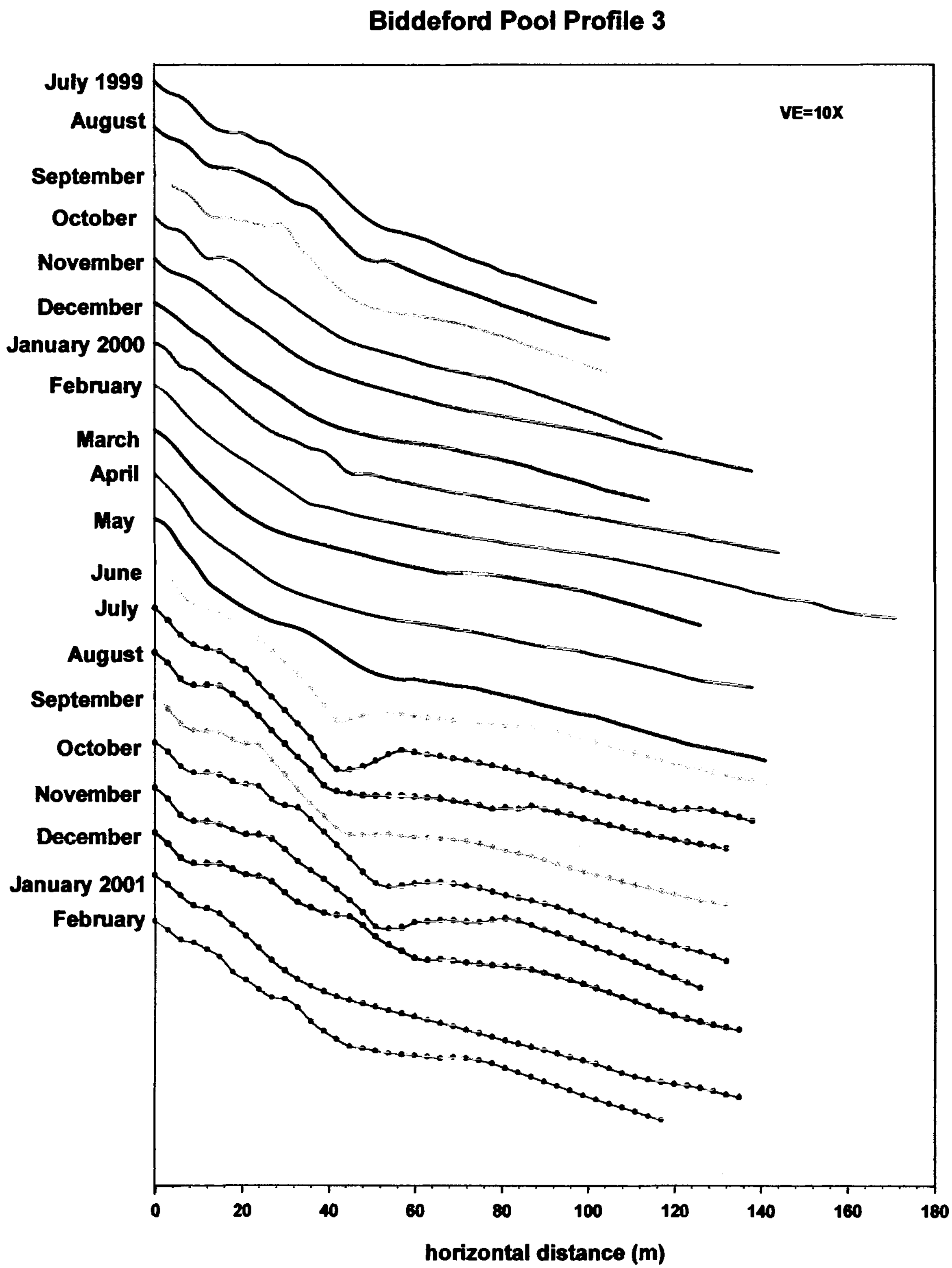


Figure B.57. Biddeford Pool Profile 3 monthly topographic changes.

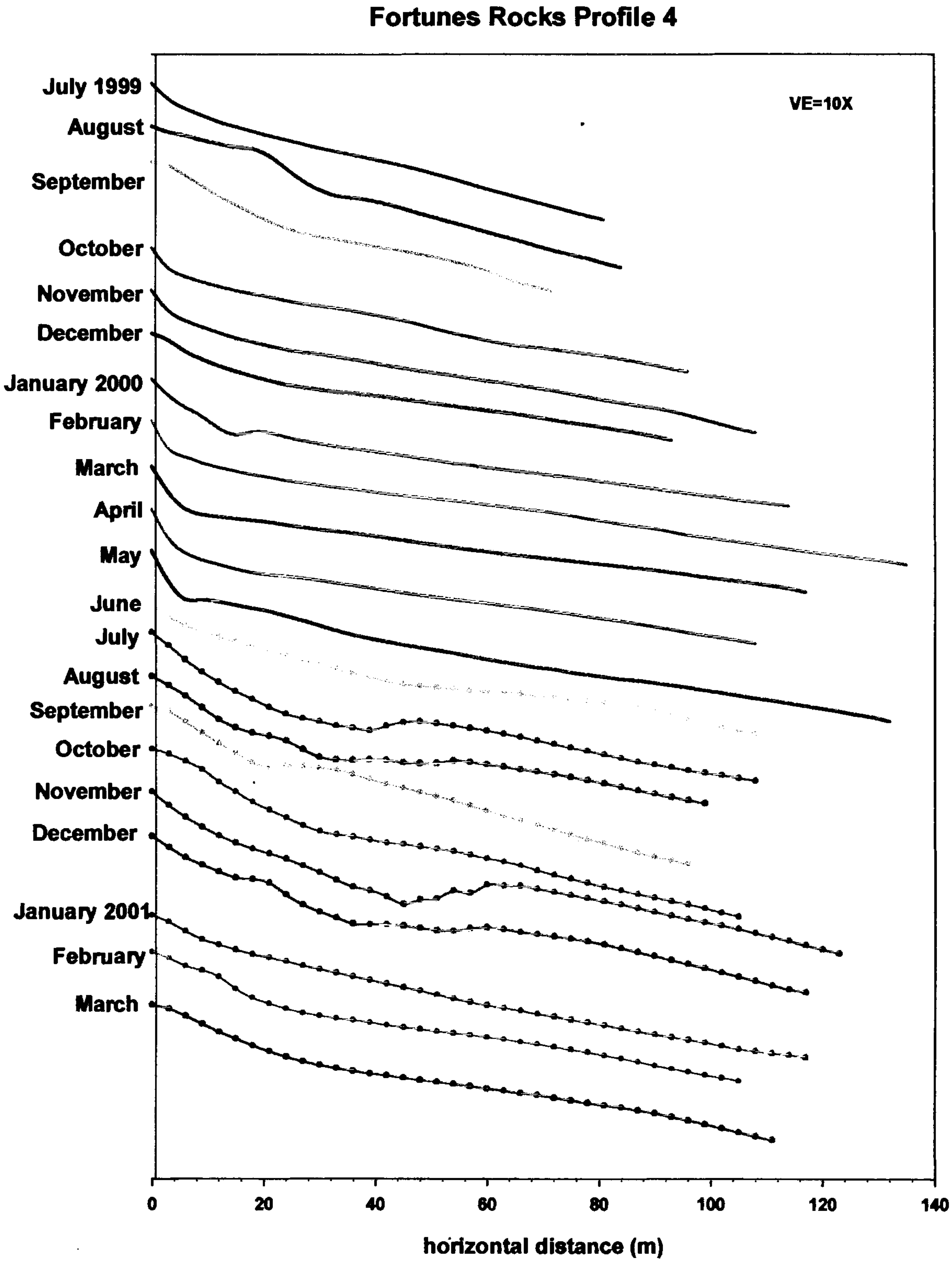


Figure B.58. Fortunes Rocks Profile 4 monthly topographic profiles.

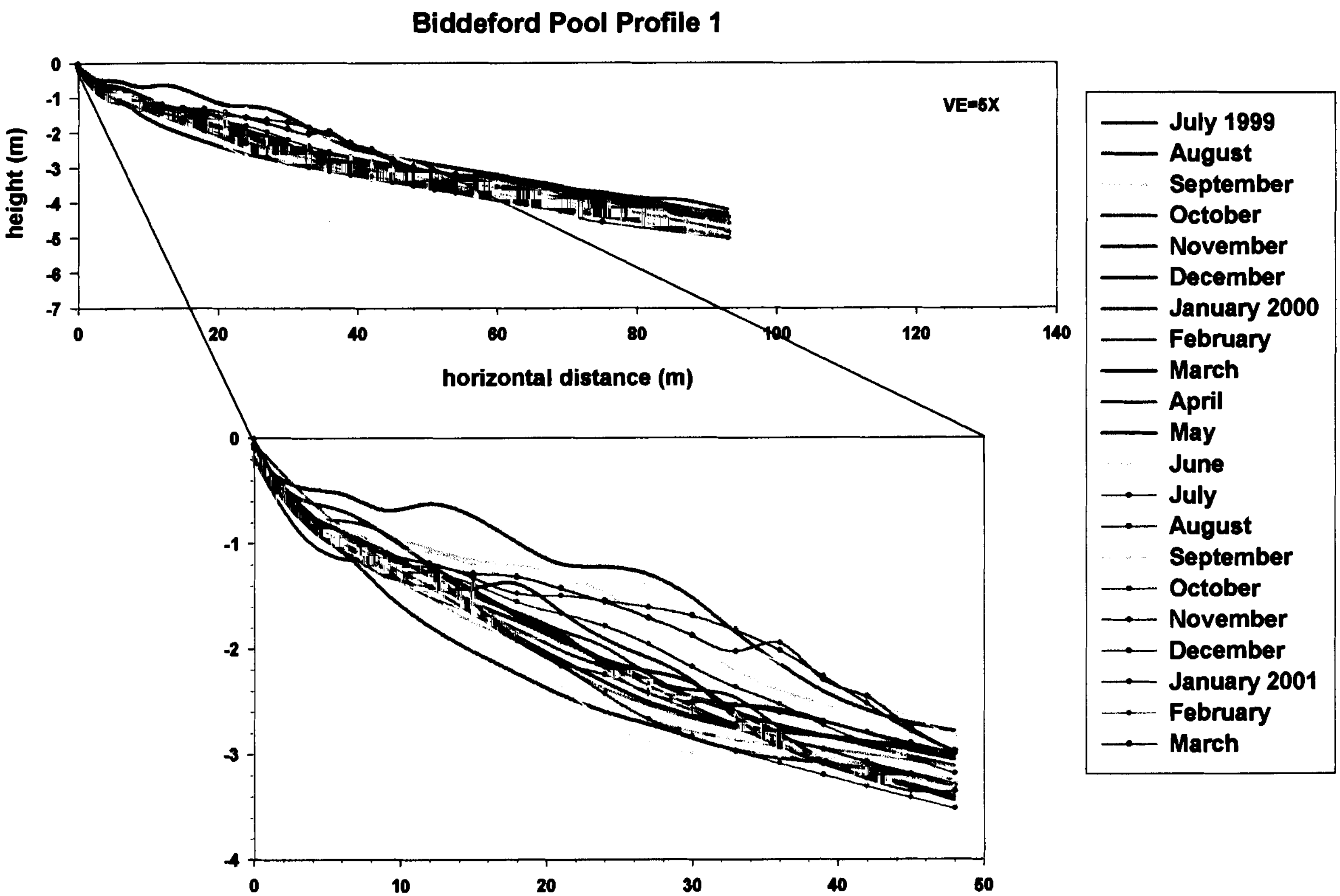


Figure B.59. Biddeford Pool Profile 1 monthly topograhic changes altered to same length.

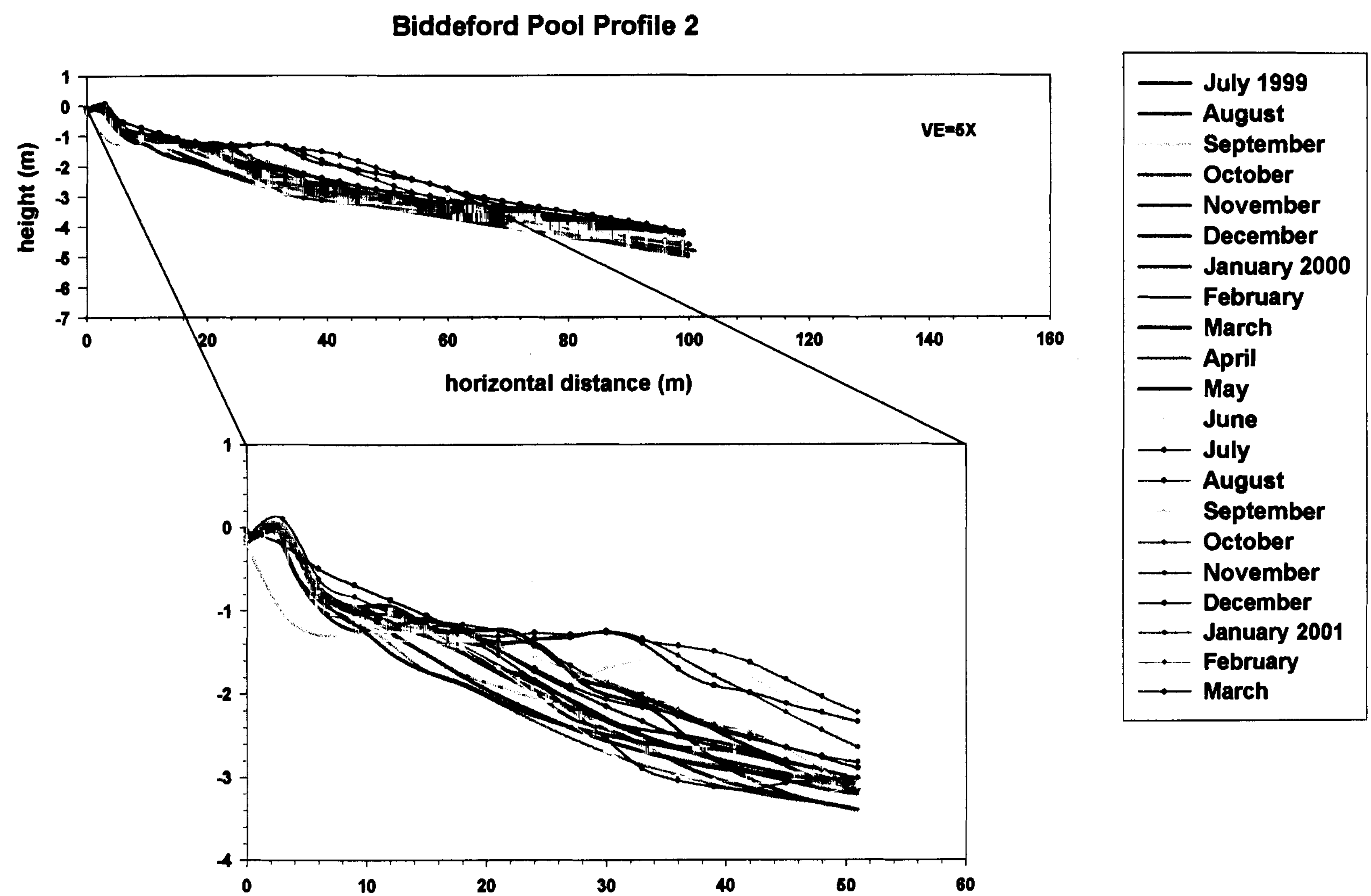


Figure B.60. Biddeford Pool Profile 2 monthly topographic changes altered to same length.

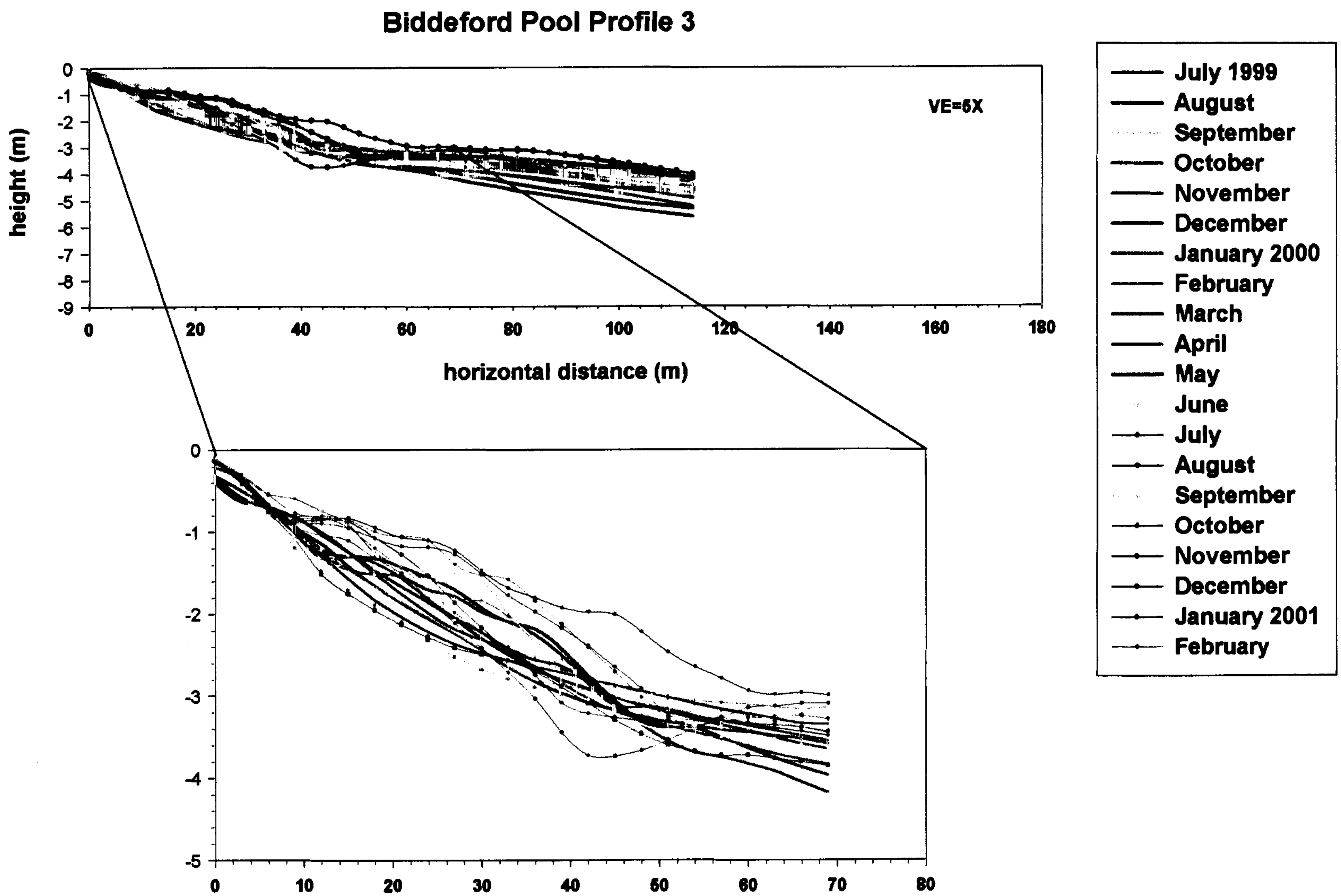


Figure B.61. Biddeford Pool Profile 3 monthly topographic changes altered to same length.

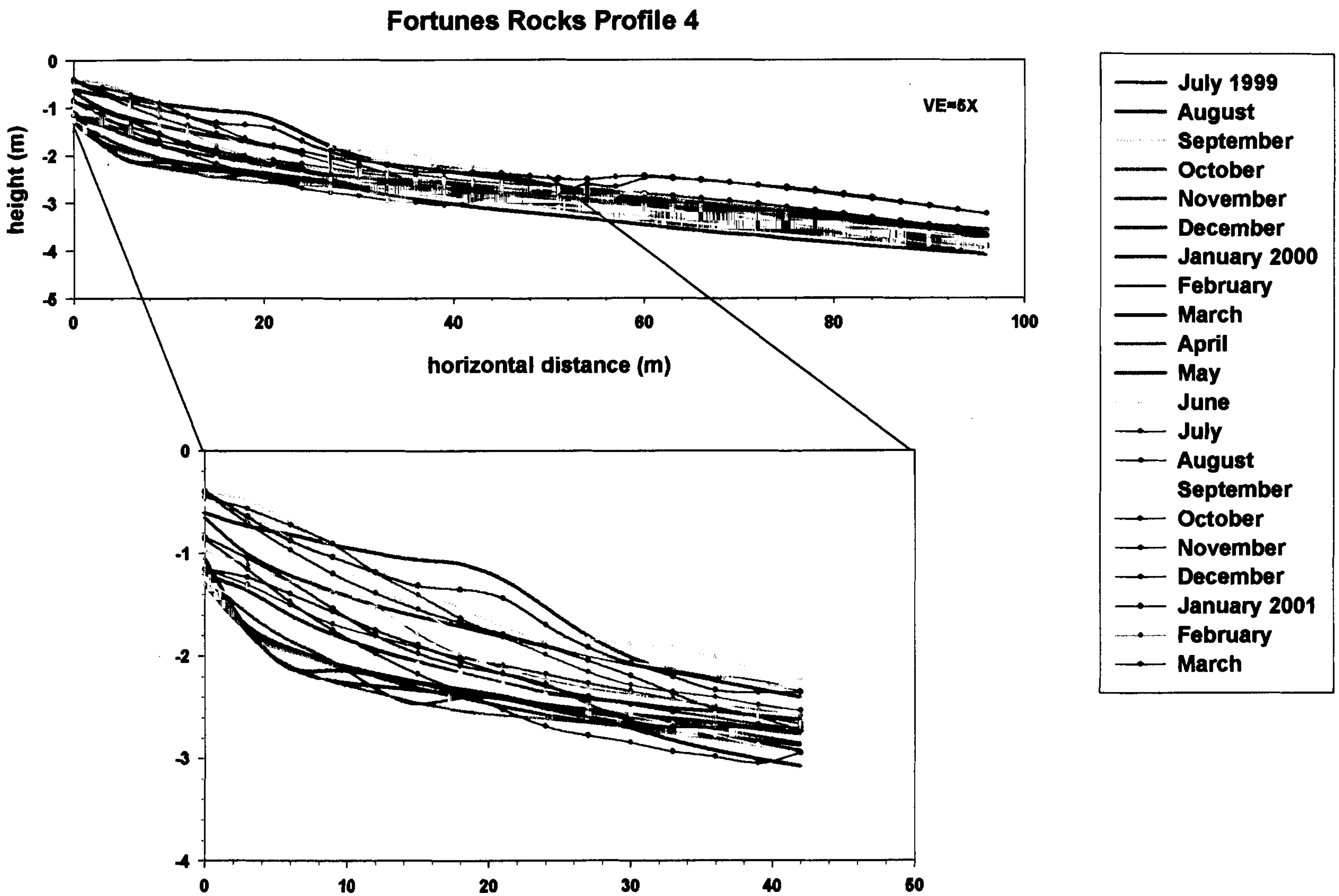


Figure B.62. Biddeford Pool Profile 4 monthly topographic changes altered to same length.

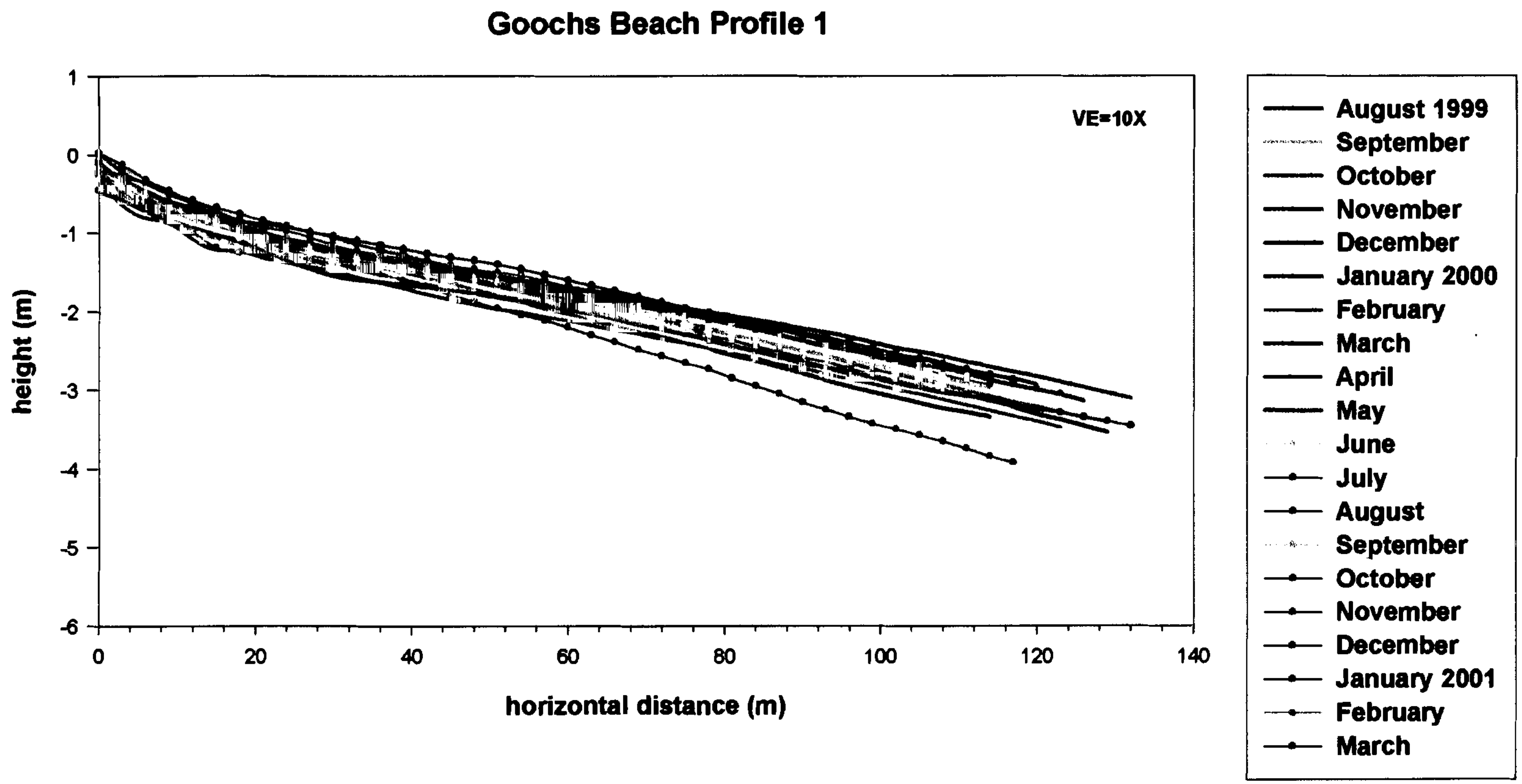


Figure B.63. Goochs Beach Topographic Profile 1 original measurements.

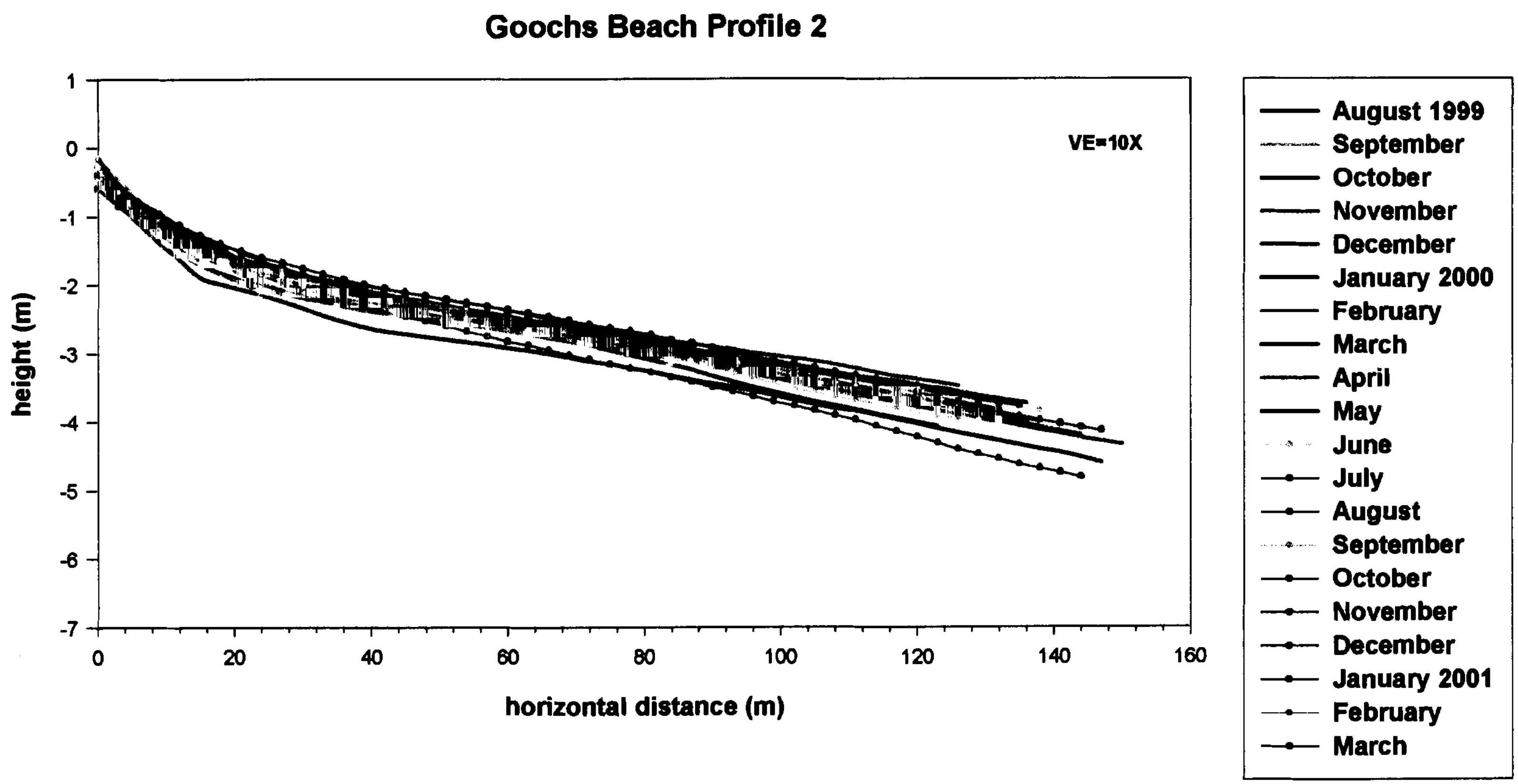


Figure B.64. Goochs Beach Topographic Profile 2 original measurements.

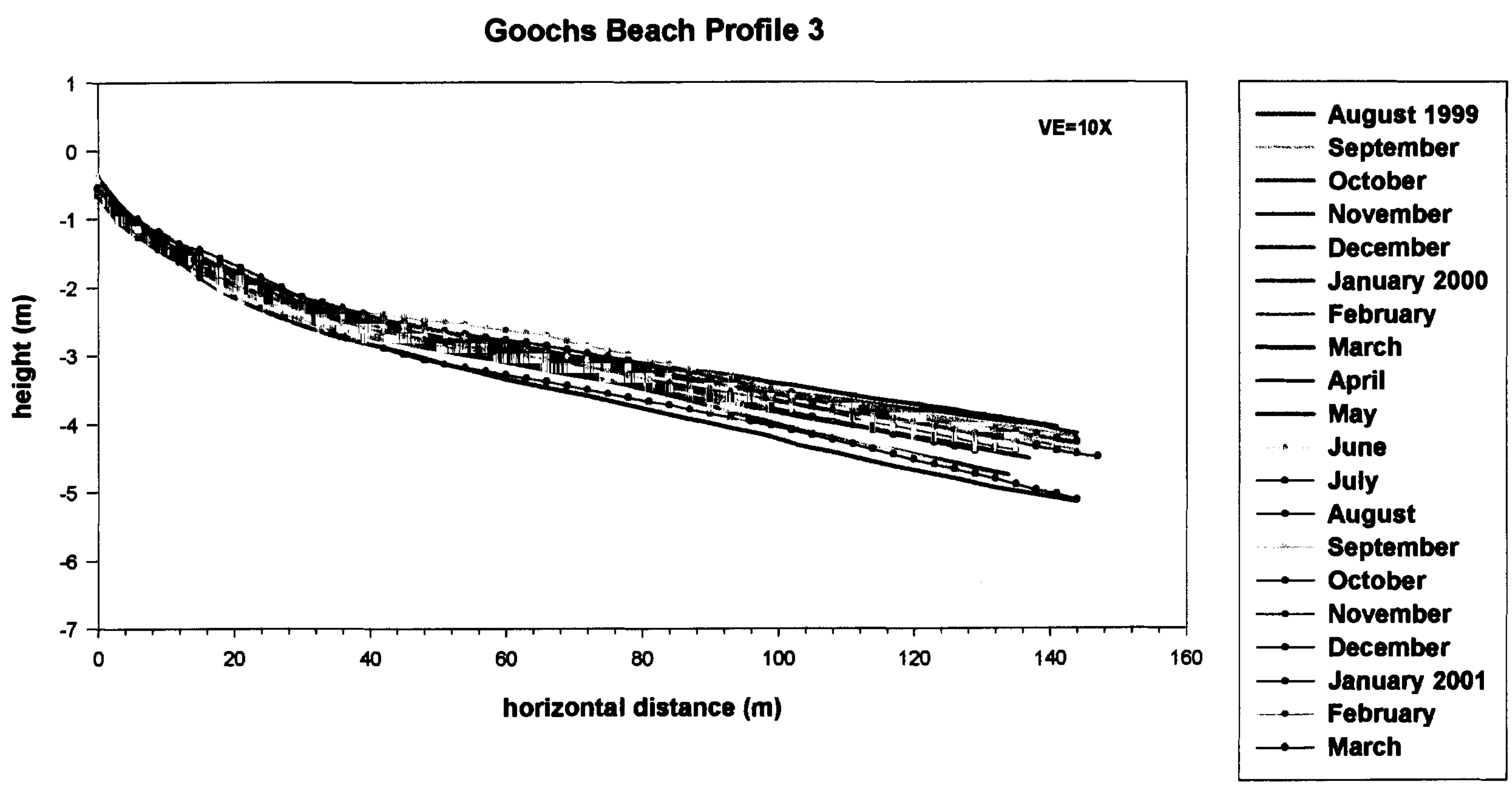


Figure B.65. Goochs Beach Topographic Profile 3 original measurements.

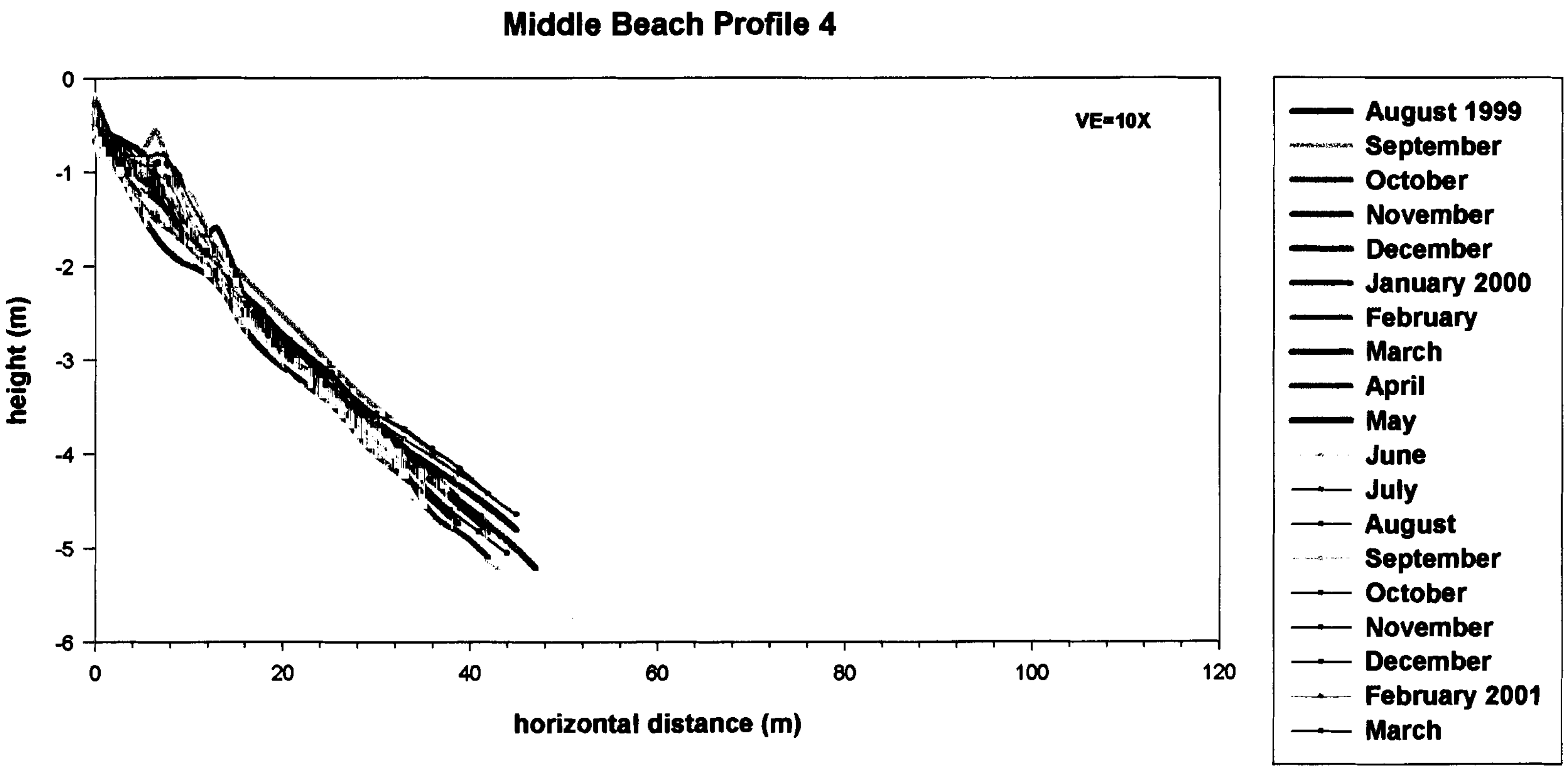


Figure B.66. Middle Beach Topographic Profile 4 original measurements.

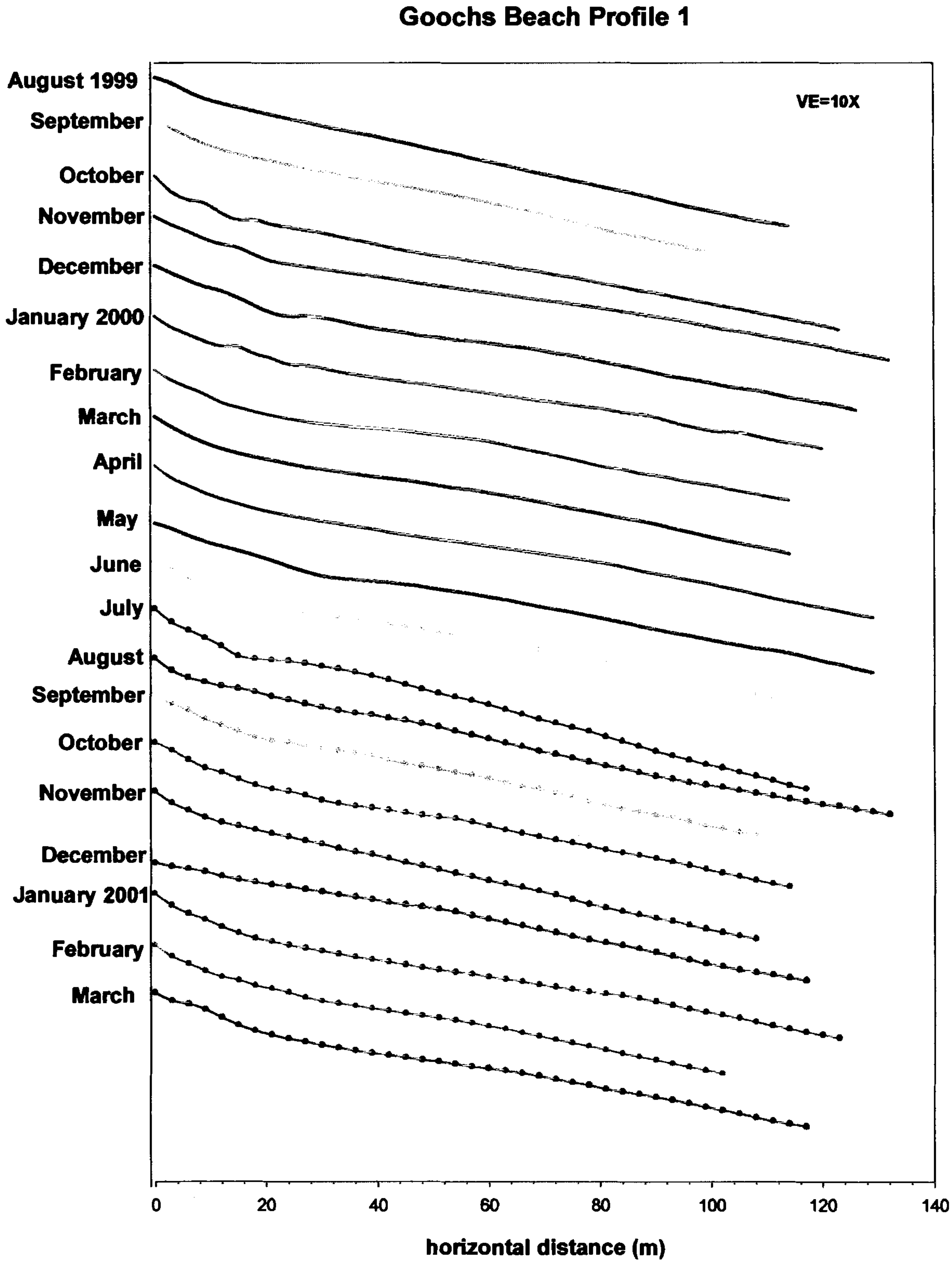


Figure B.67. Goochs Beach Profile 1 monthly topograhic changes.

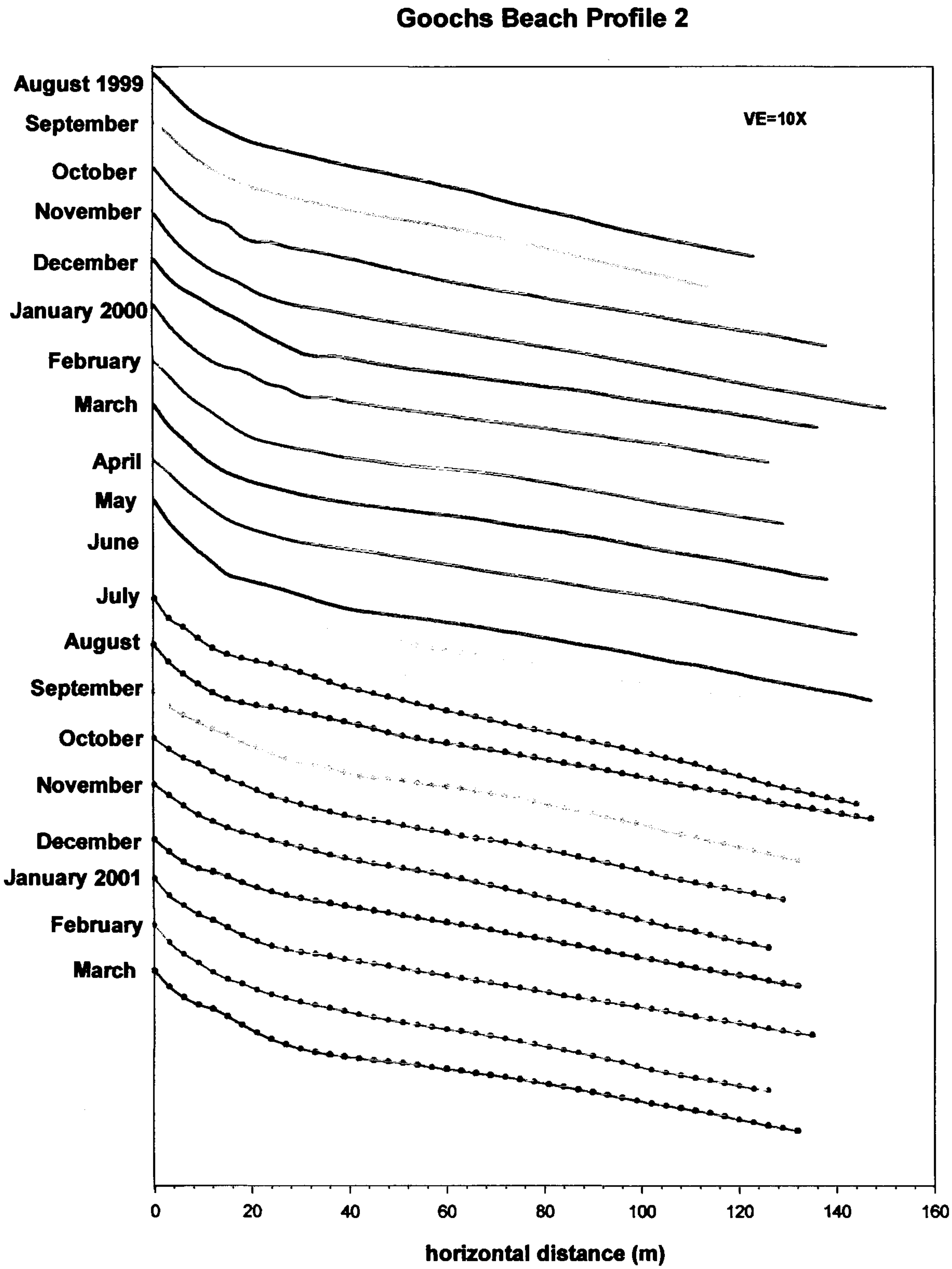


Figure B.68. Goochs Beach Profile 2 monthly topograhic changes.

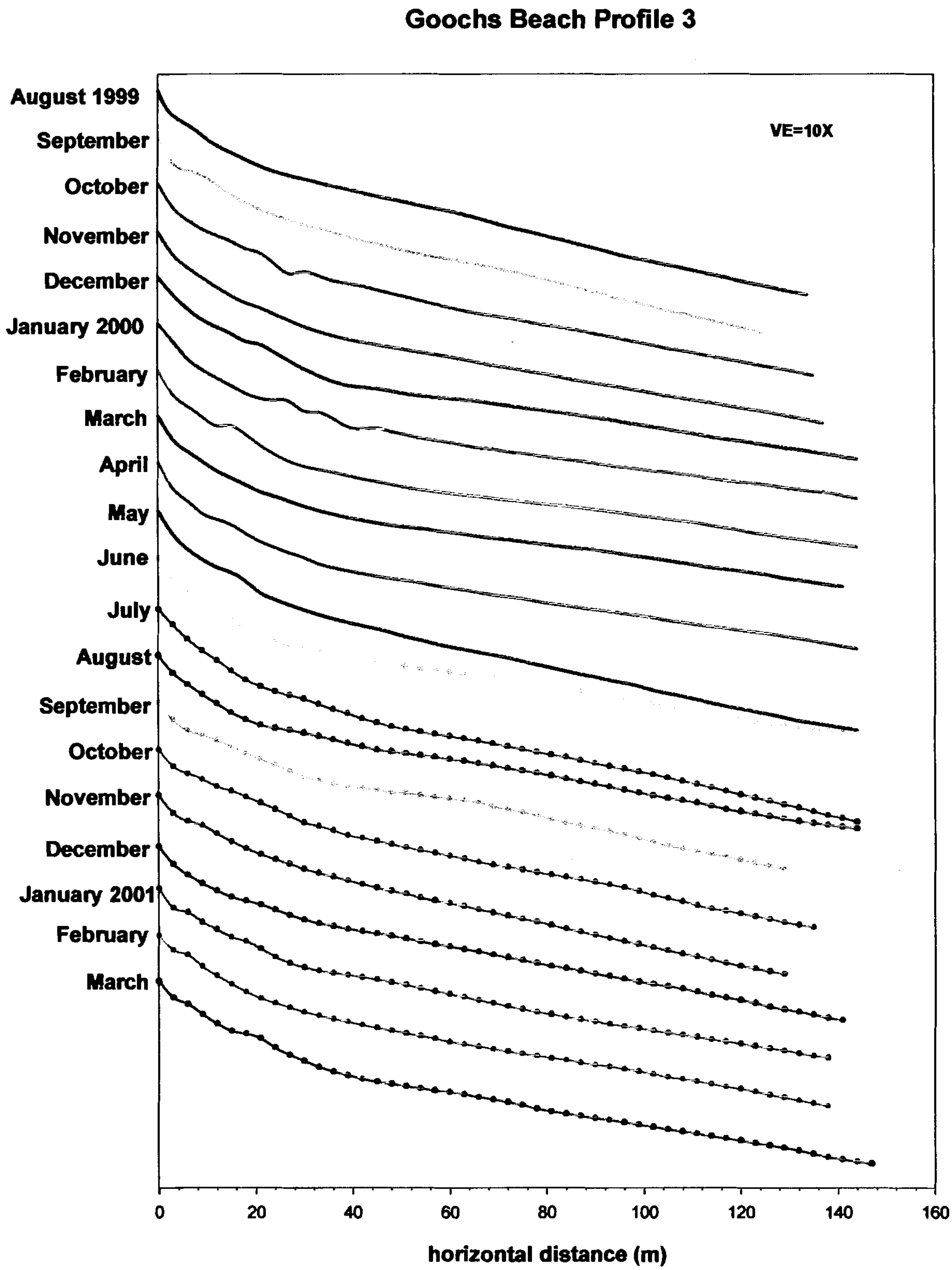


Figure B.69. Goochs Beach Profile 3 monthly topographic changes.

Middle Beach

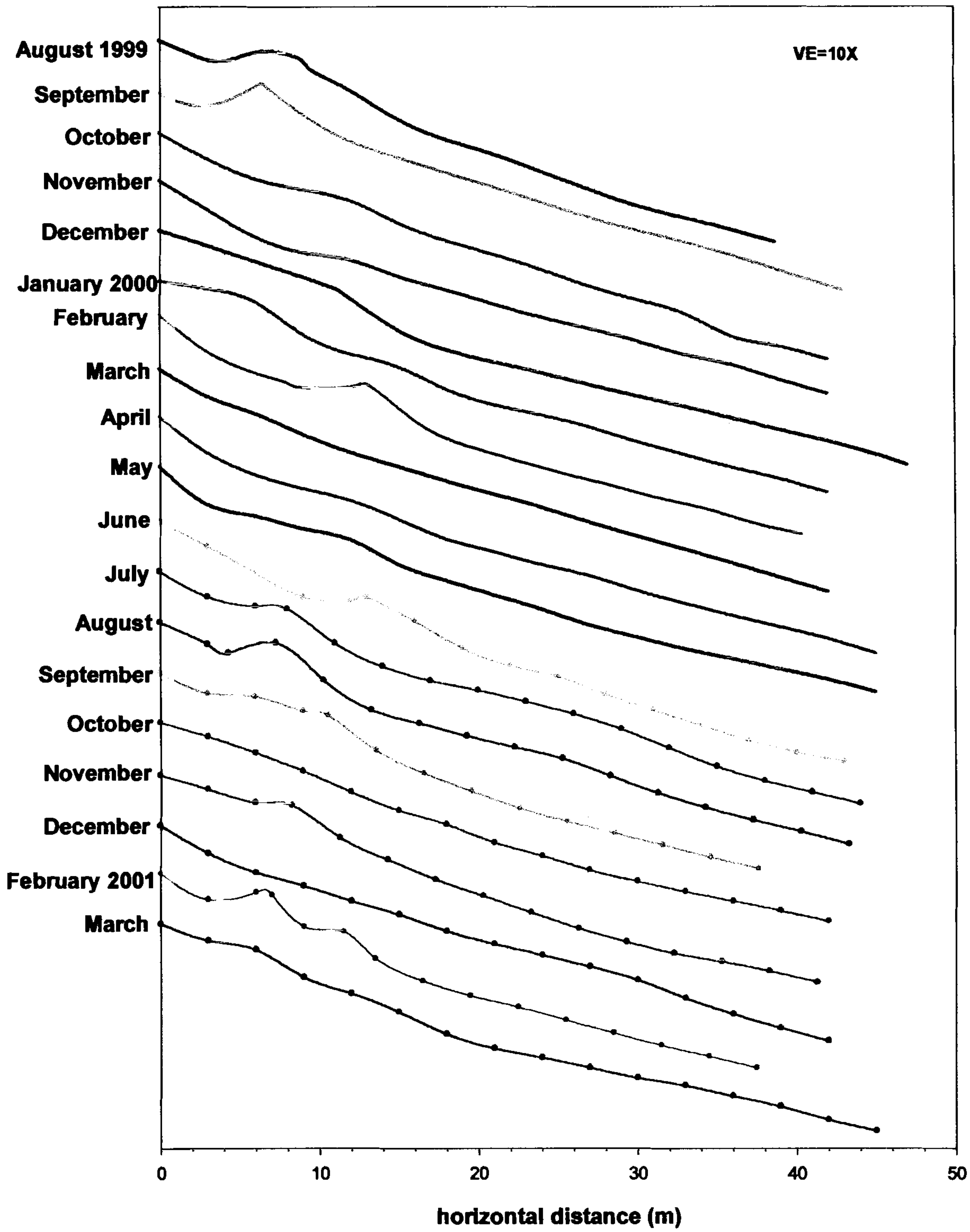


Figure B.70. Middle Beach Profile 4 monthly topographic changes.

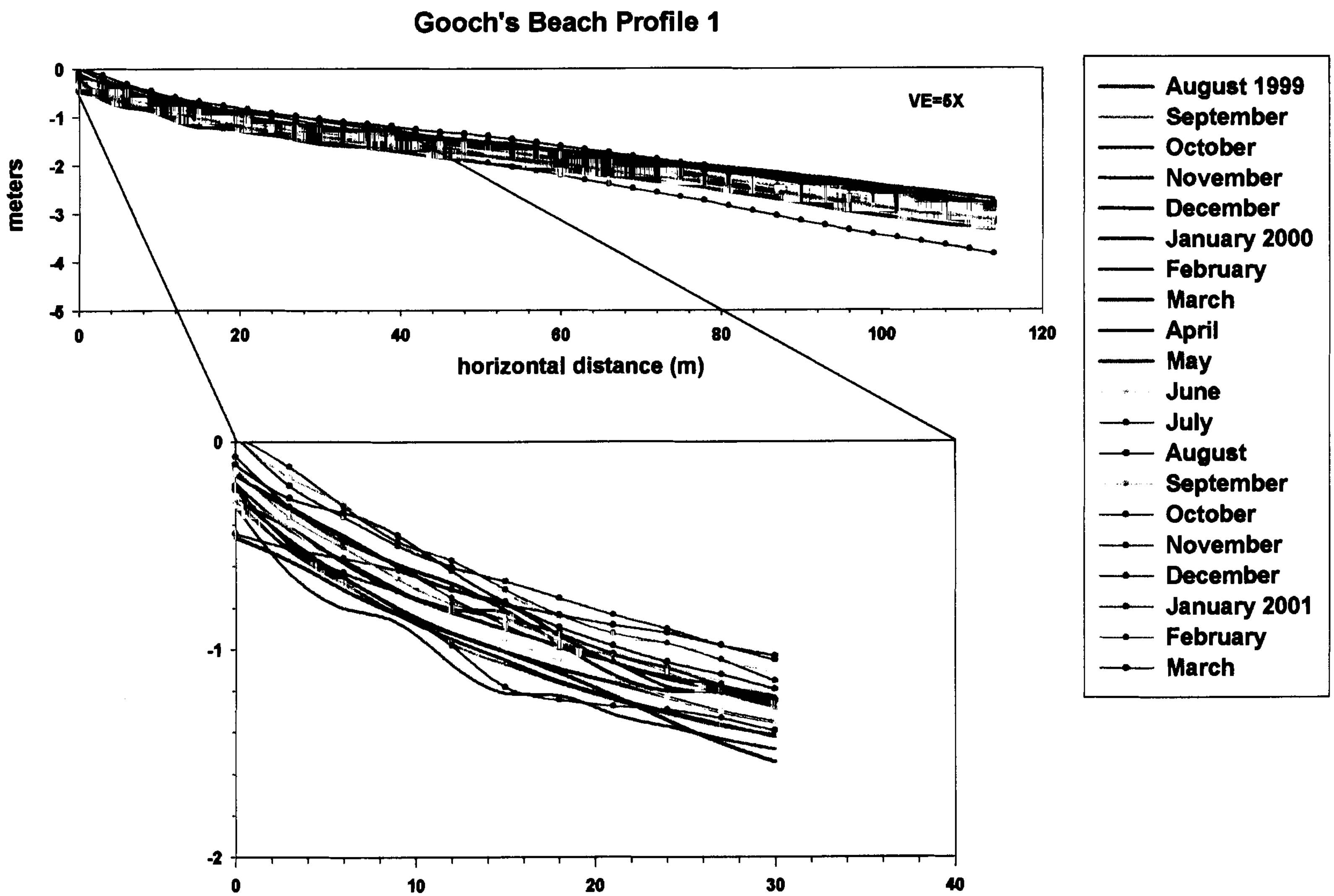


Figure B.71. Goochs Beach Profile 1 monthly topographic changes altered to same length.

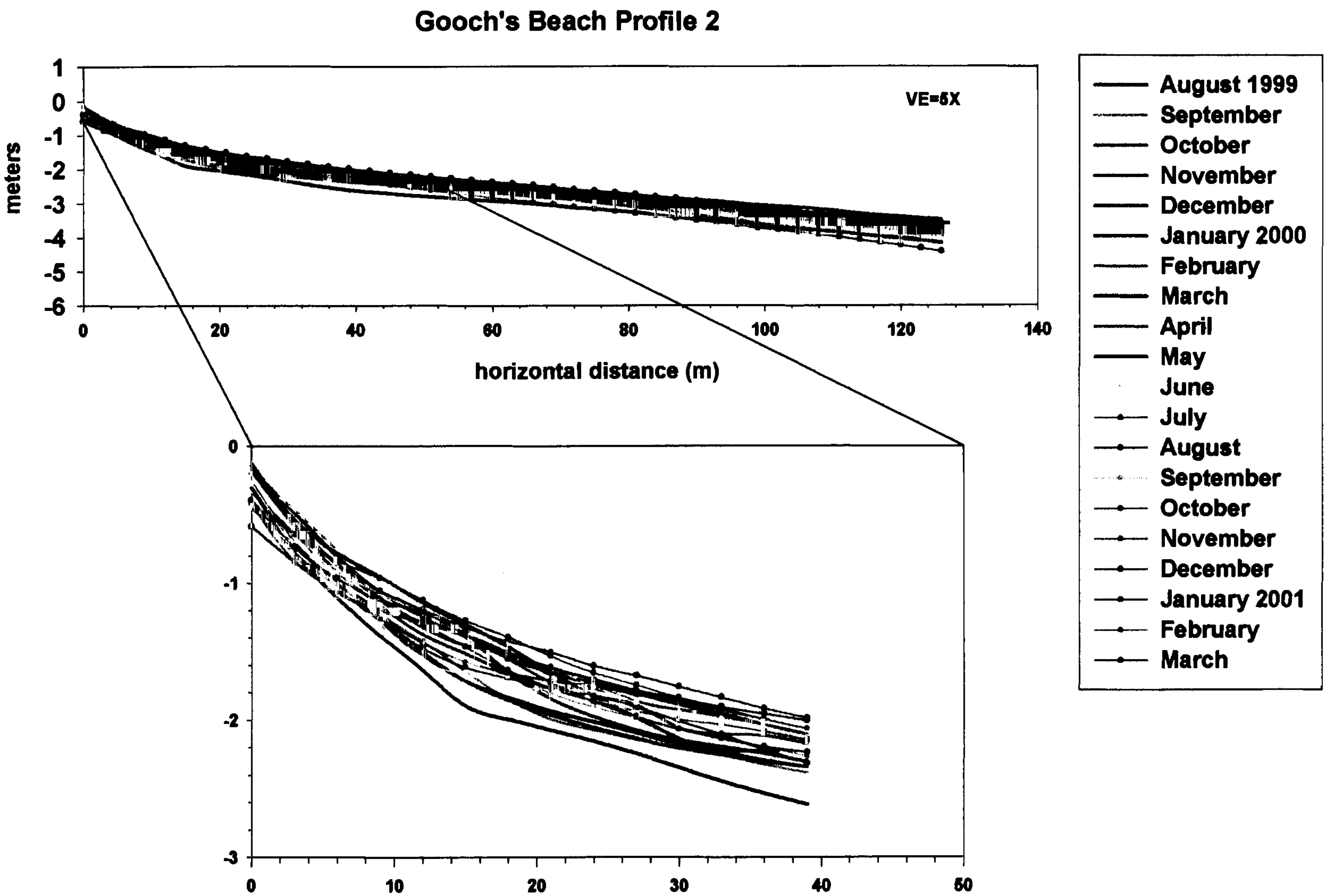


Figure B.72. Goochs Beach Profile 2 monthly topographic changes altered to same length.

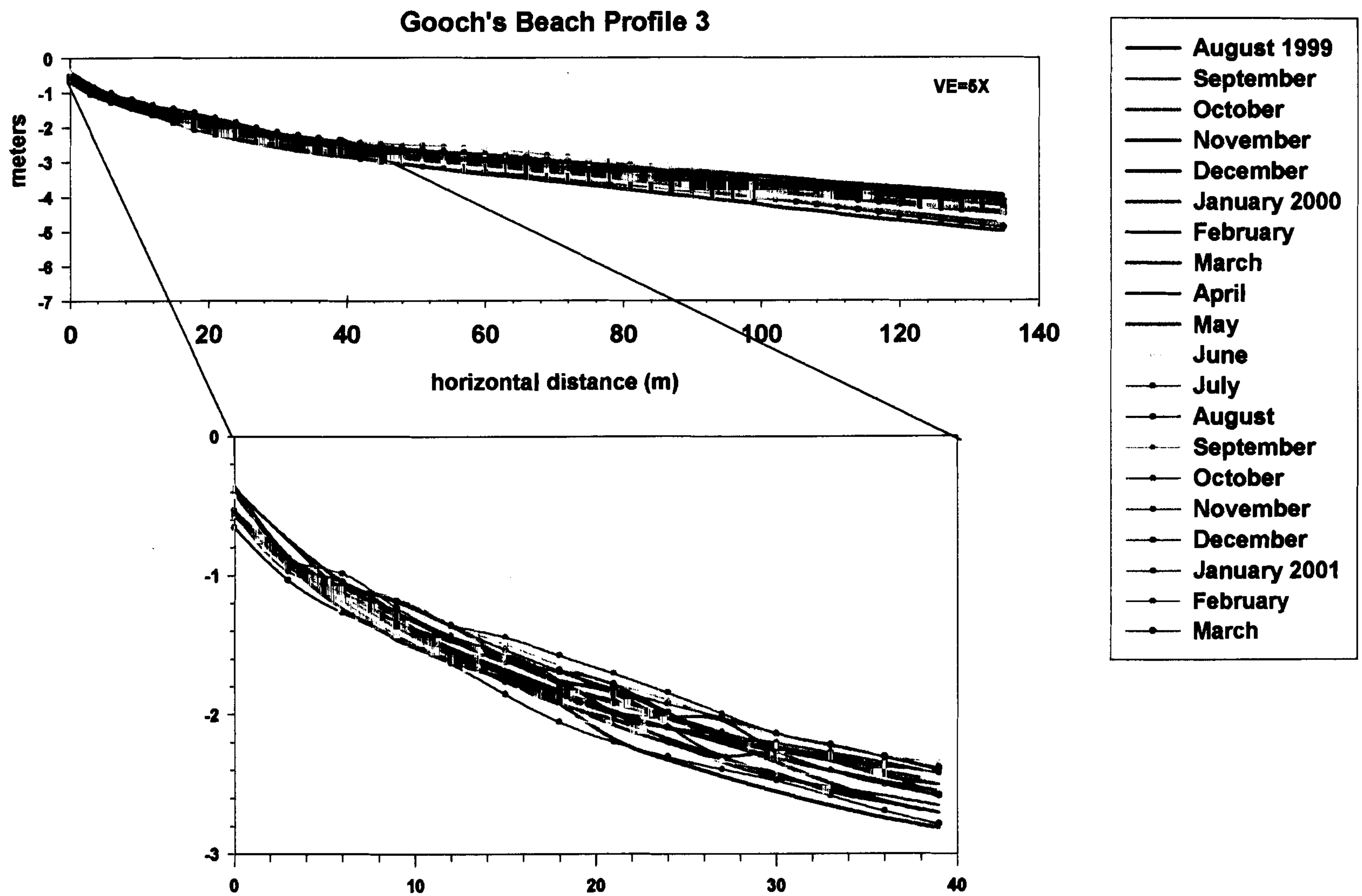


Figure B.73. Goochs Beach Profile 3 monthly topographic changes altered to same length.

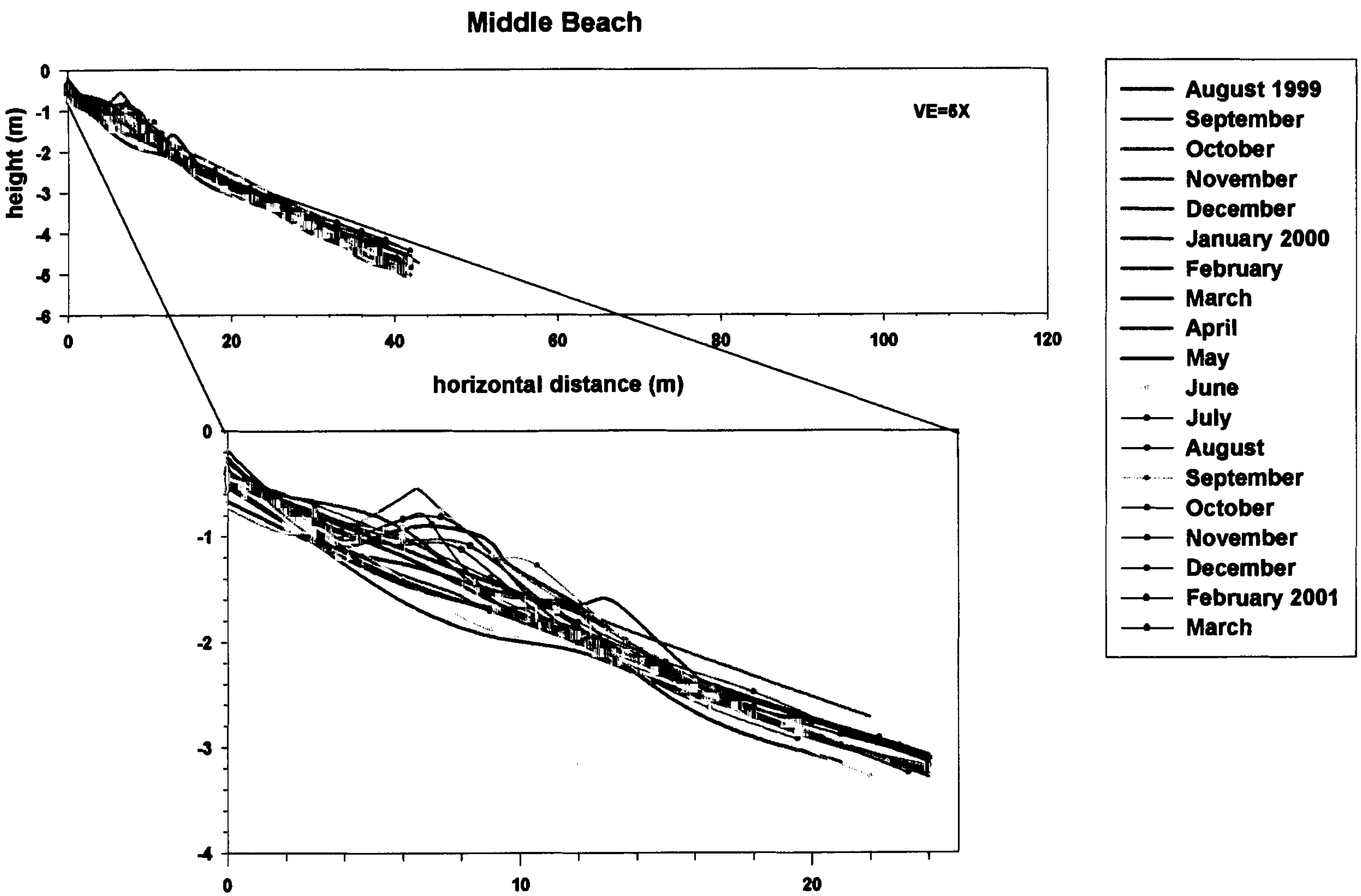


Figure B.74. Middle Beach Profile 4 monthly topographic changes altered to same length.

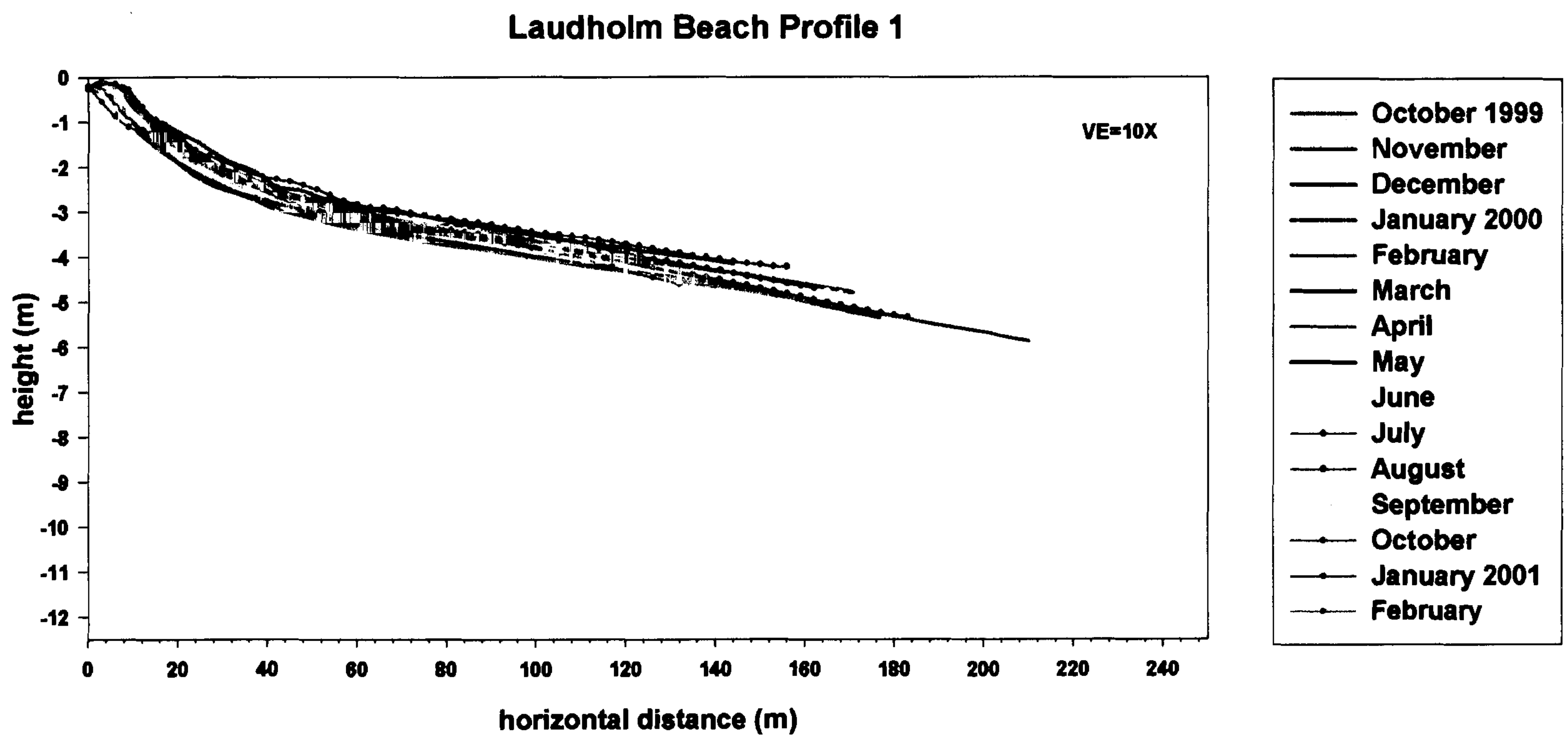


Figure B.75. Laudholm Beach Topograhic Profile 1 original measurements.

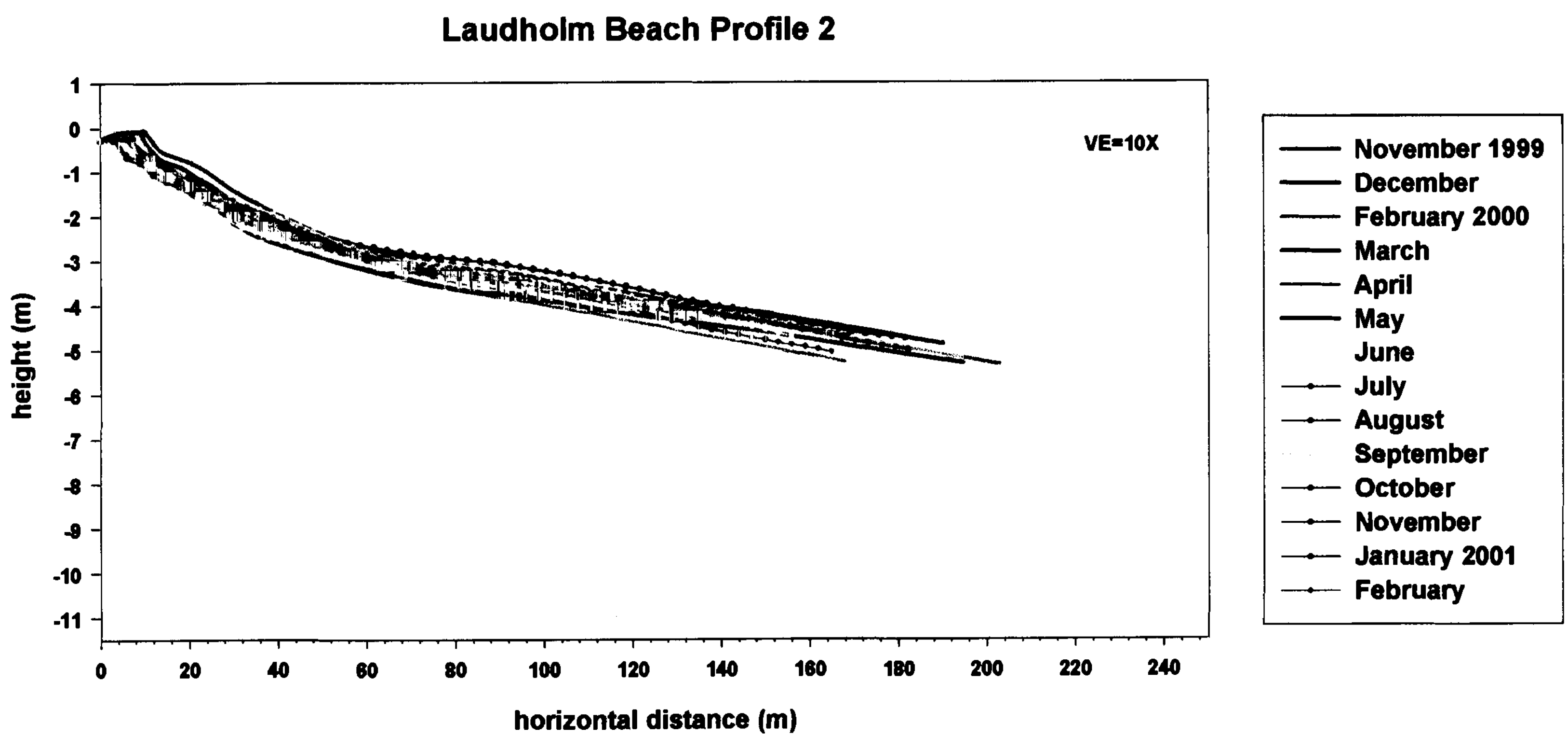


Figure B.76. Laudholm Beach Profile 2 original measurements.

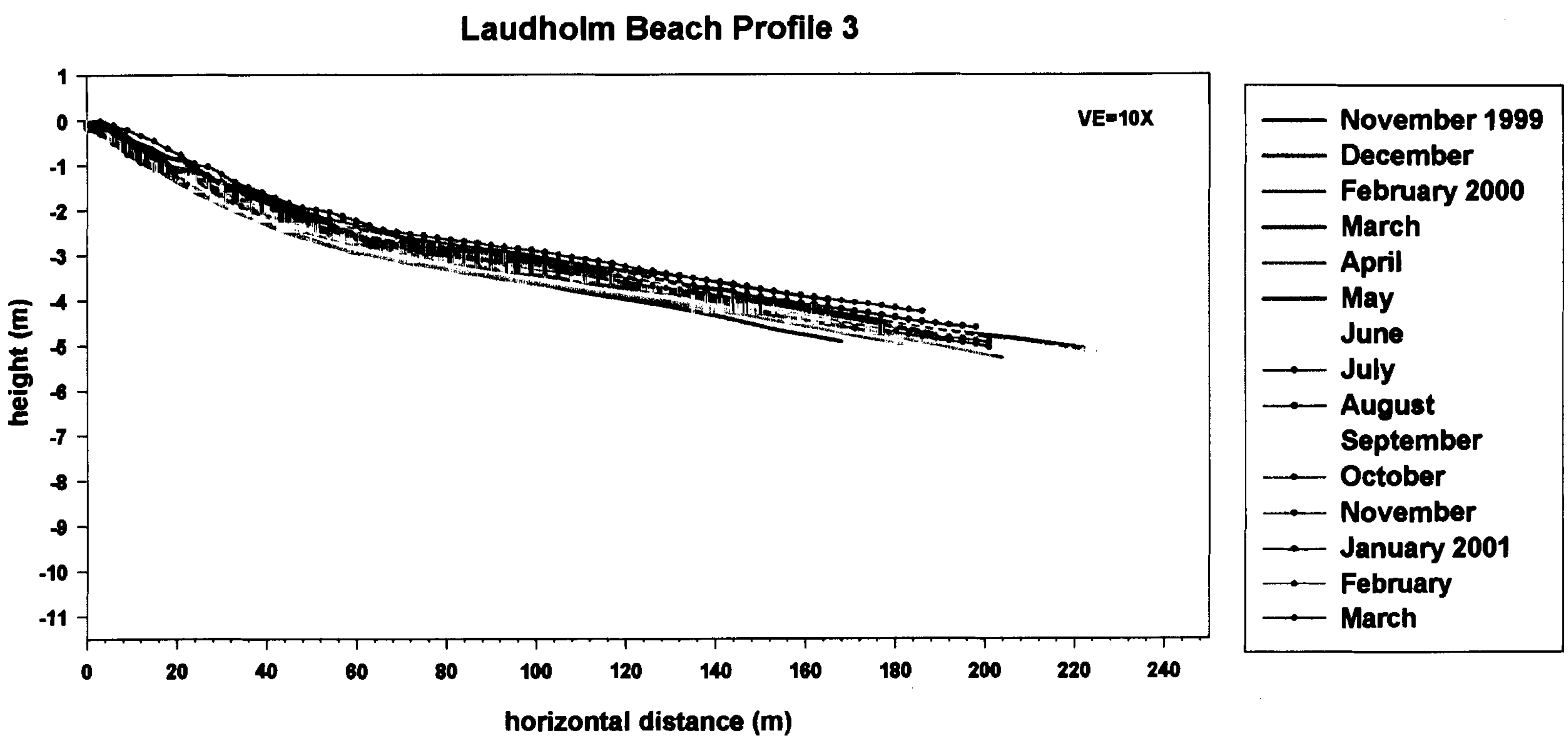


Figure B.77. Laudholm Beach Topographic Profile 3 original measurements.

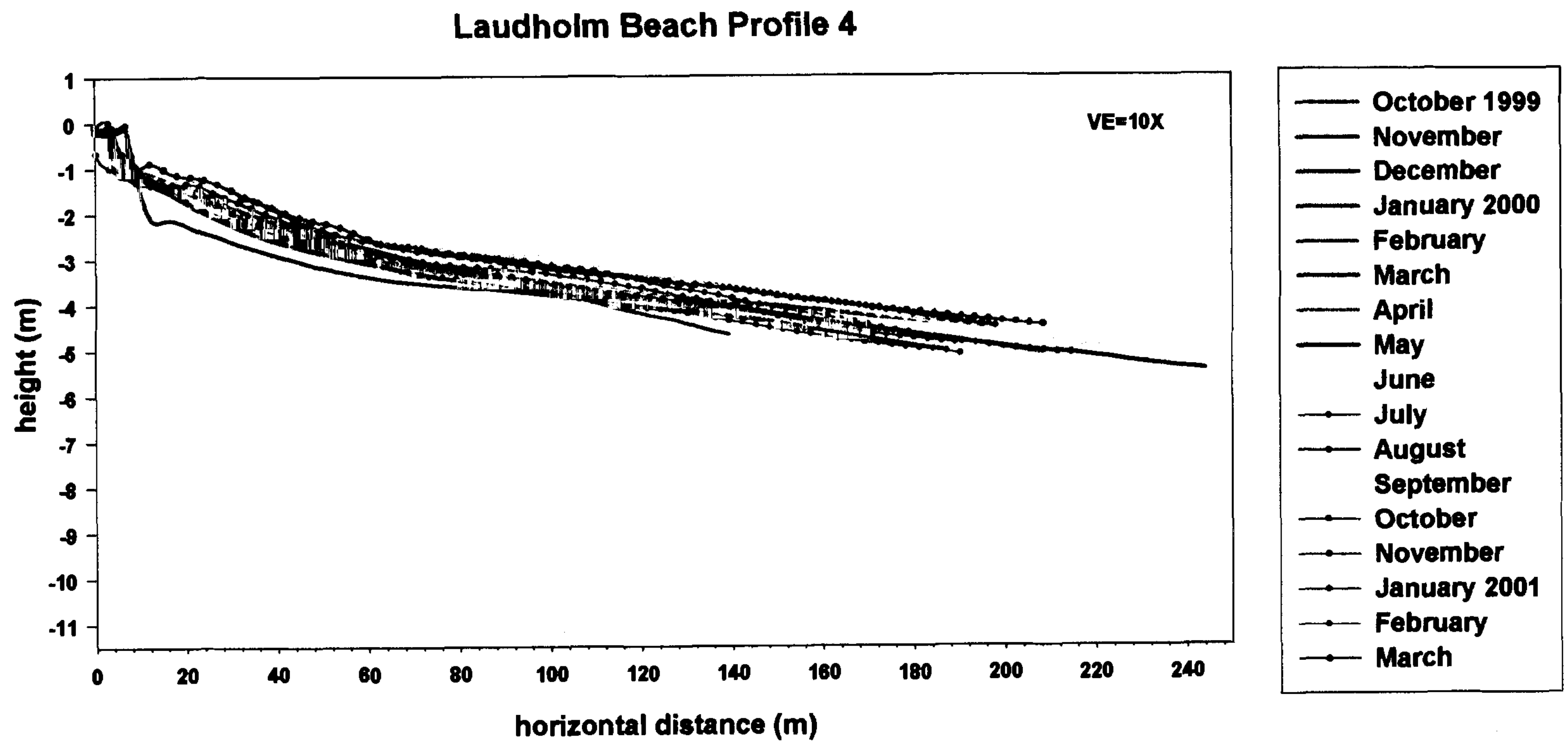


Figure B.78. Laudholm Beach Topographic Profile 4 original measurements.

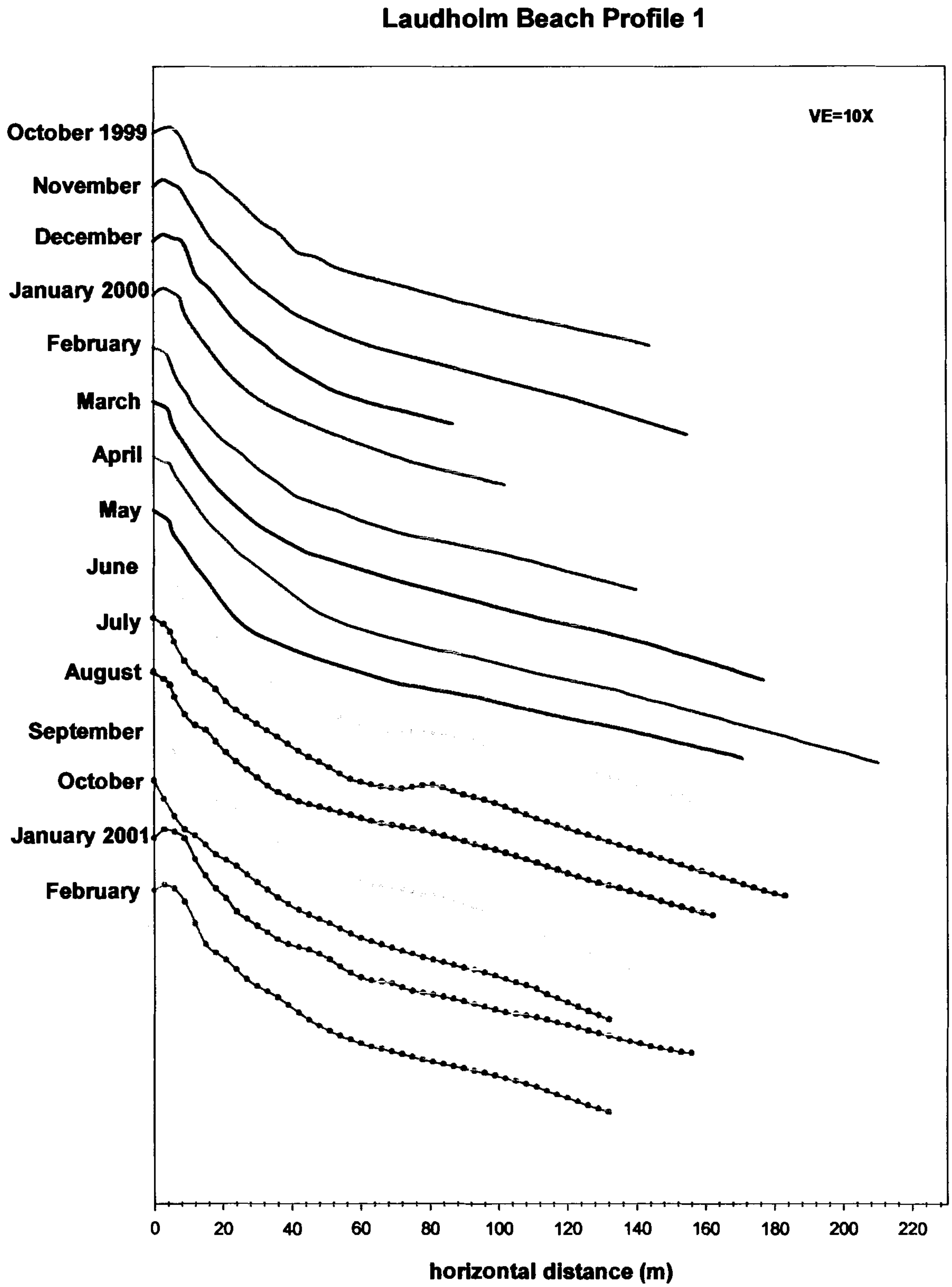


Figure B.79. Laudholm Beach Profile 1 monthly topographic changes.

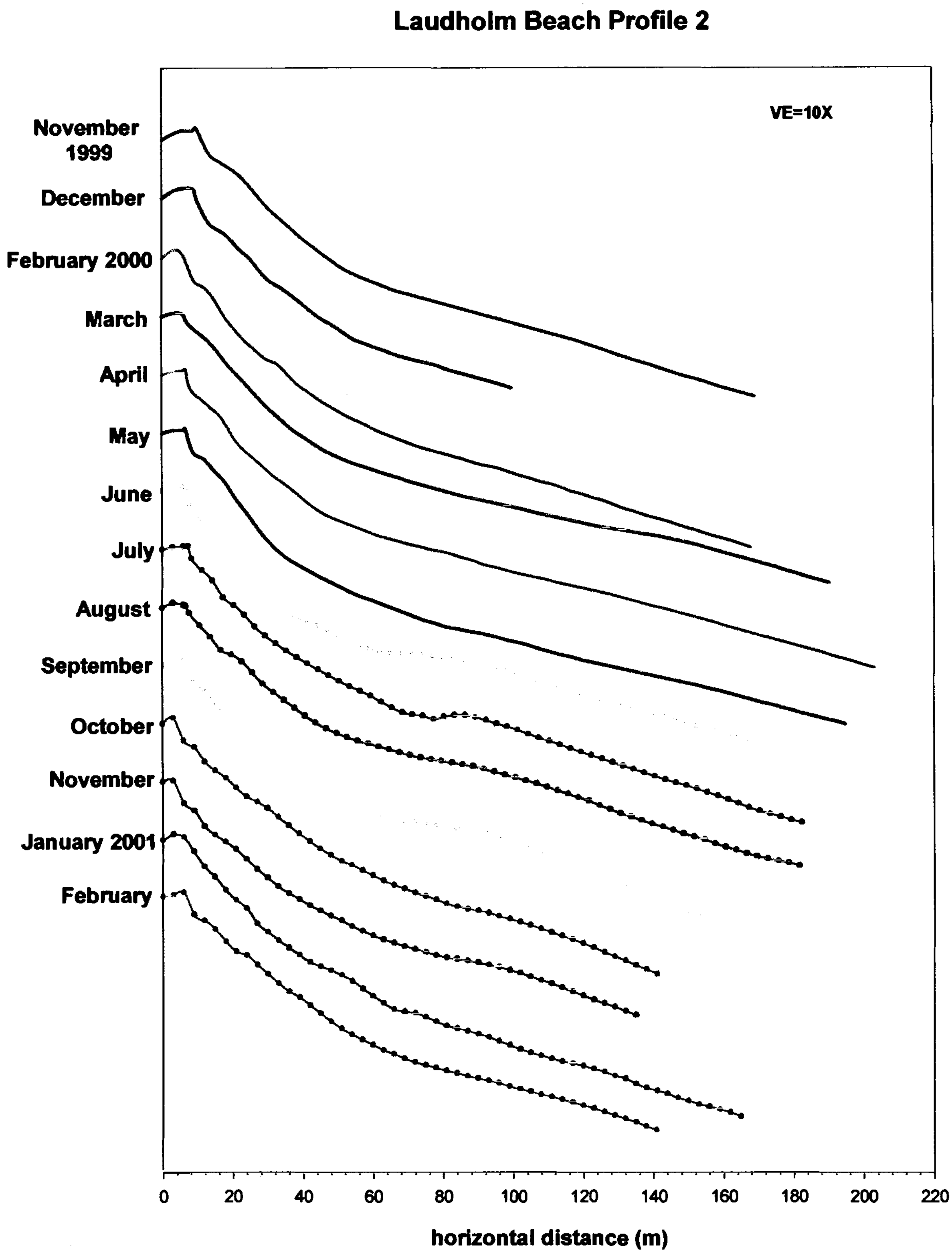


Figure B.80. Laudholm Beach Profile 2 monthly topographic changes.

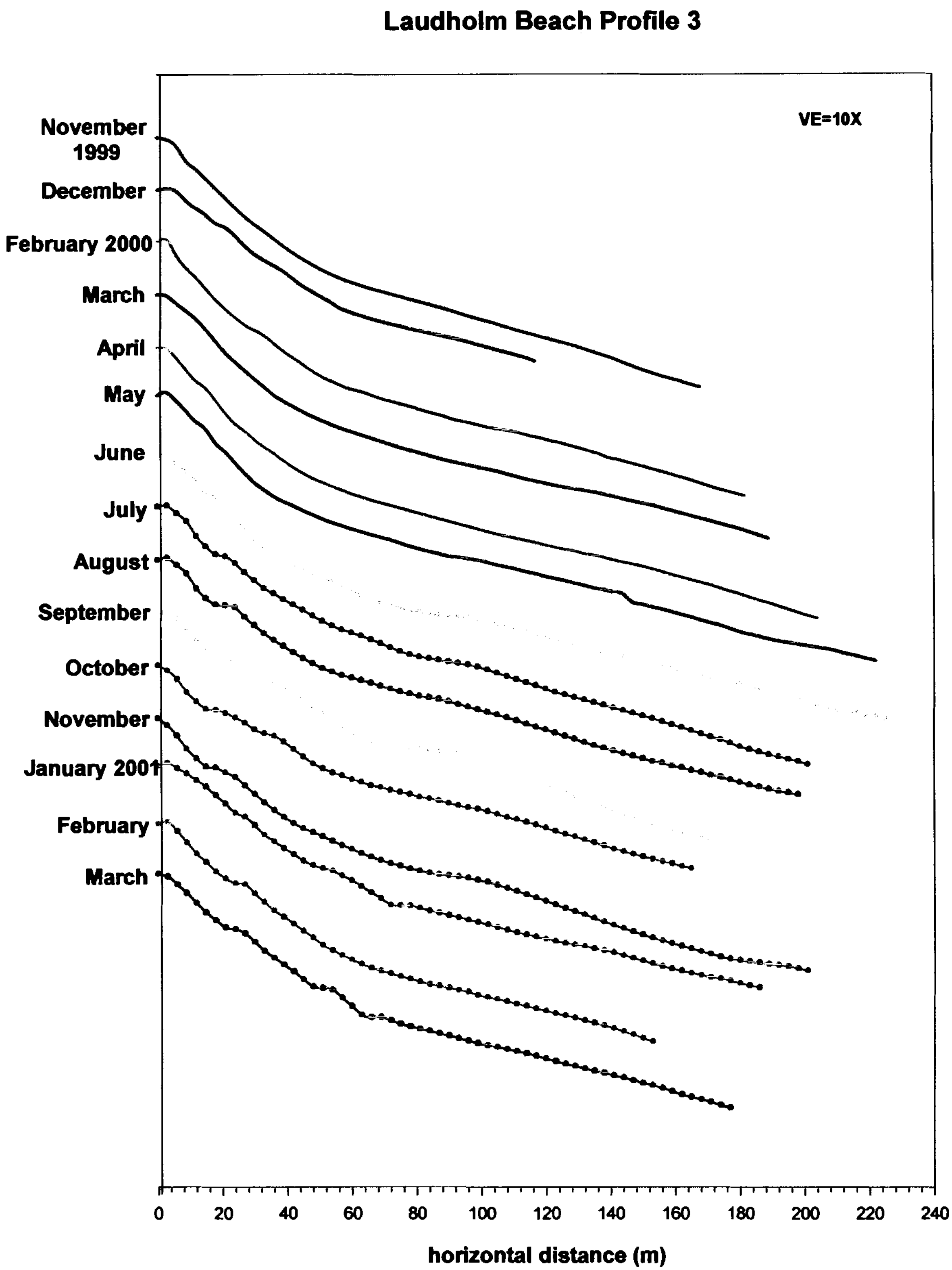


Figure B.81. Laudholm Beach Profile 3 monthly topographic changes.

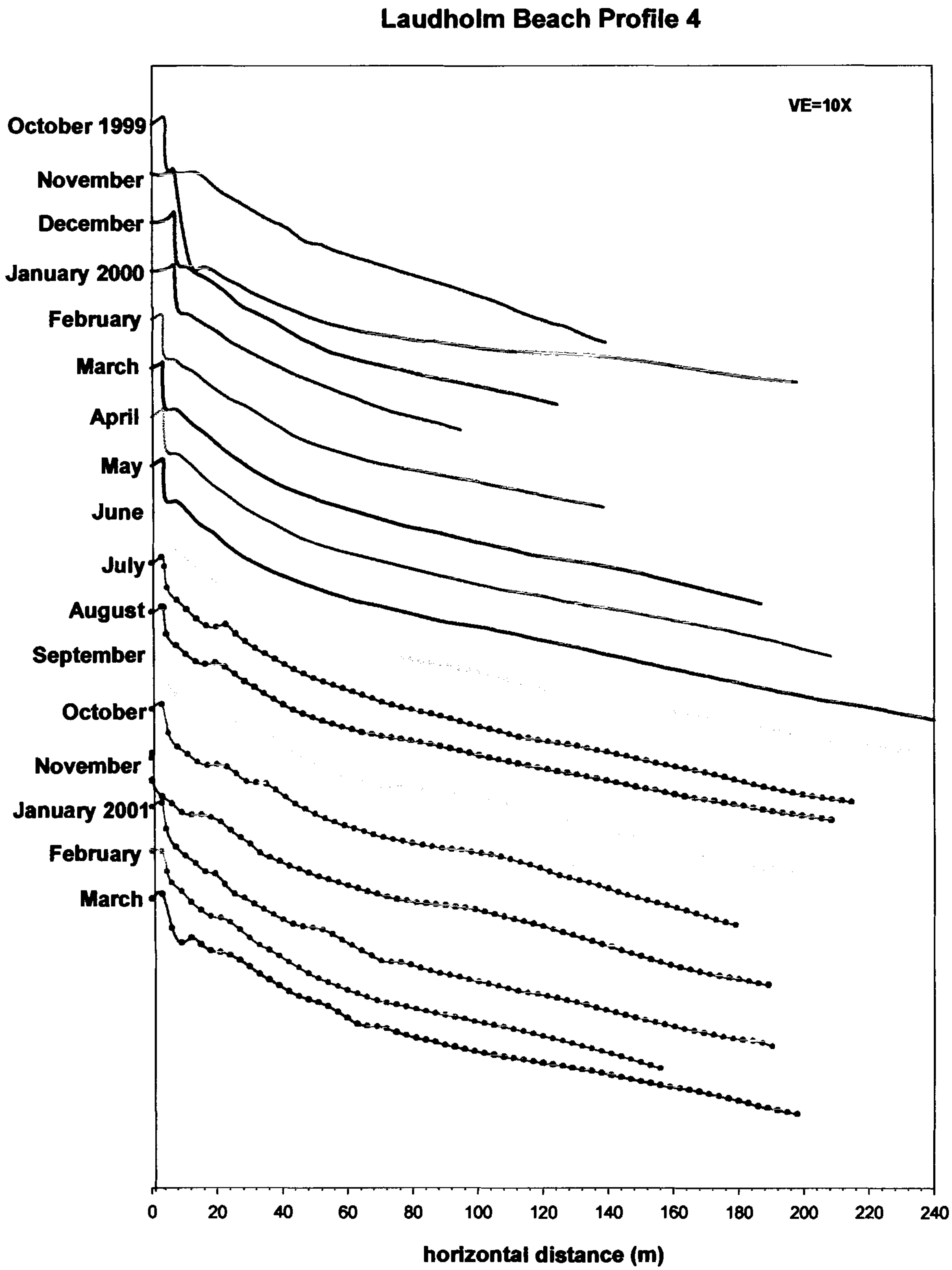


Figure B.82. Laudholm Beach Profile 4 monthly topograhic changes.

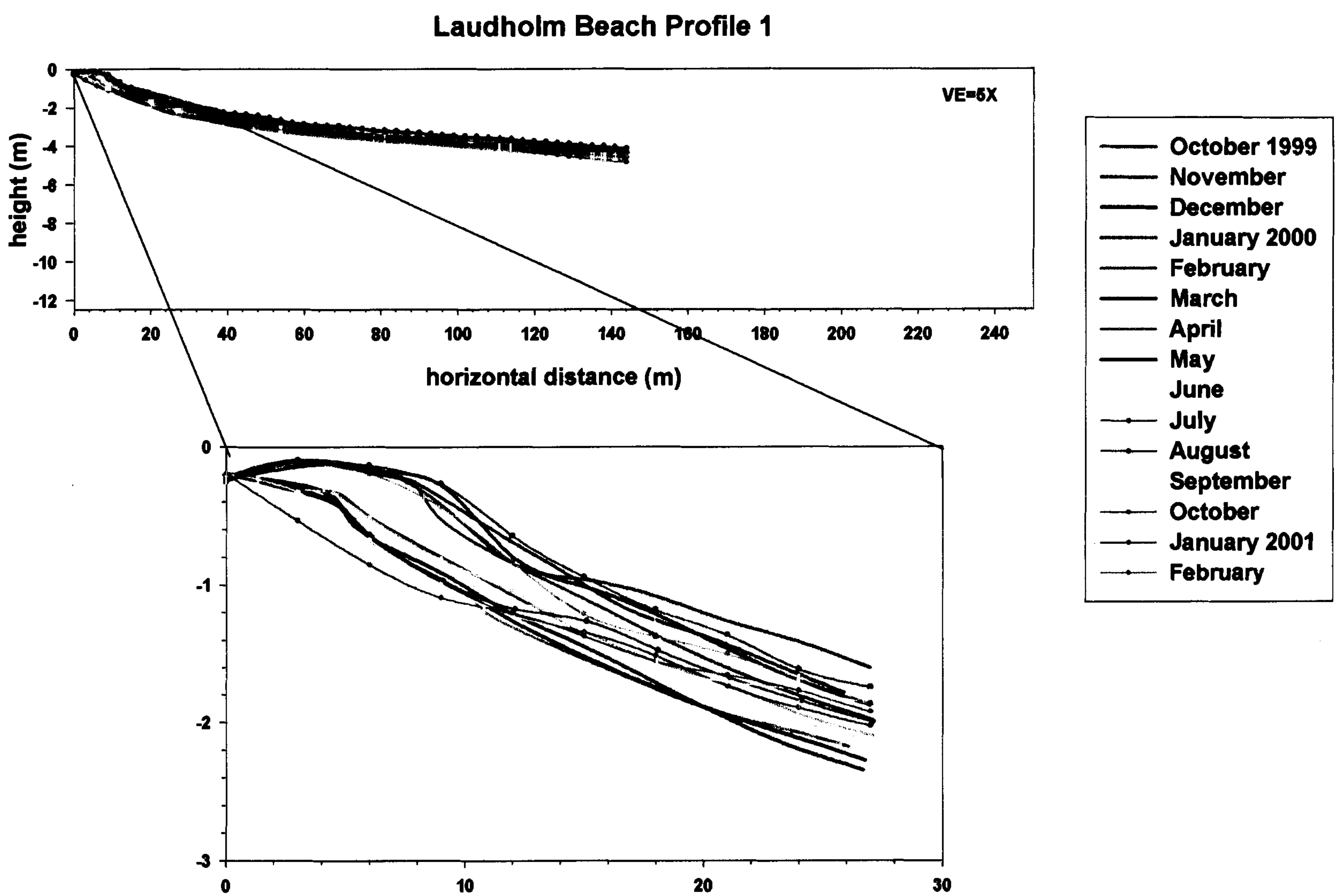


Figure B.83. Laudholm Beach Profile 1 monthly topographic changes altered to same length.

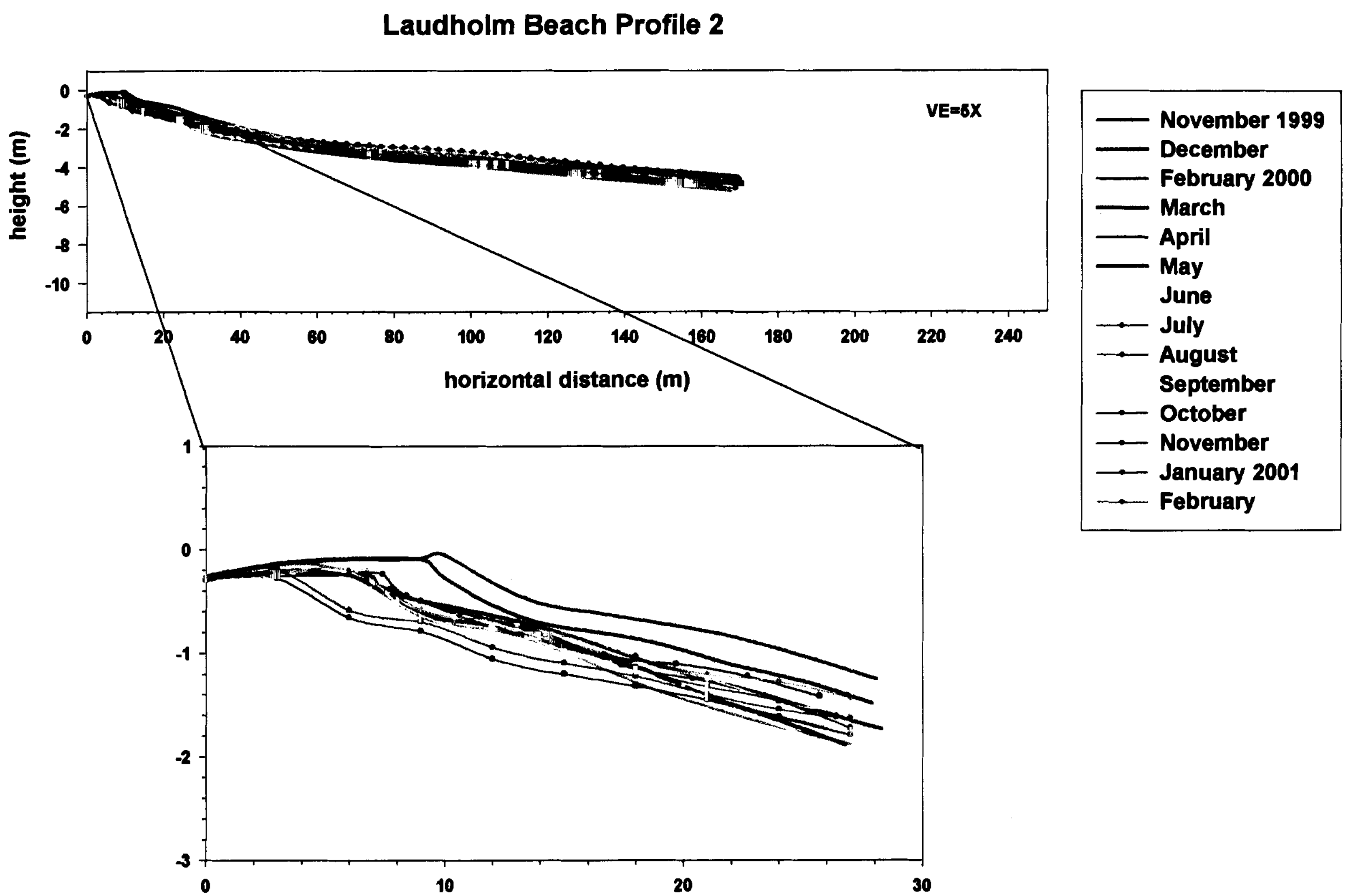


Figure B.84. Laudholm Beach Profile 2 monthly topograhic changes altered to same length.

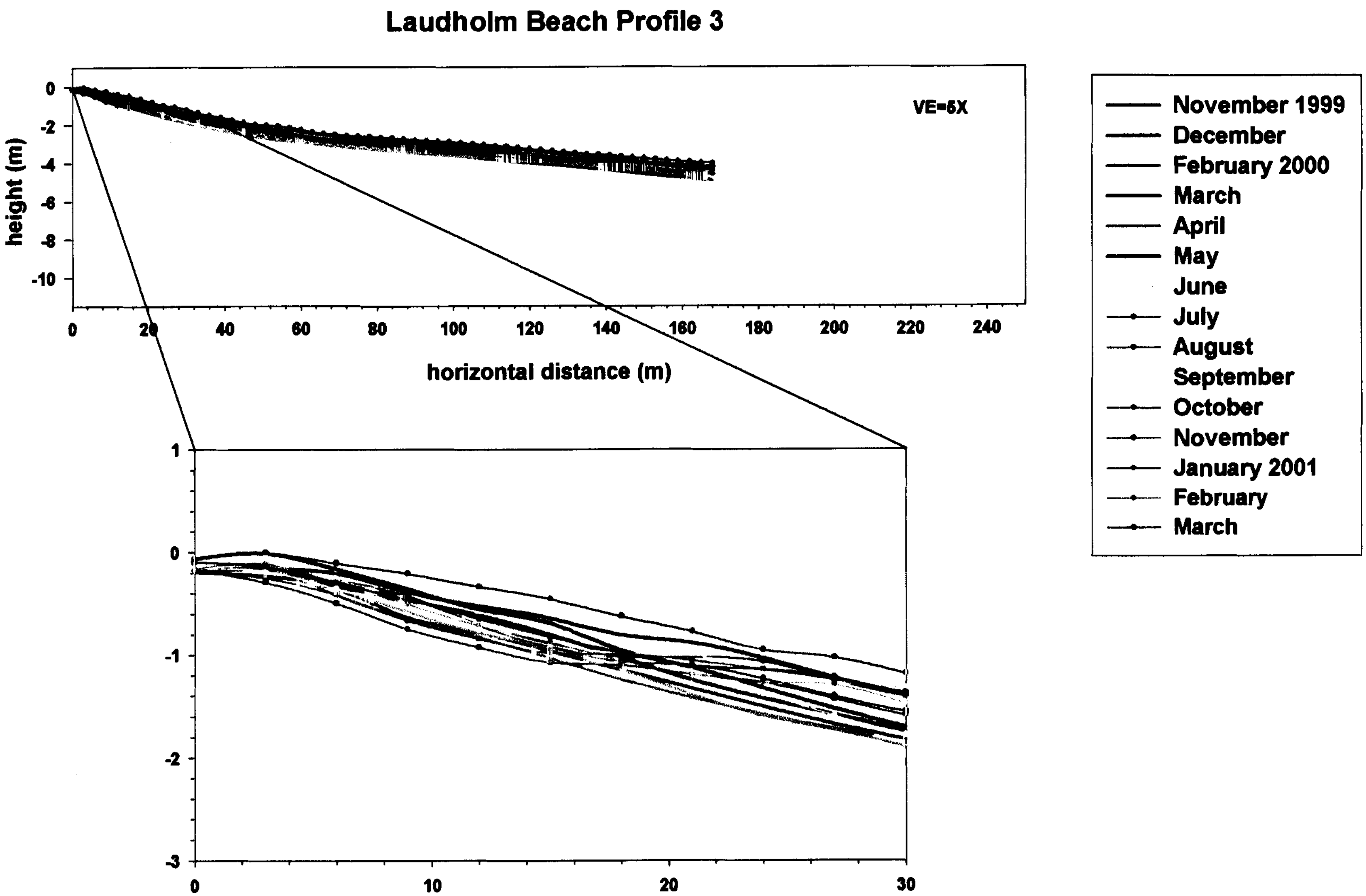


Figure B.85. Laudholm Beach Profile 3 monthly topographic changes altered to same length.

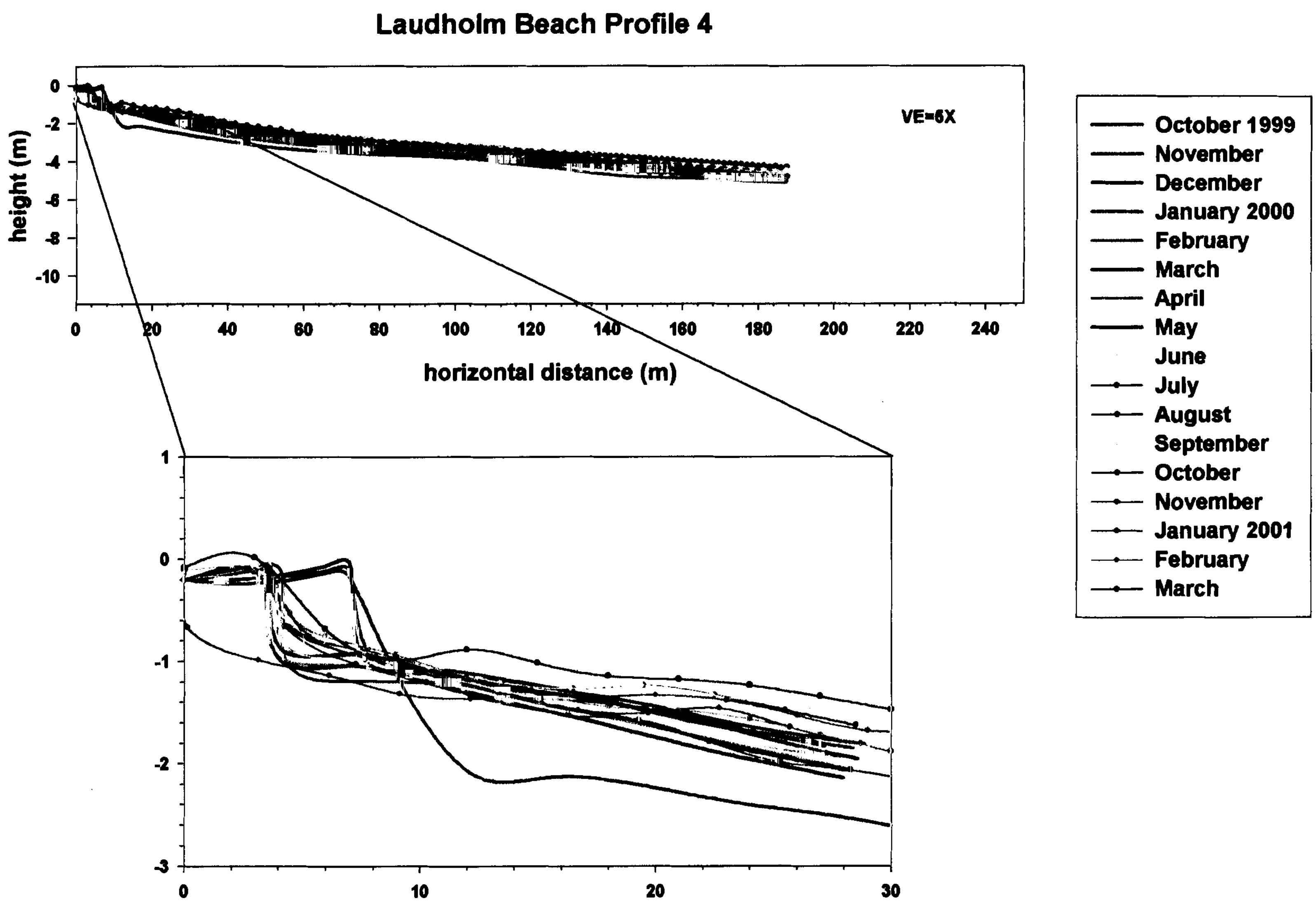


Figure B.86. Laudholm Beach Profile 4 monthly topographic changes altered to same length.

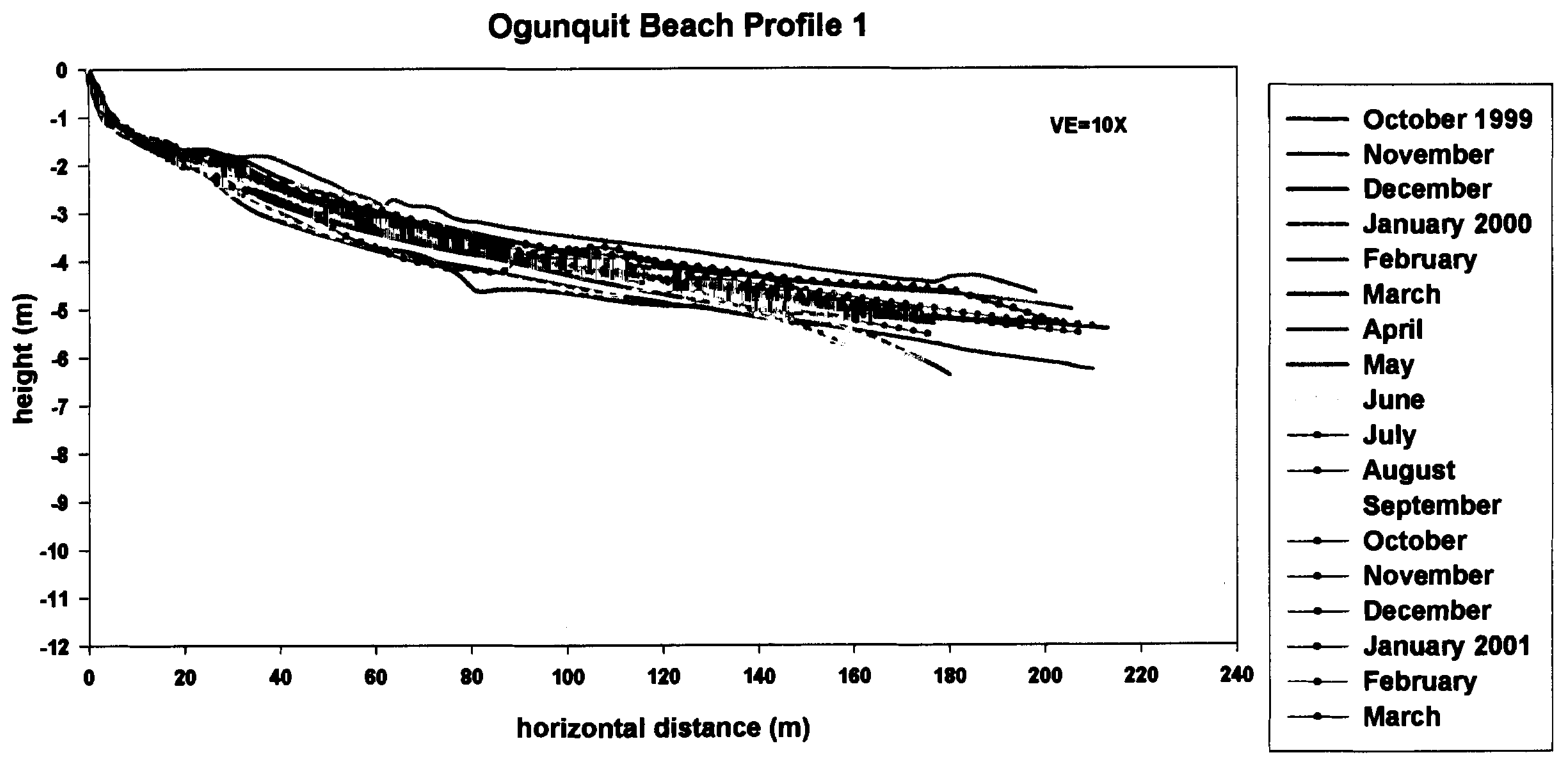


Figure B.87. Ogunquit Beach Topographic Profile 1 original measurements.

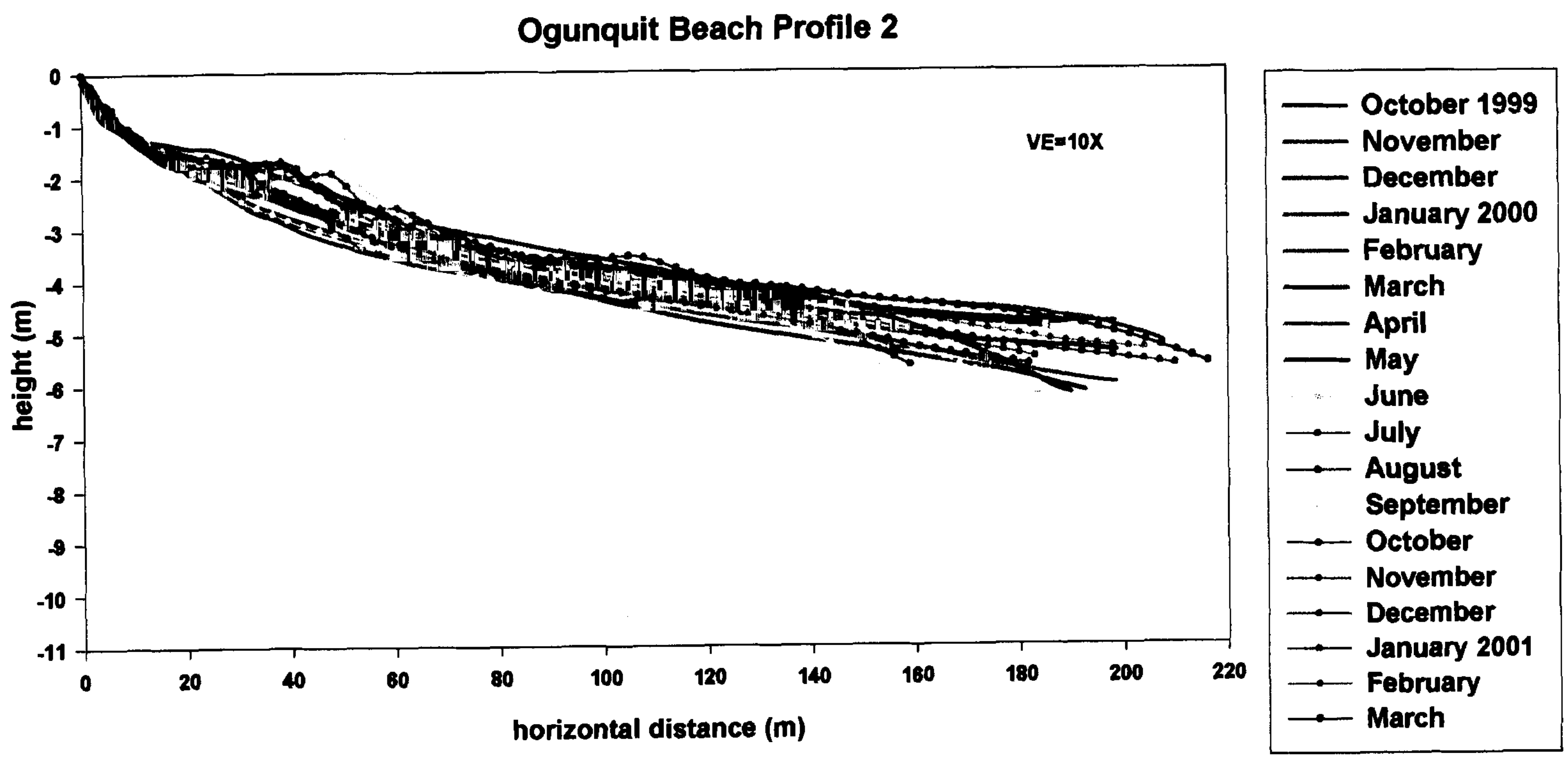


Figure B.88. Ogunquit Beach Topographic Profile 2 original measurements.

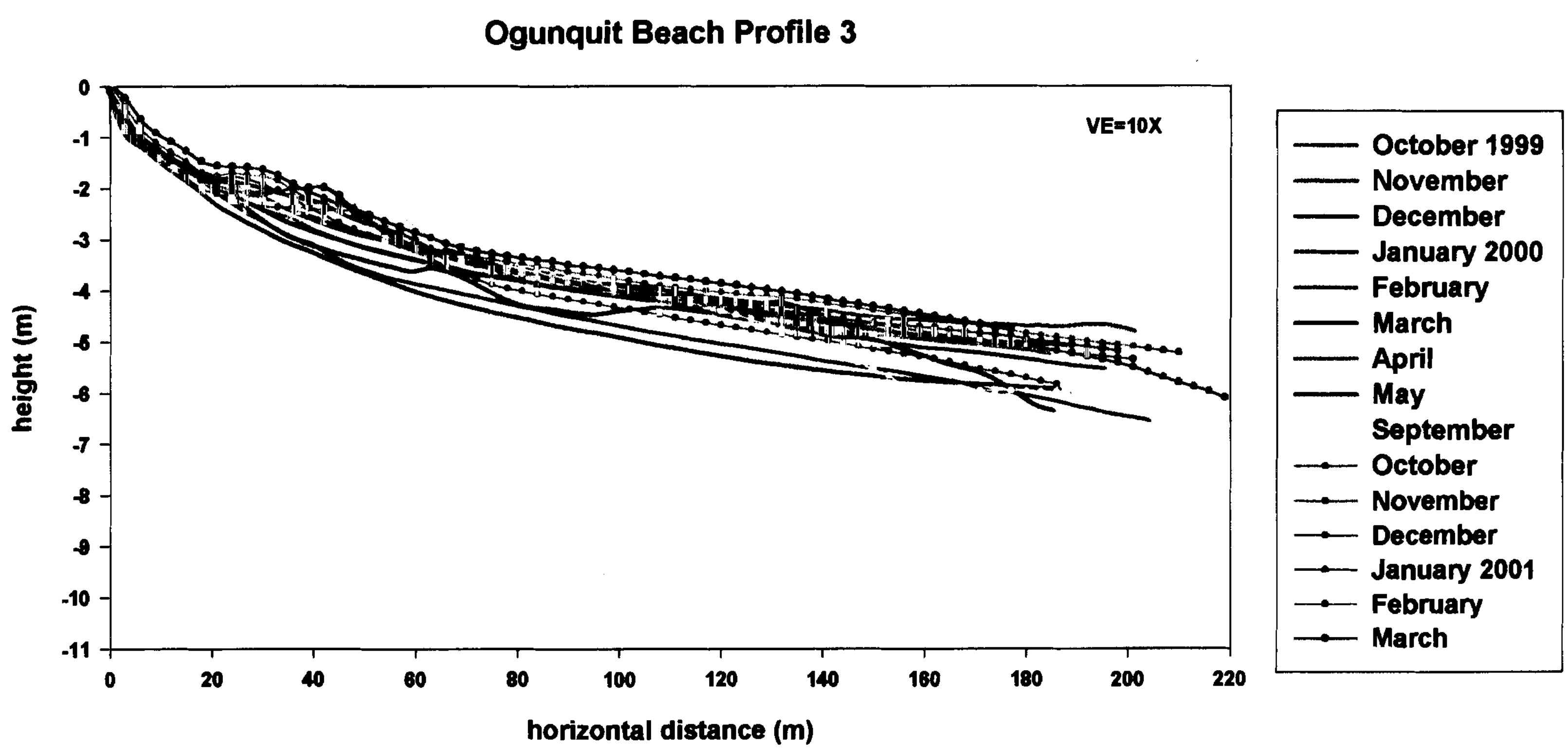


Figure B.89. Ogunquit Beach Topographic Profile 3 original measurements.

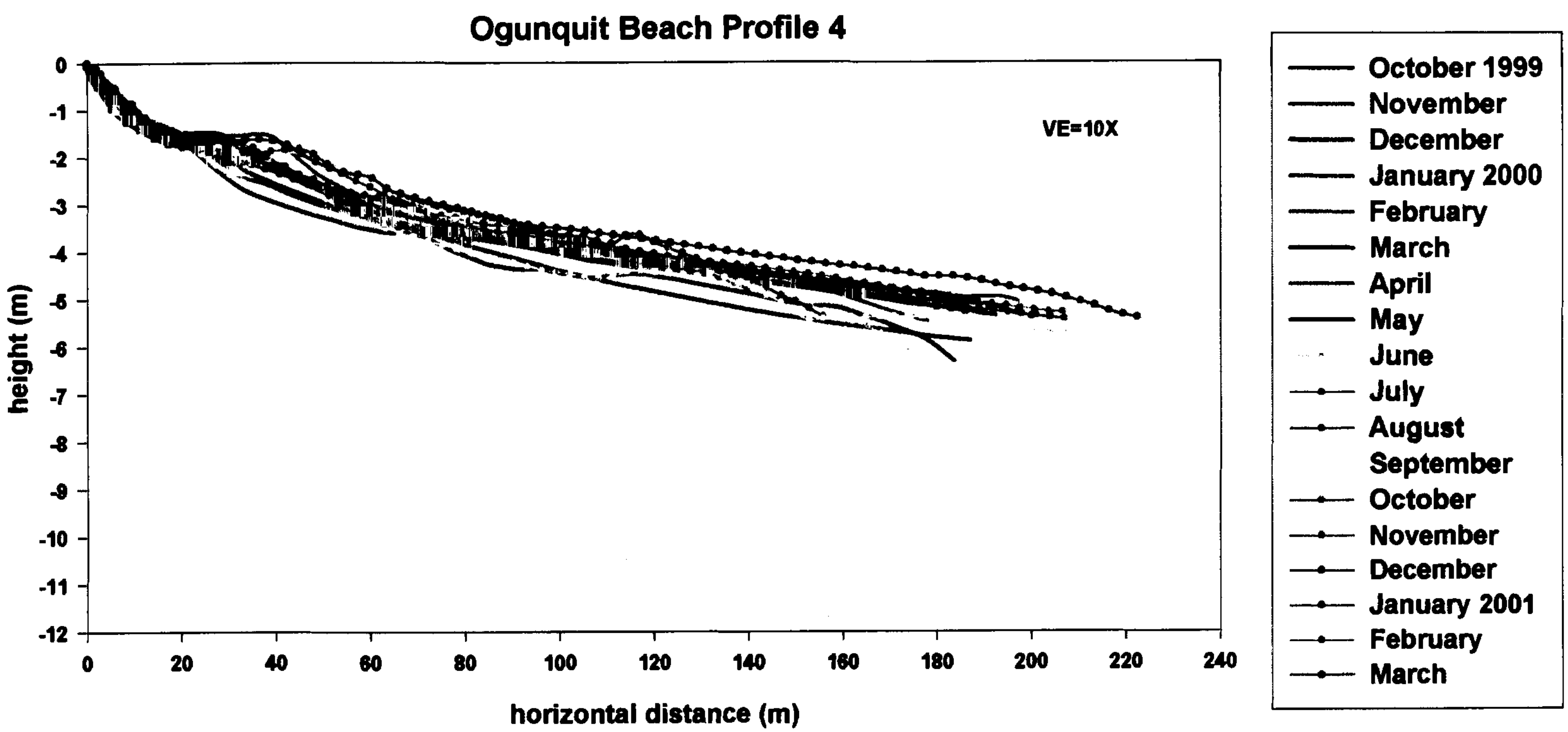


Figure B.90. Ogunquit Beach Topographic Profile 4 original measurements.

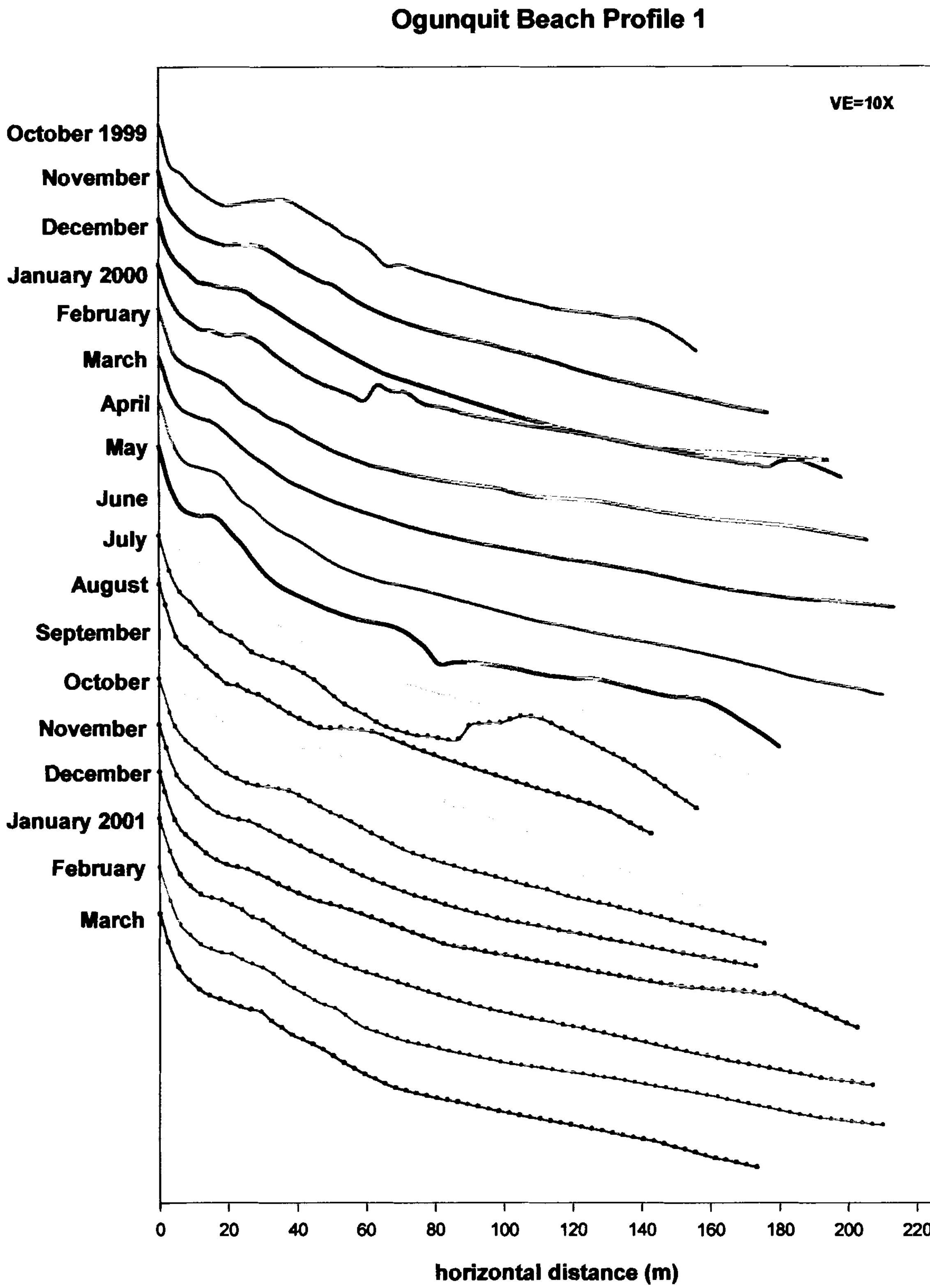


Figure B.91. Oguinquit Beach Profile 1 monthly topographic changes.

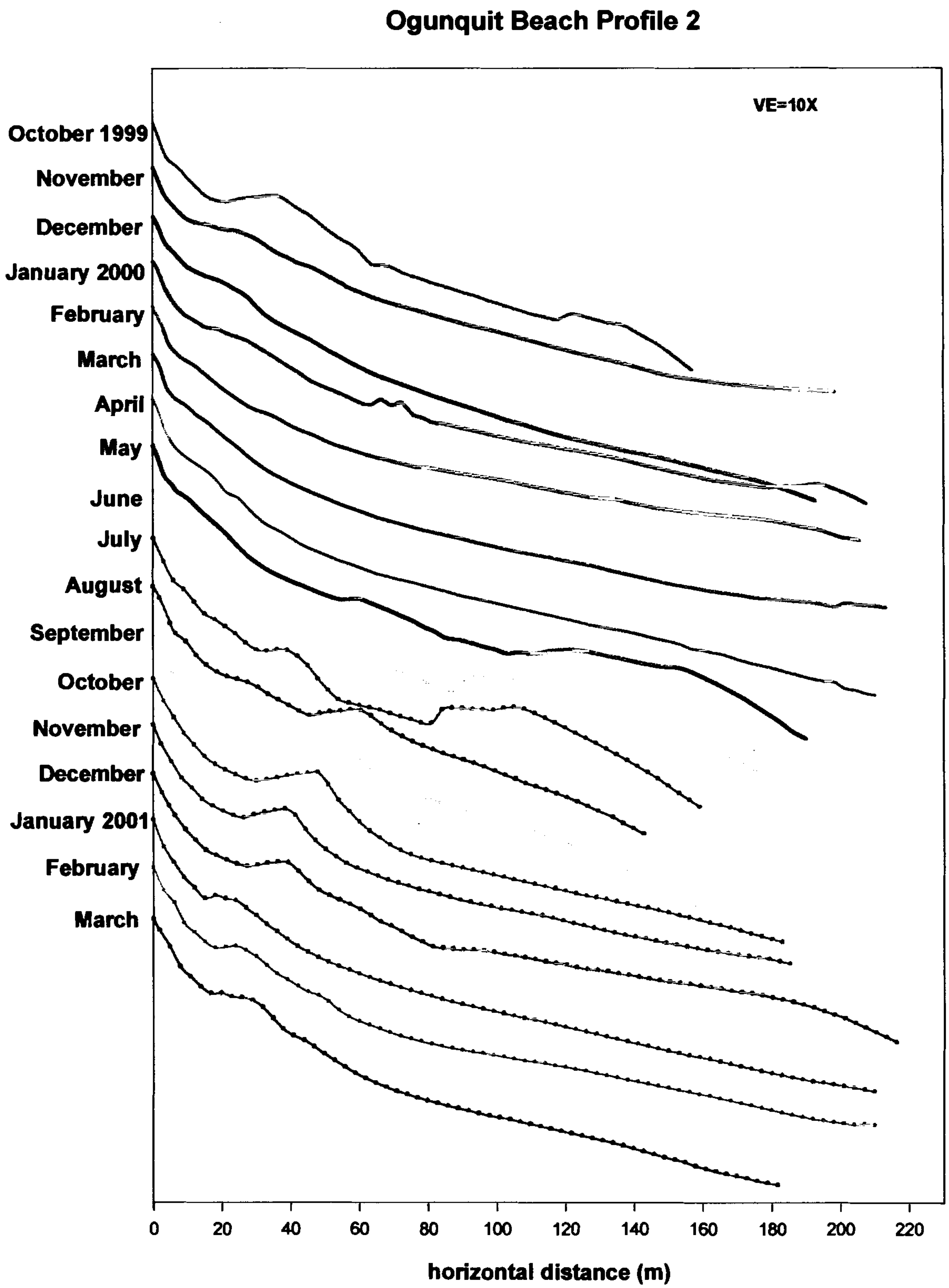


Figure B.92. Ogunquit Beach Profile 2 monthly topographic changes.

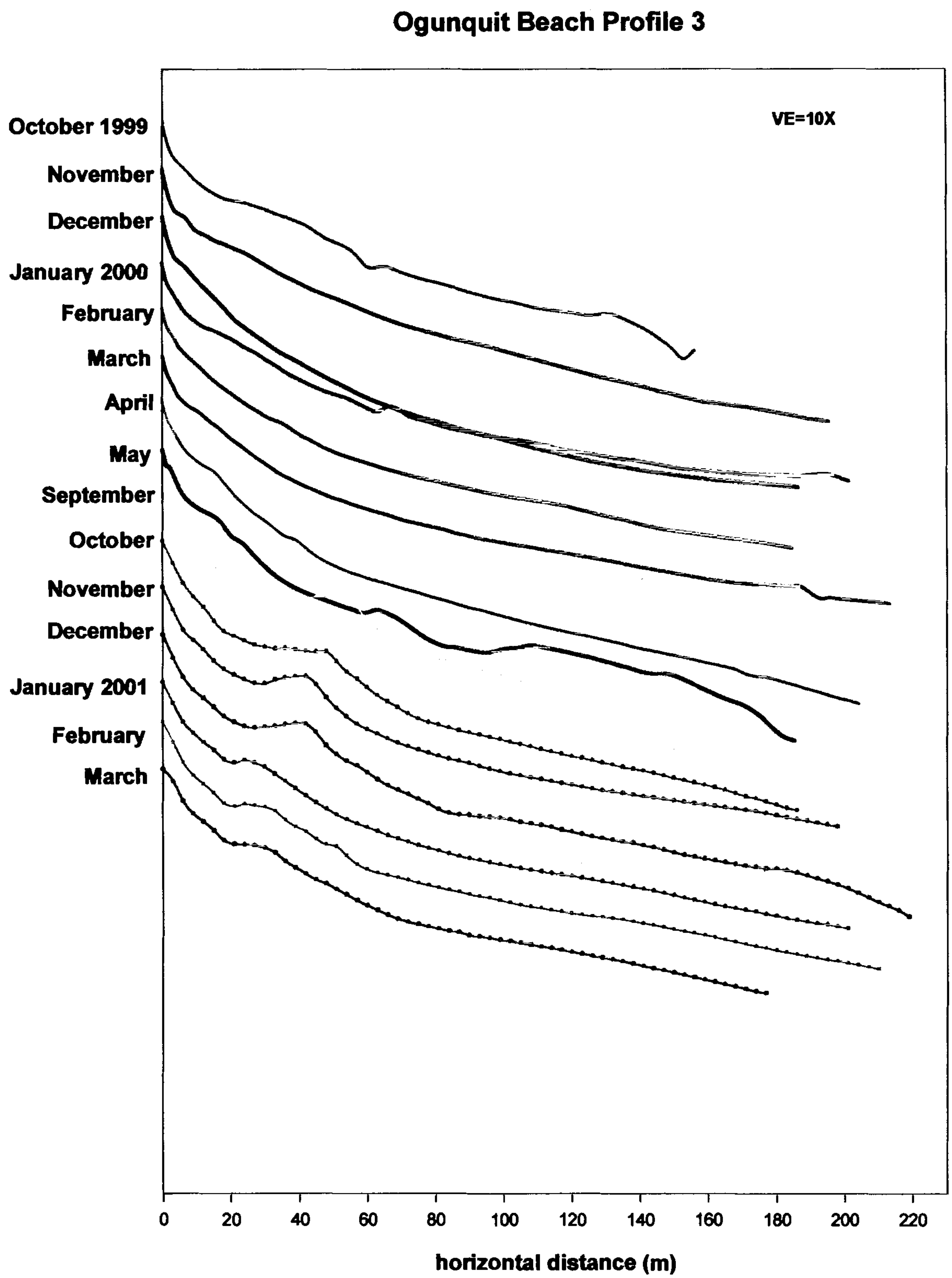


Figure B.93. Ogunquit Beach Profile 3 monthly topographic changes.

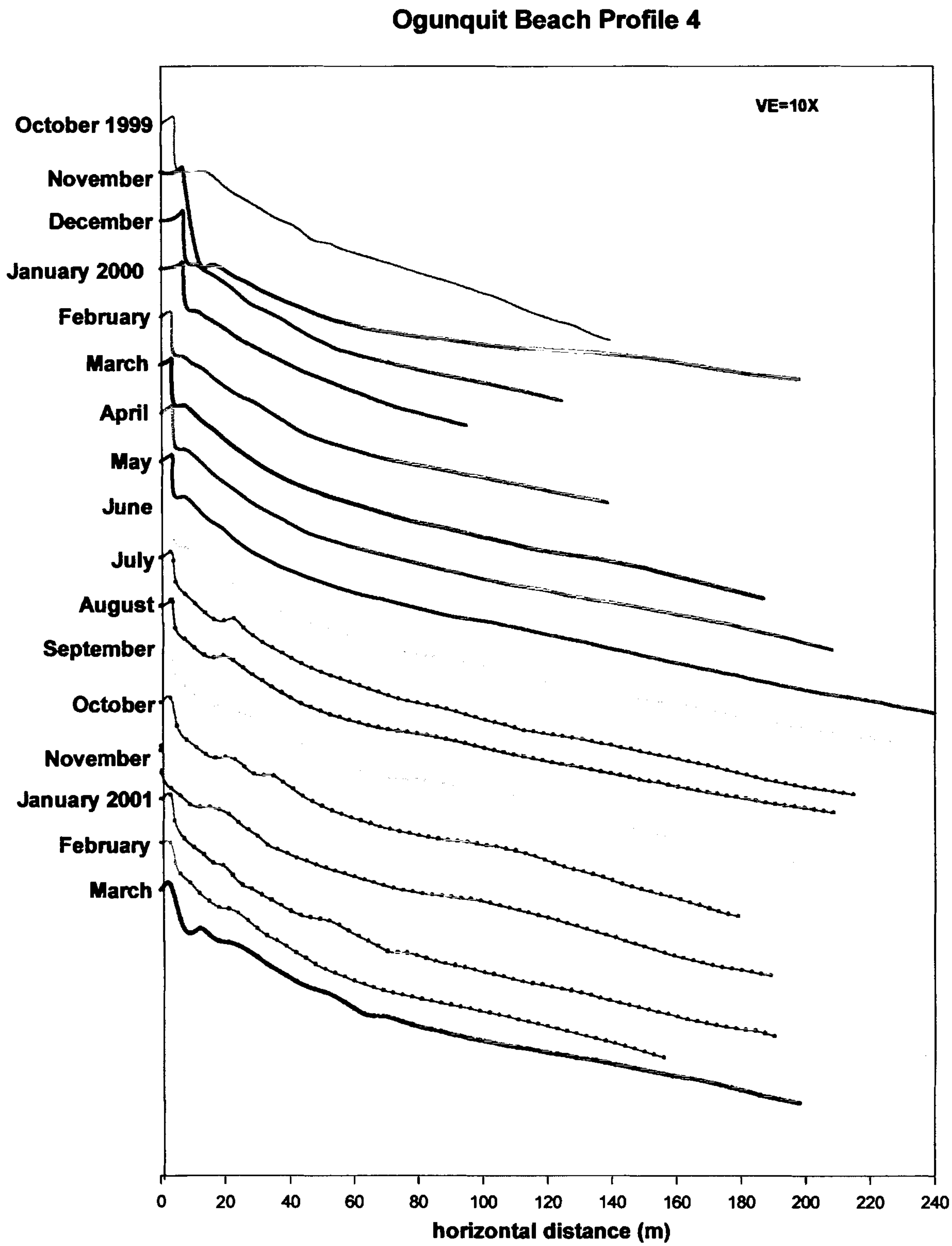


Figure B.94. Ogunquit Beach Profile 4 monthly topographic changes.

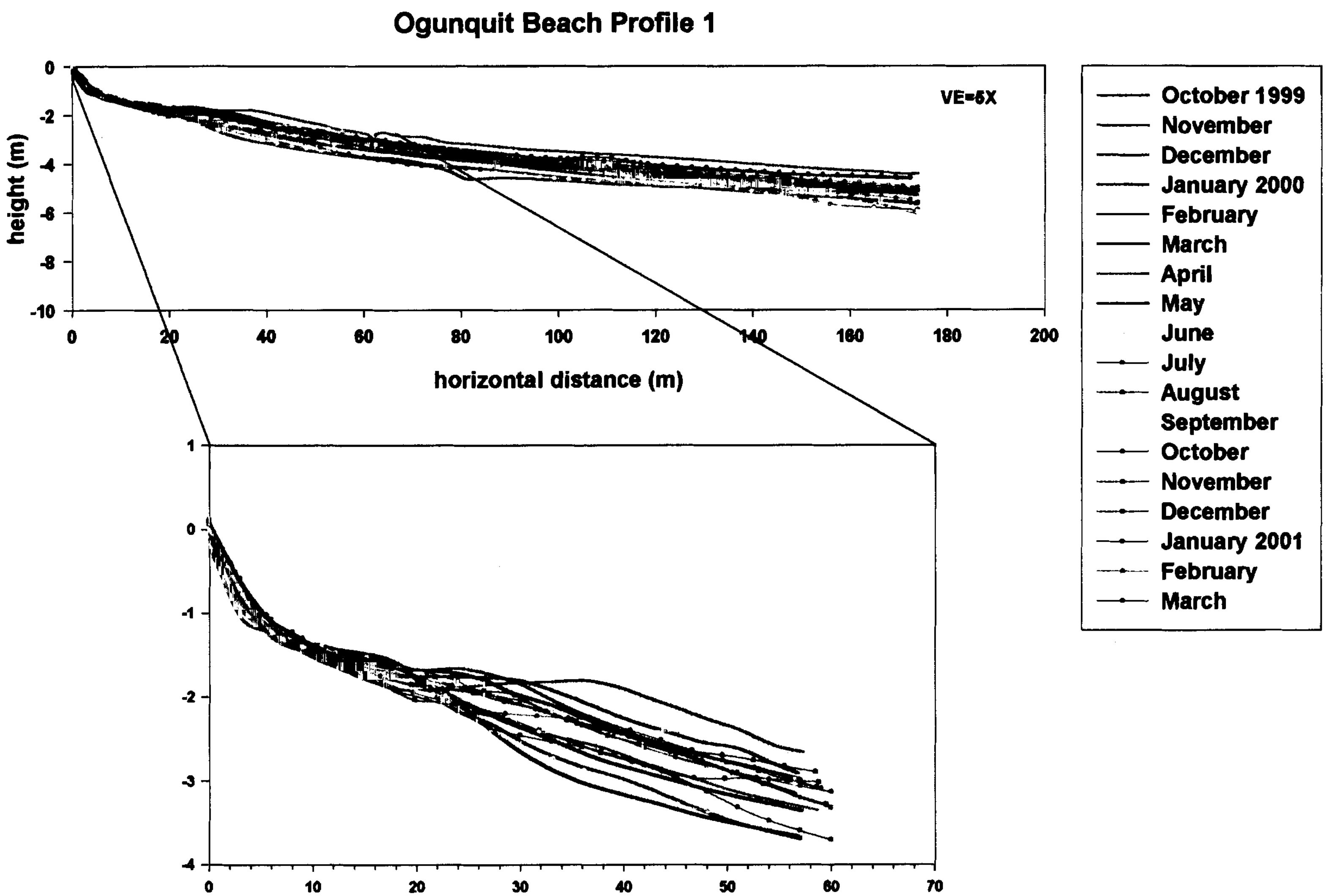


Figure B.95. Ogunquit Beach Profile 1 monthly topographic changes altered to same length.

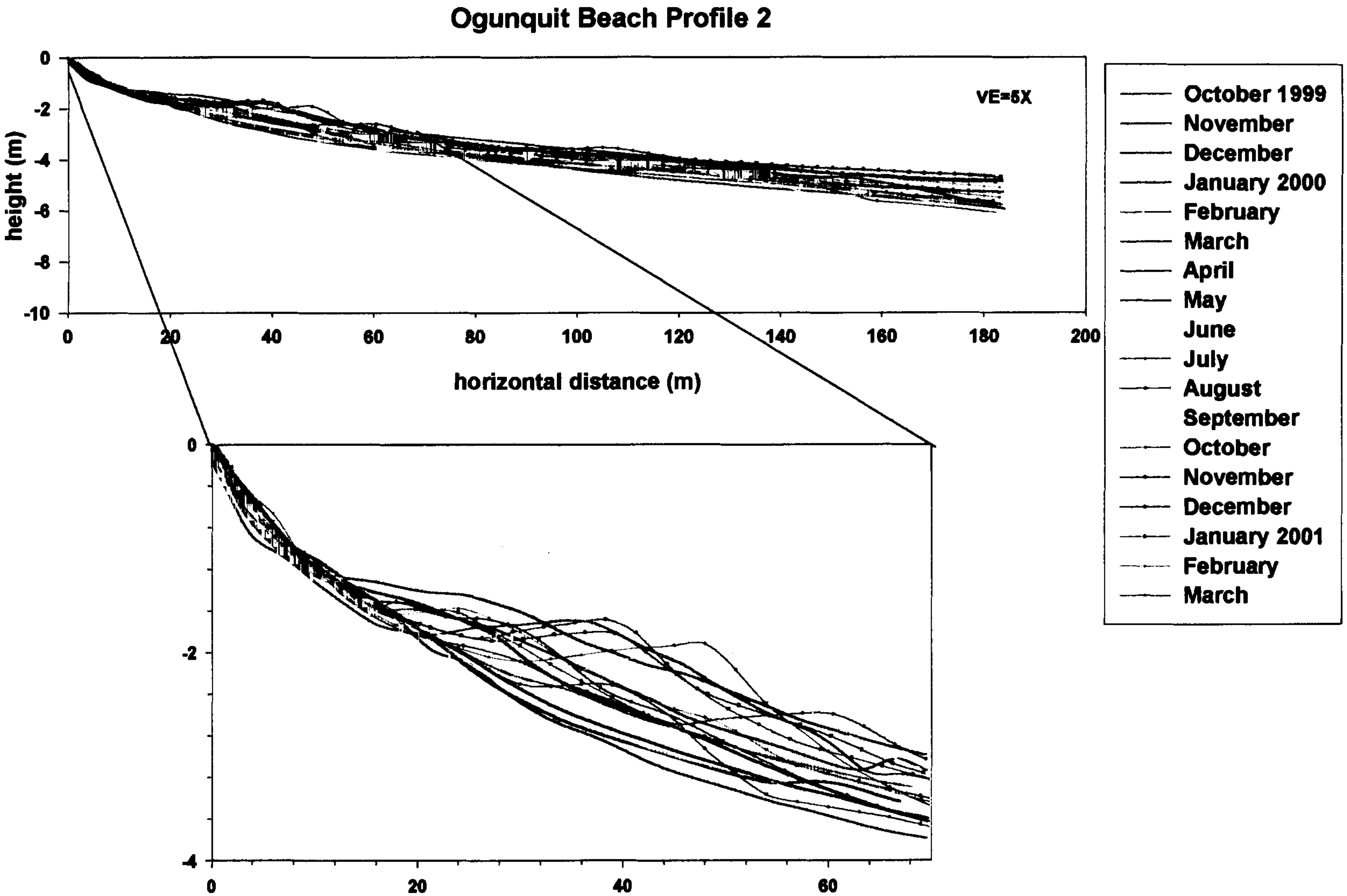


Figure B.96. Ogunquit Beach Profile 2 monthly topographic changes altered to same length.

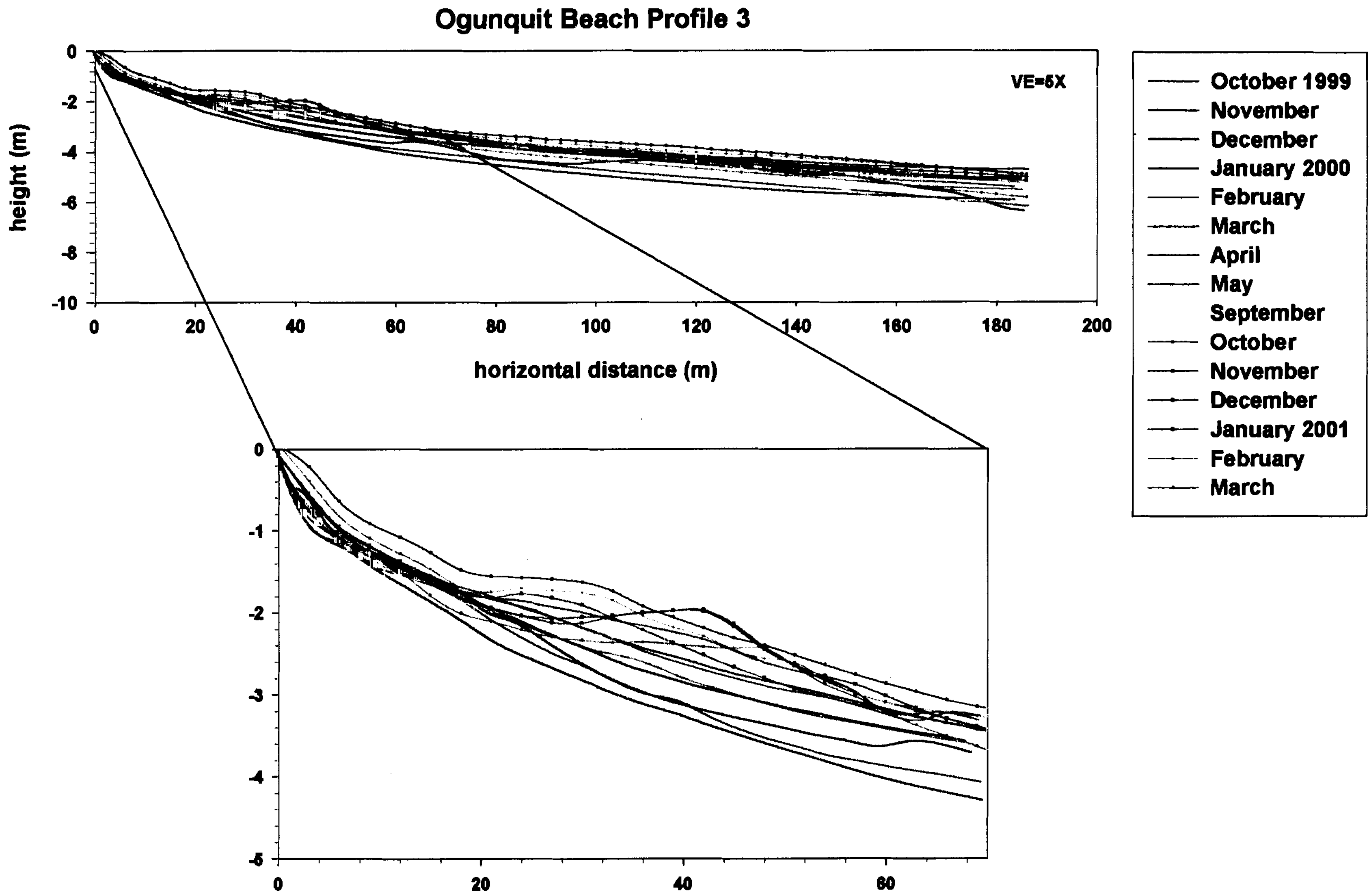


Figure B.97. Ogunquit Beach Profile 3 monthly topographic changes altered to same length.

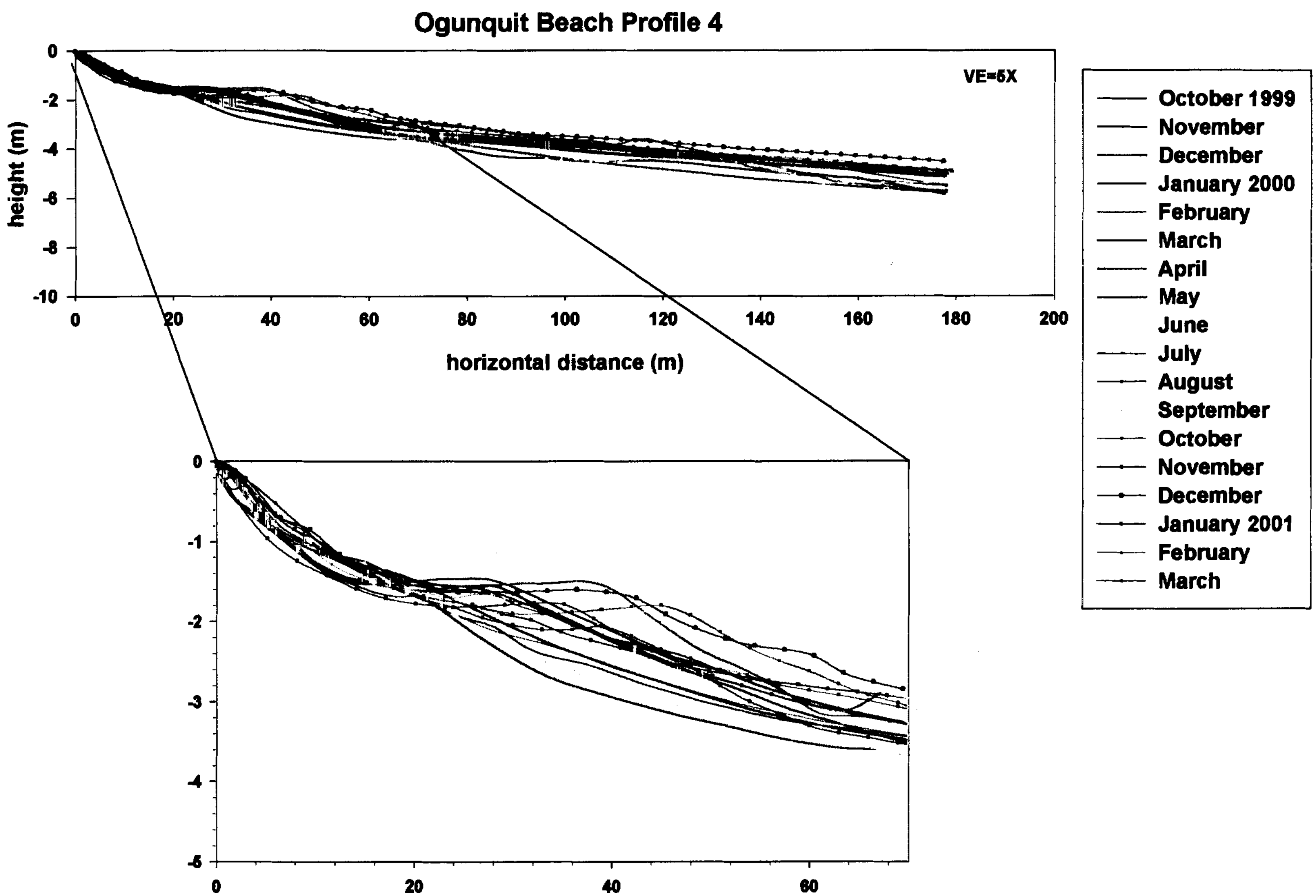
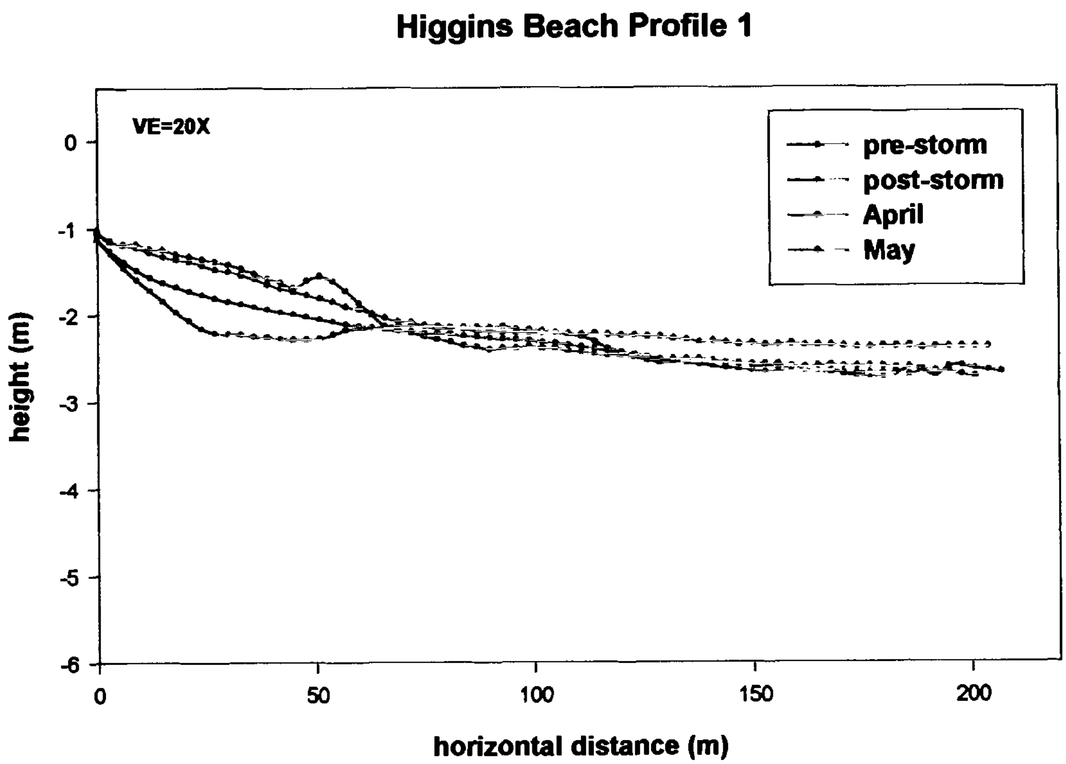


Figure B.98. Ogunquit Beach Profile 4 monthly topographic changes altered to same length.

Appendix C

TOPOGRAPHIC PROFILES FOLLOWING A STORM

Original topographic profile measurements, prior to, and following the March 5th-6th, 2001 northeast storm. Beaches were included where measurements were taken.



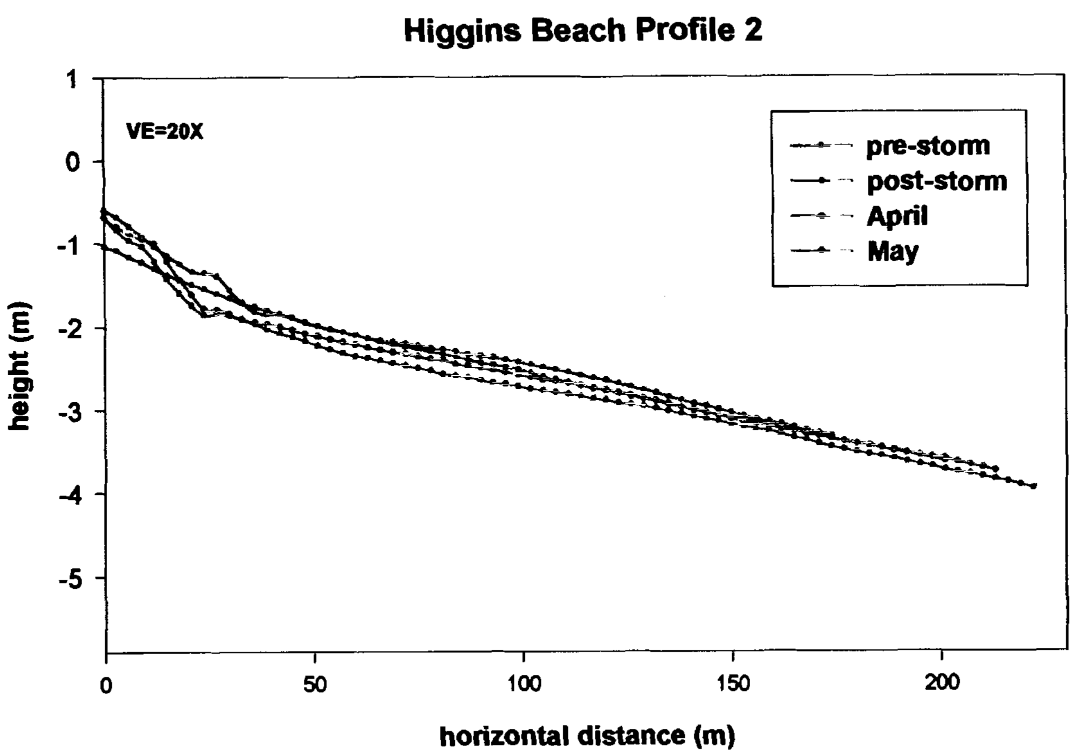


Figure C.1. Higgins Beach Profile 1 and Profile 2 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.

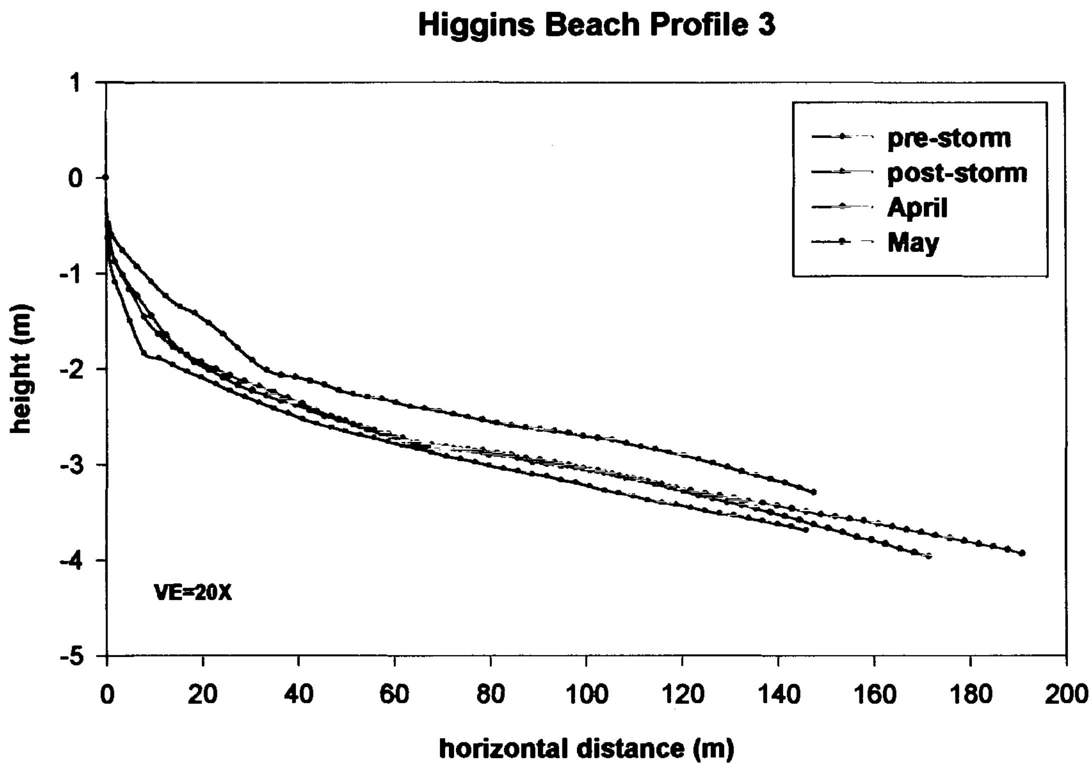
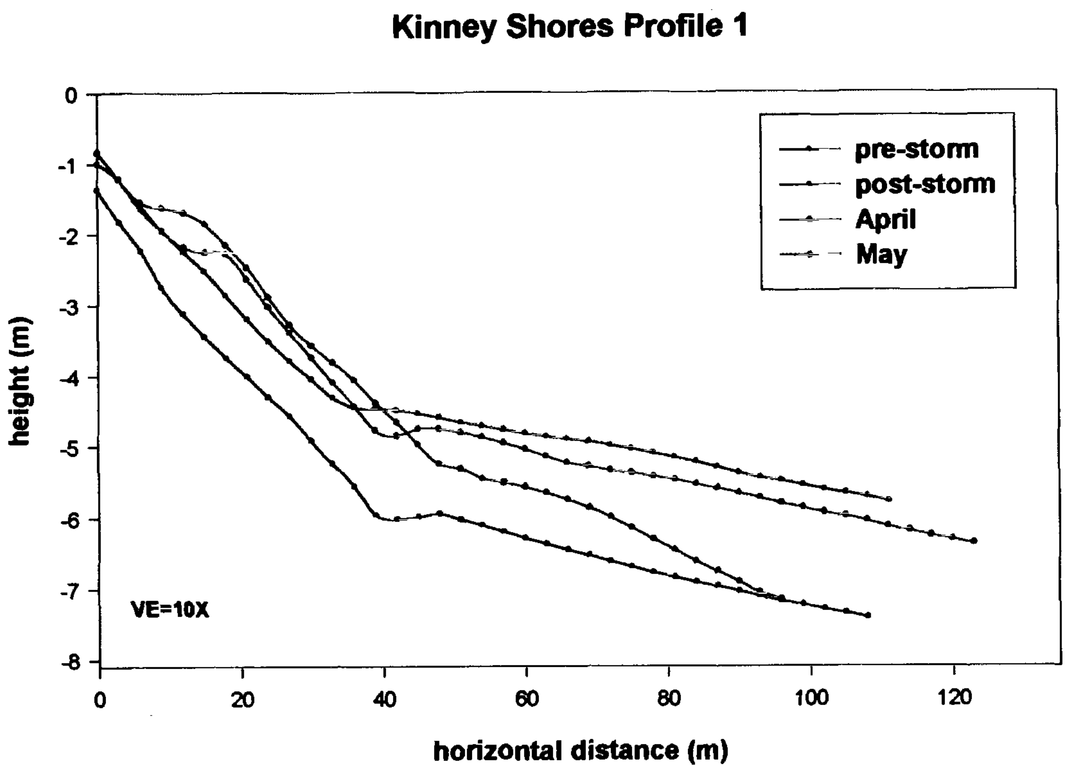


Figure C.2. Higgins Beach Profile 3 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.



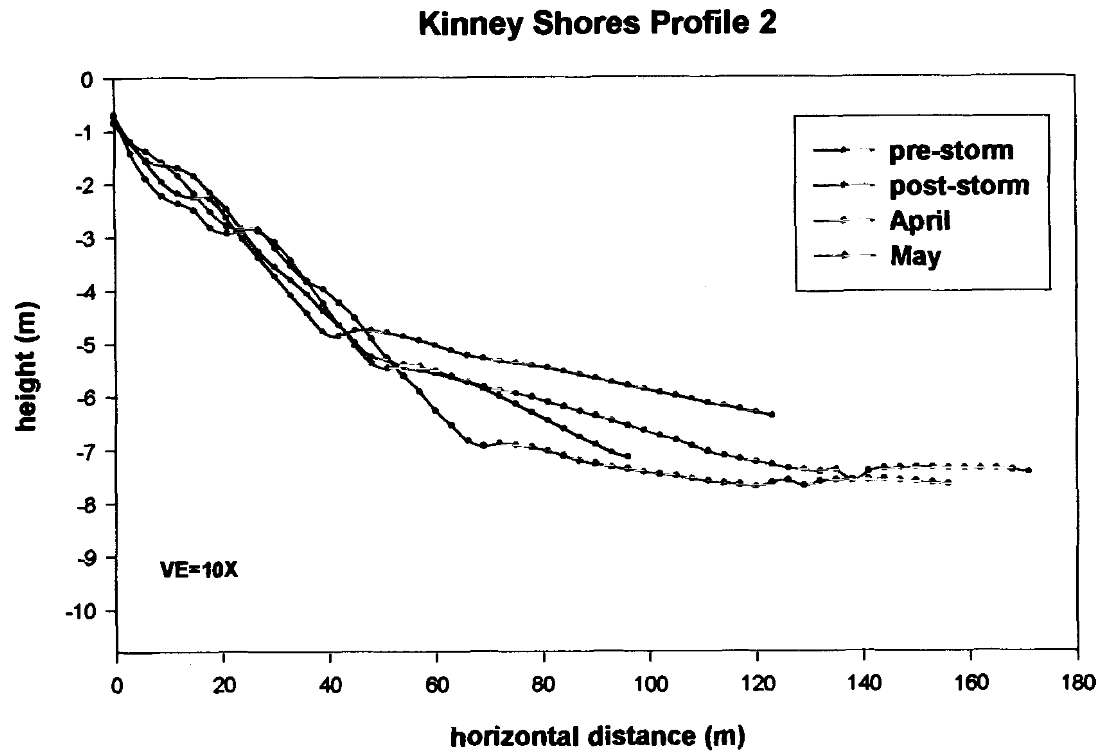
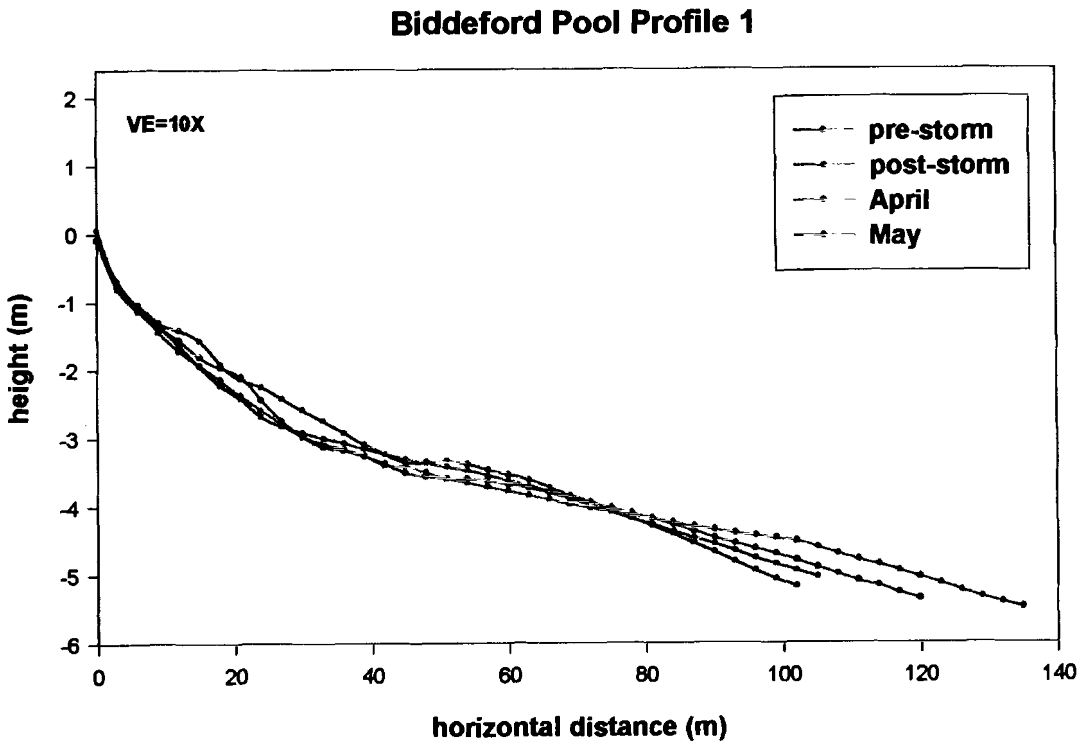


Figure C.3. Kinney Shores Profile 1 and Profile 2 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.



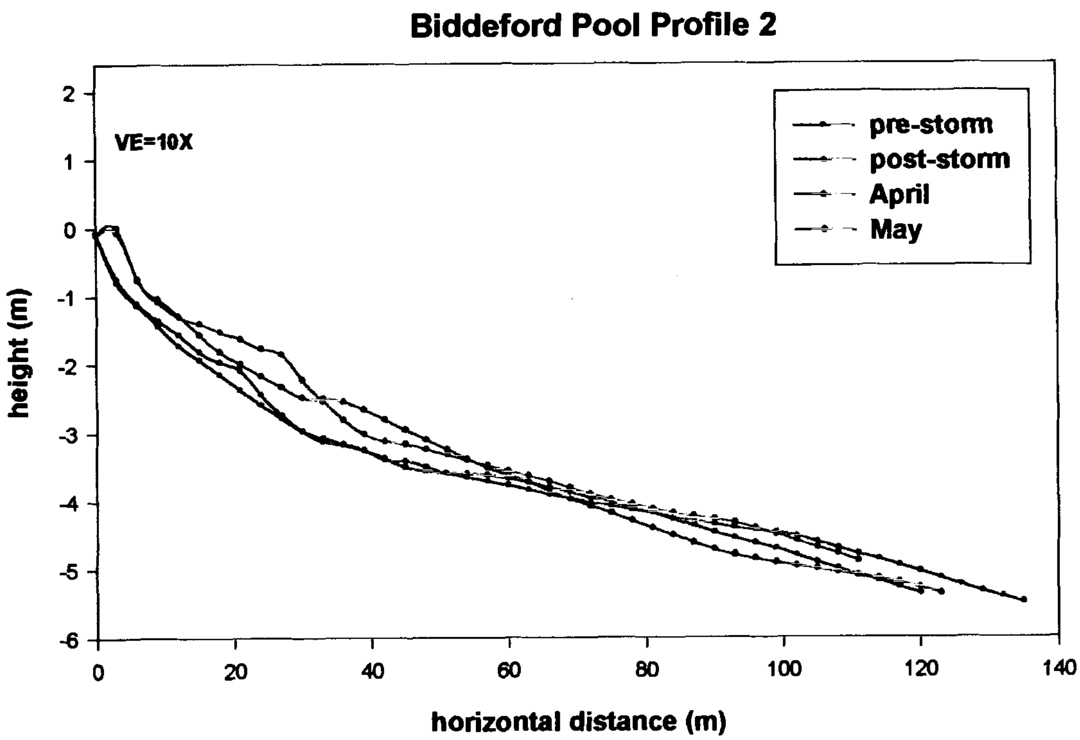
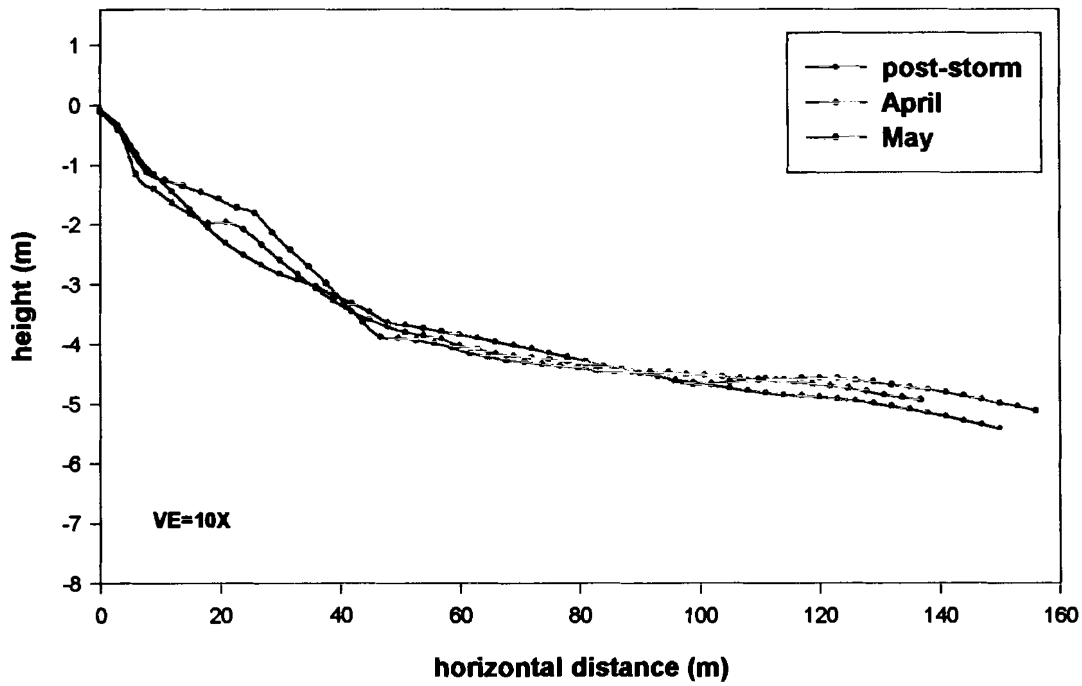


Figure C.4. Biddeford Pool Profile 1 and Profile 2 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.

Biddeford Pool Profile 3



Fortunes Rocks Profile 4

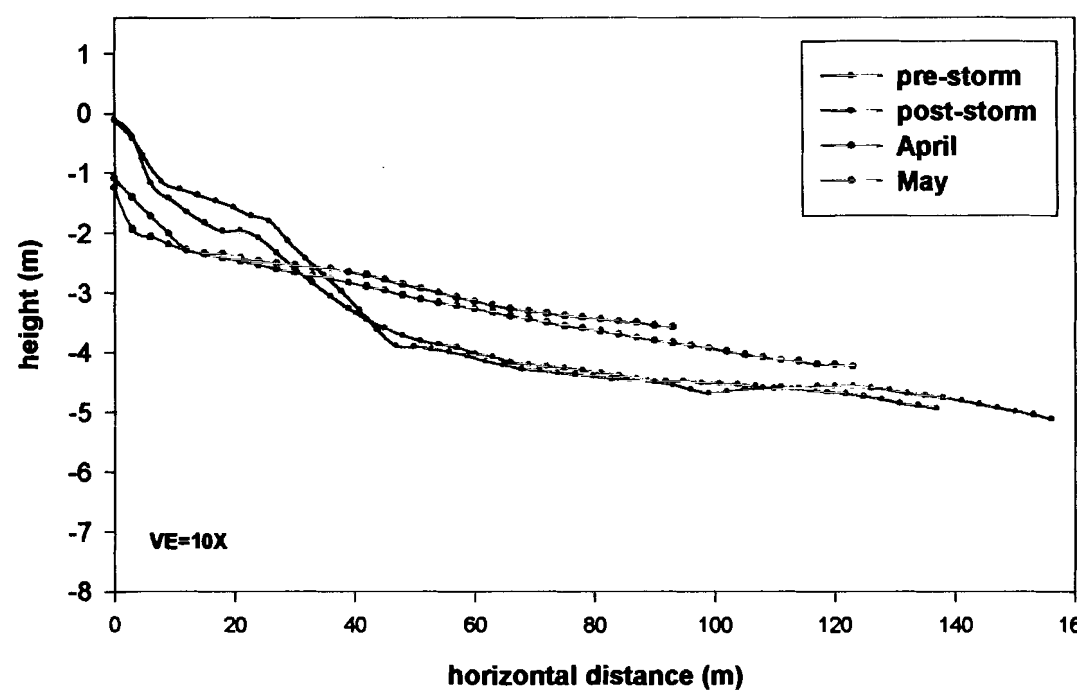
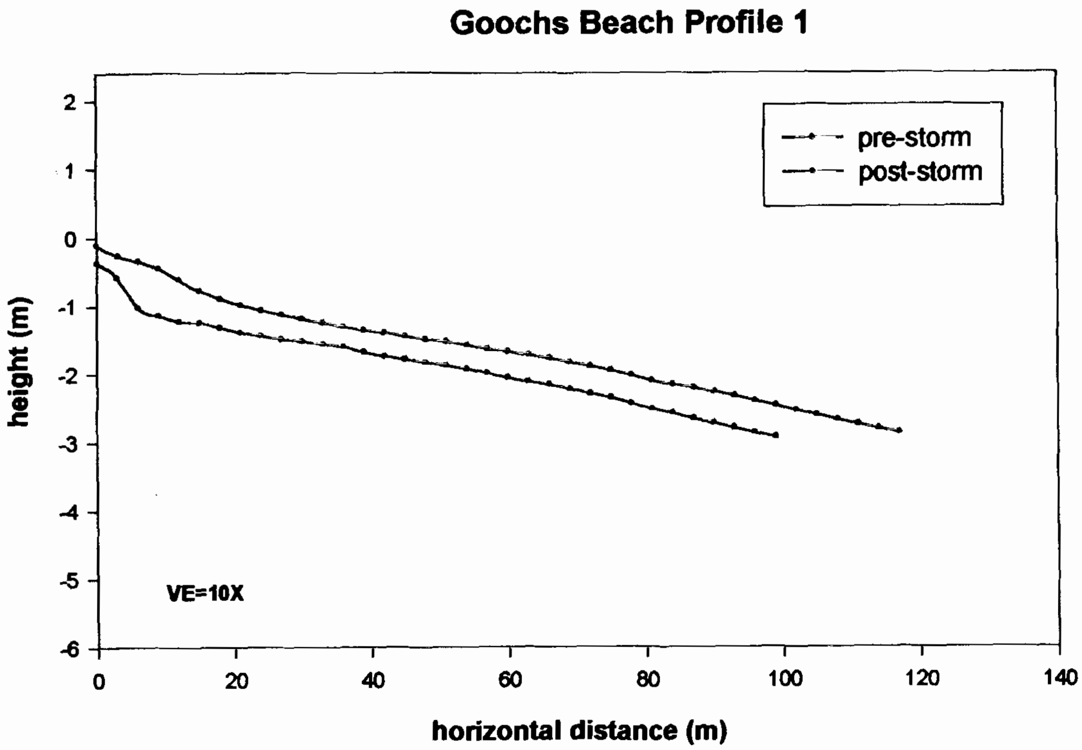


Figure C.5. Biddeford Pool Profile 3 and Profile 4 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.



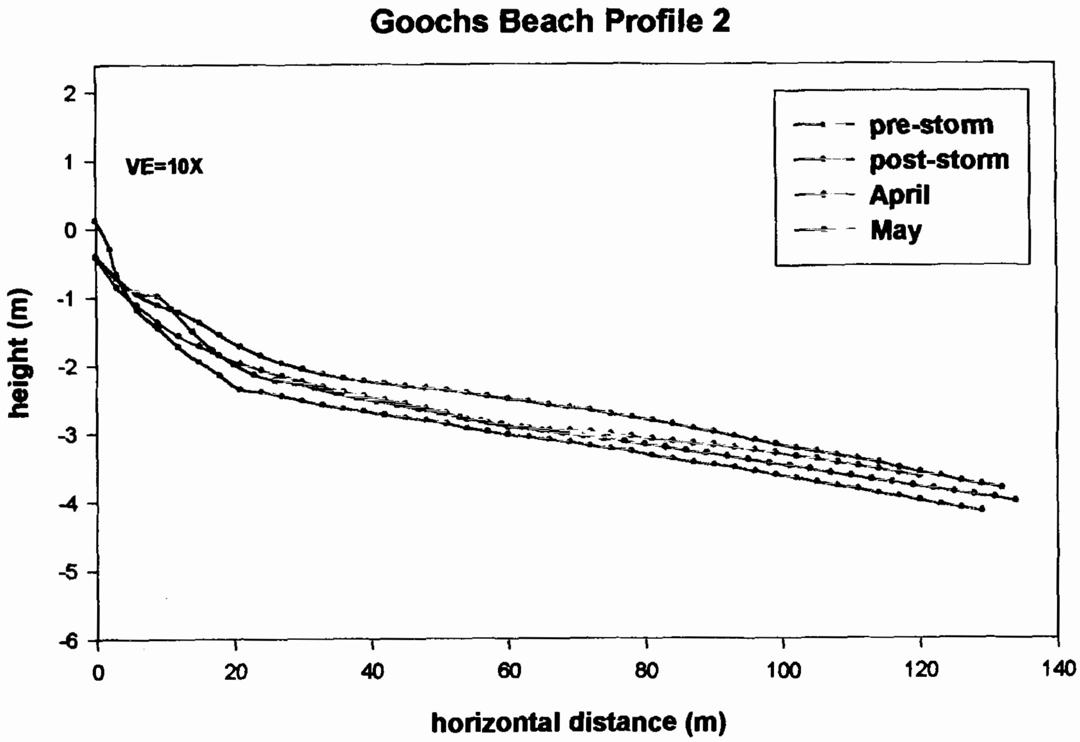
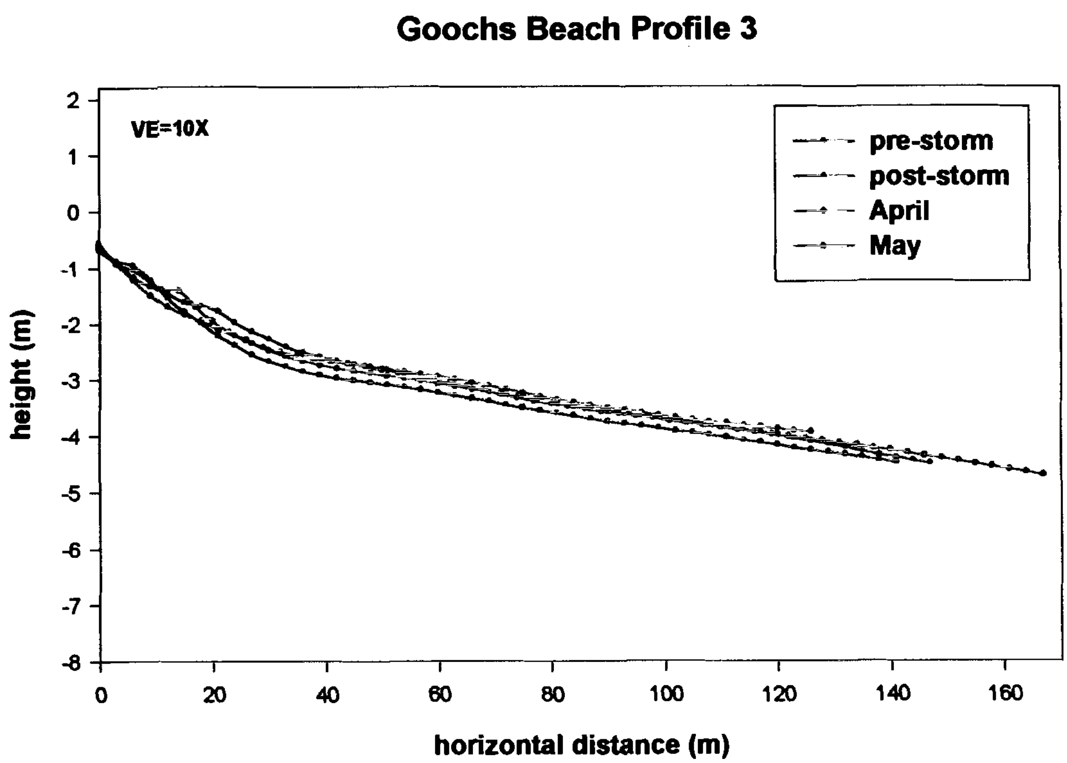


Figure C.6. Goochs Beach Profile 1 and Profile 2 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.



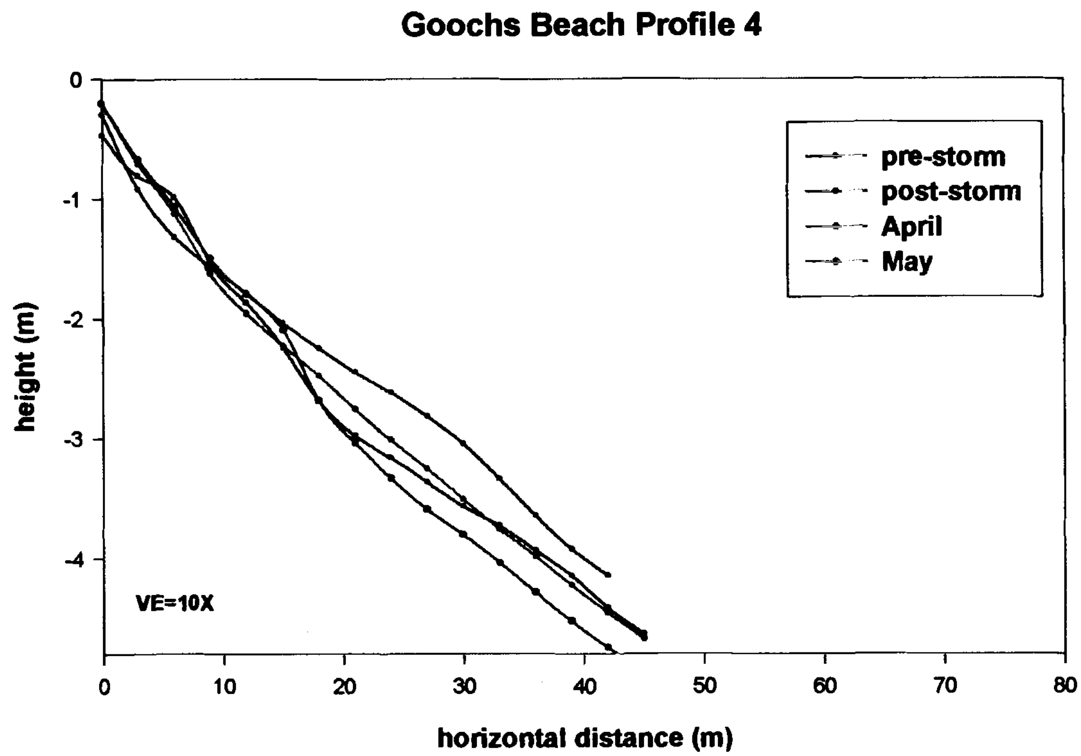
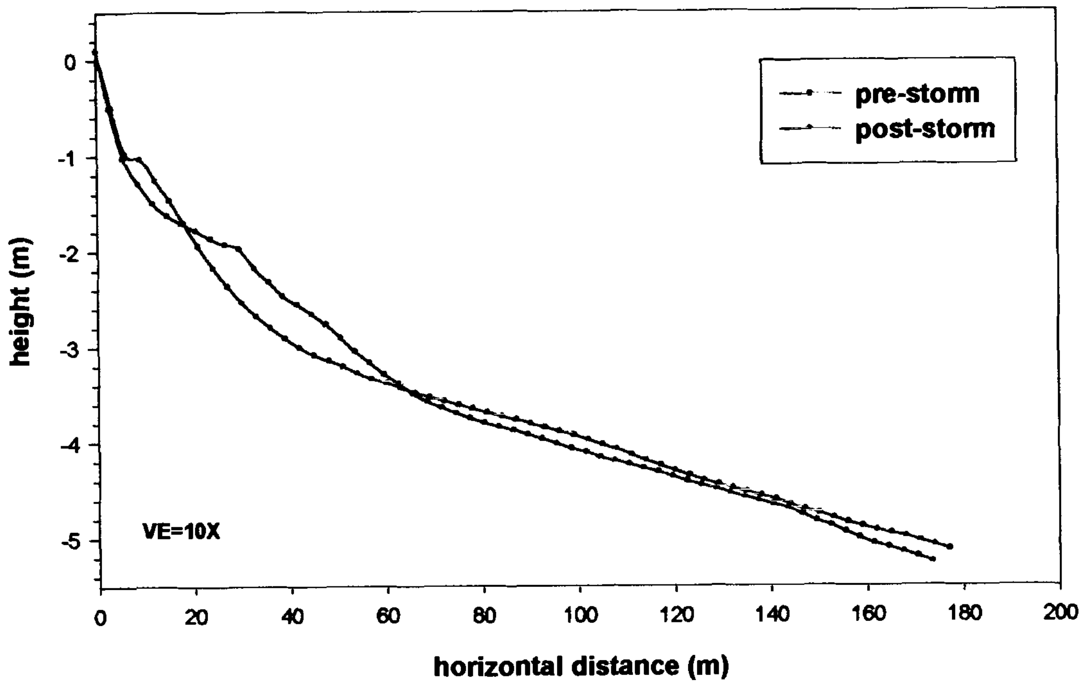


Figure C.7. Goochs Beach Profile 3 and Profile 4 before and after the northeast storm on March 5-6th, 2001. The pre and post-storm profiles were taken within a week of the storm.

Ogunquit Beach Profile 1



Ogunquit Beach Profile 2

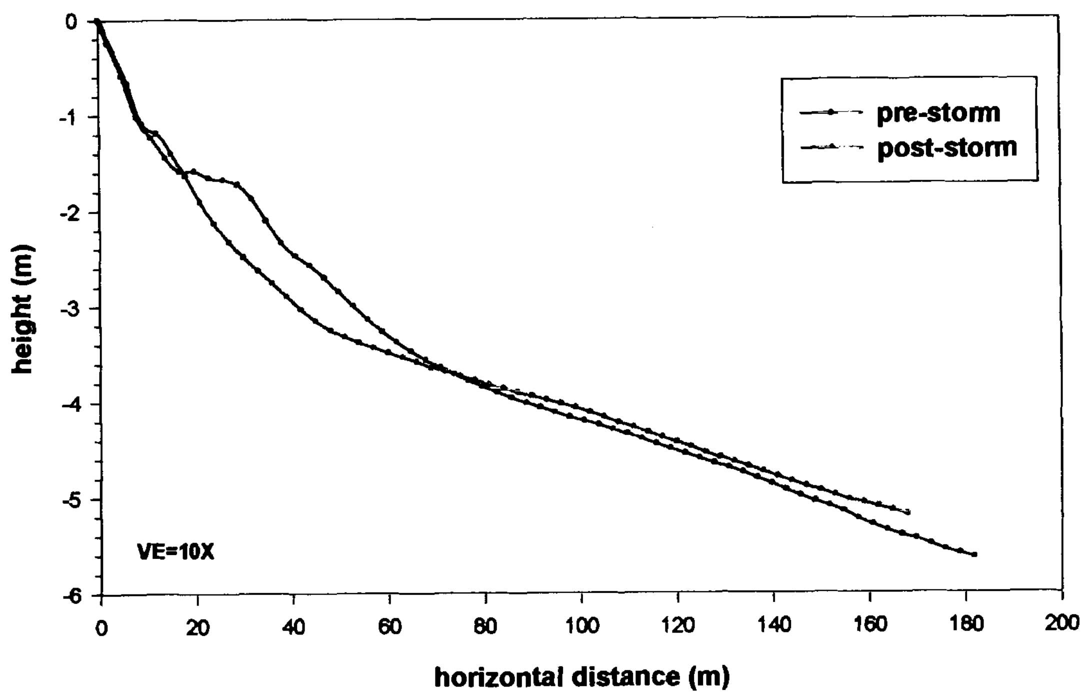
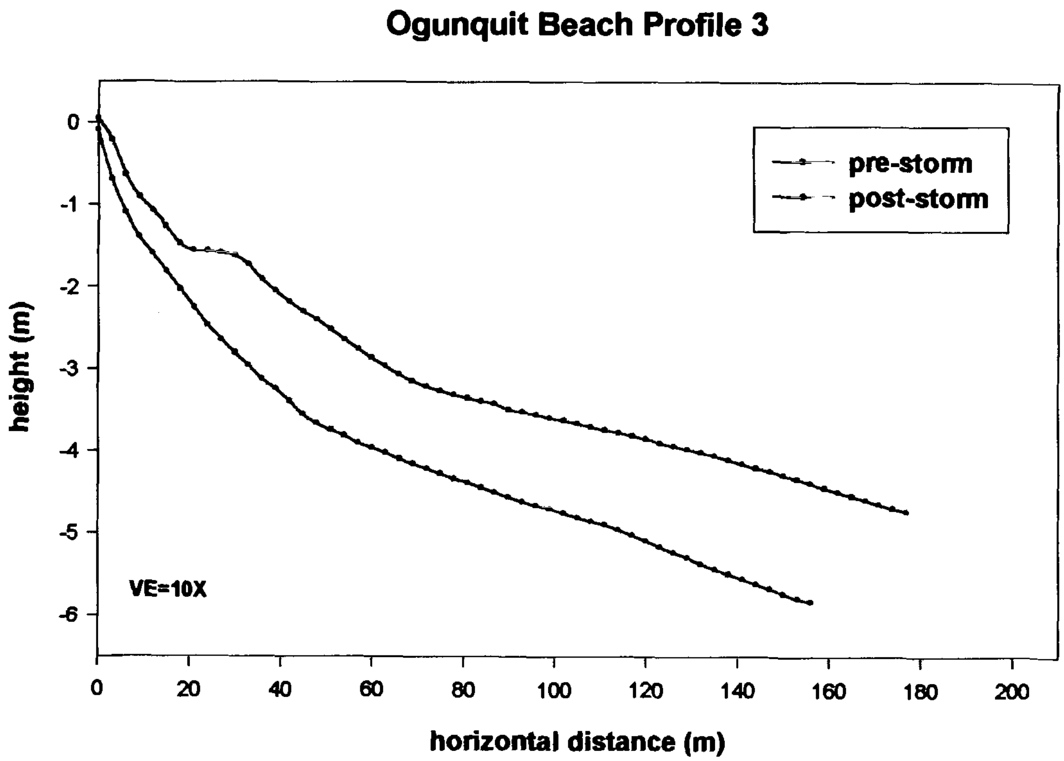


Figure C.8. Ogunquit Beach Profile 1 and Profile 2 before and after the northeast storm on March 5-6, 2001. The pre and post-storm profiles were taken within a week of the storm.



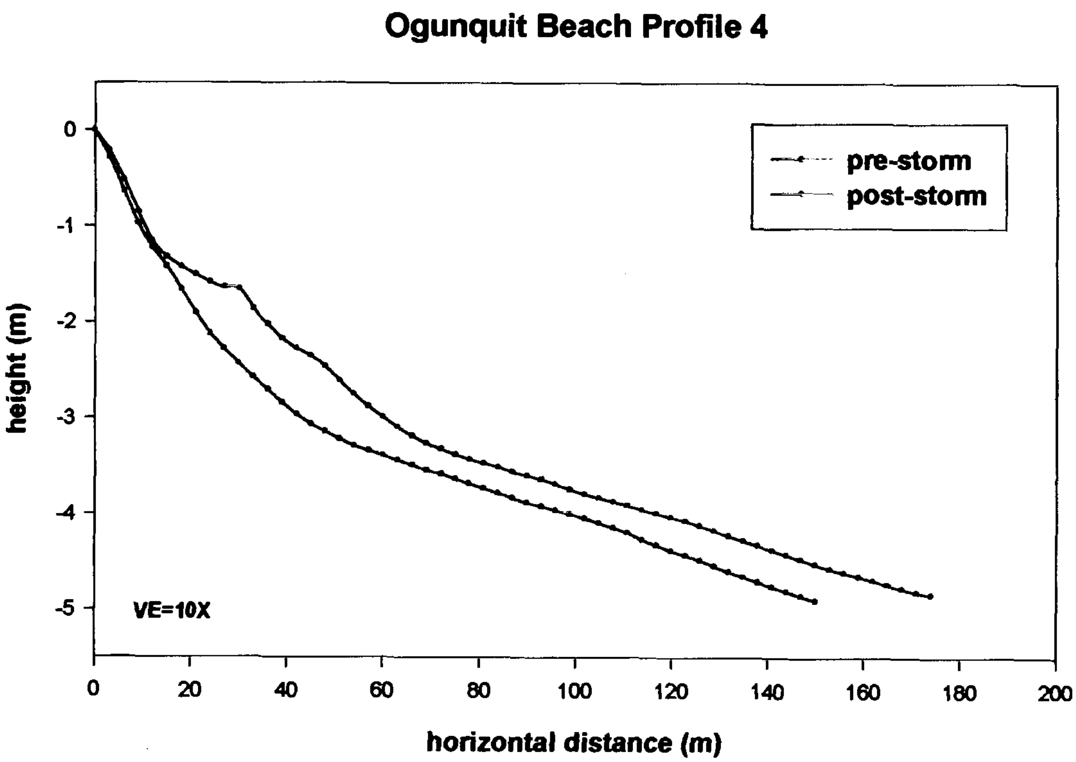


Figure C.9. Ogunquit Beach Profile 3 and Profile 4 before and after the northeast storm on March 5-6, 2001. The pre and post-storm profiles were taken within a week of the storm.

Appendix D

CURRENT METER DATA

For significant storm events (defined-chapter 3) recorded by the current meters:

- Combined flow current magnitude and velocity.
- Burst current velocities.
- Progressive vector plot of combined flow.
- Wind speed and direction at the NOAA 44007 buoy (Portland, ME).

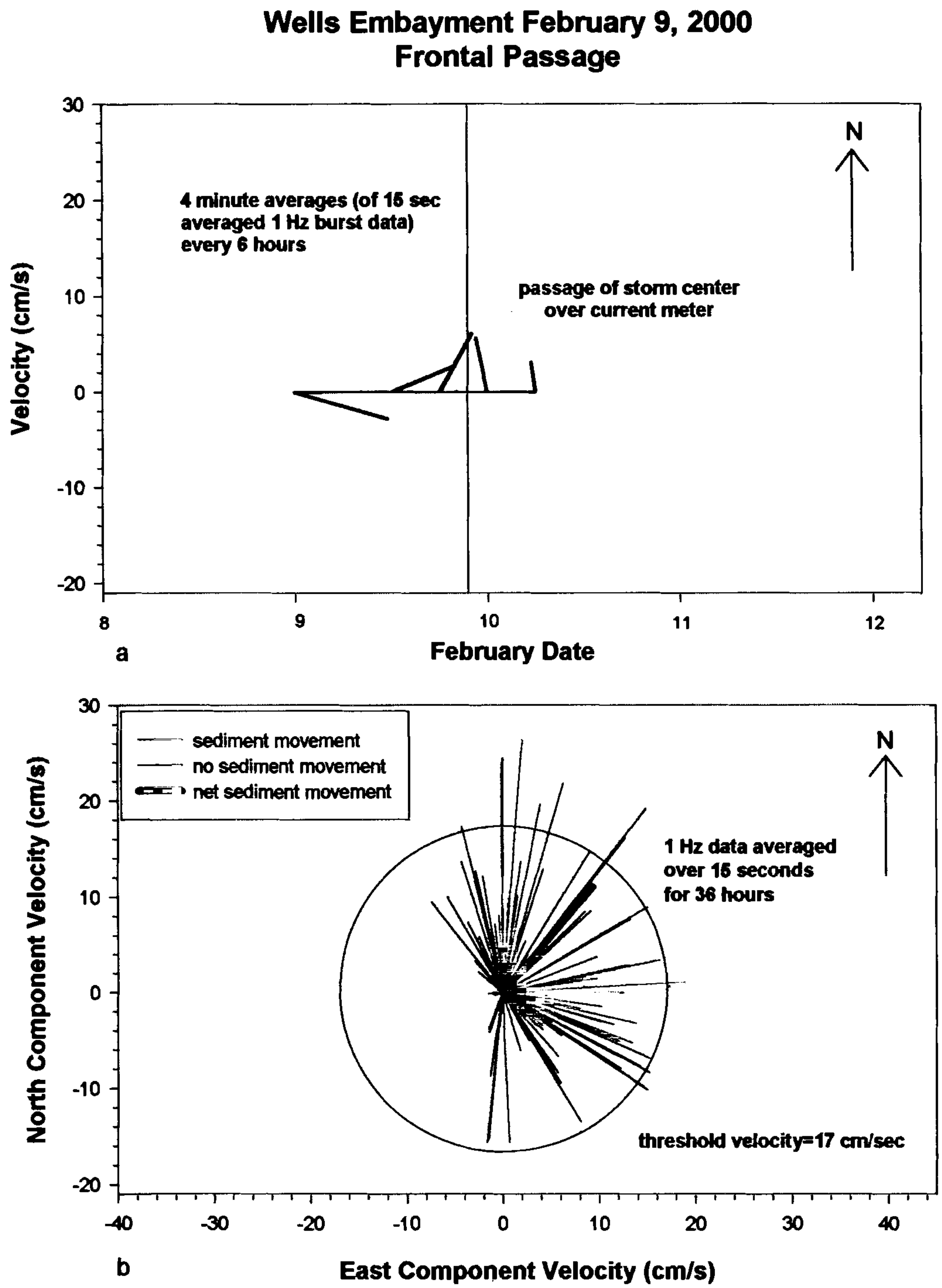
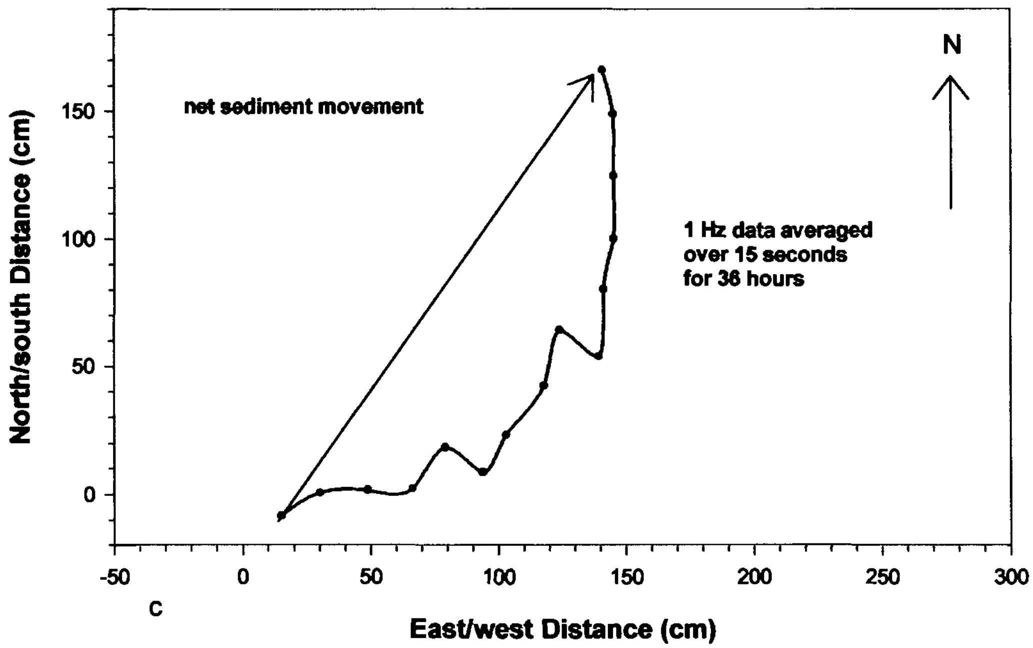


Figure D.1. Wells Embayment February 9, 2000 frontal passage: a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.



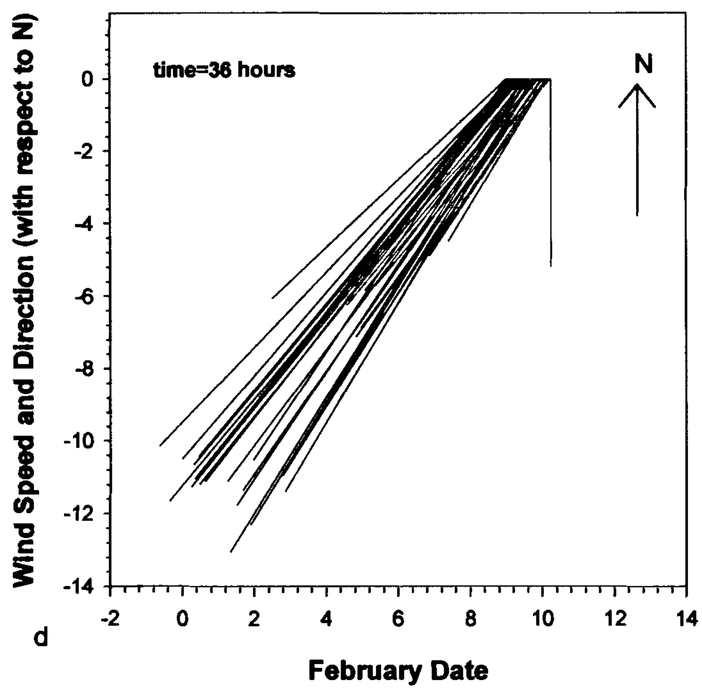


Figure D.1 (cont). c. Progressive vector plot of combined flow and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

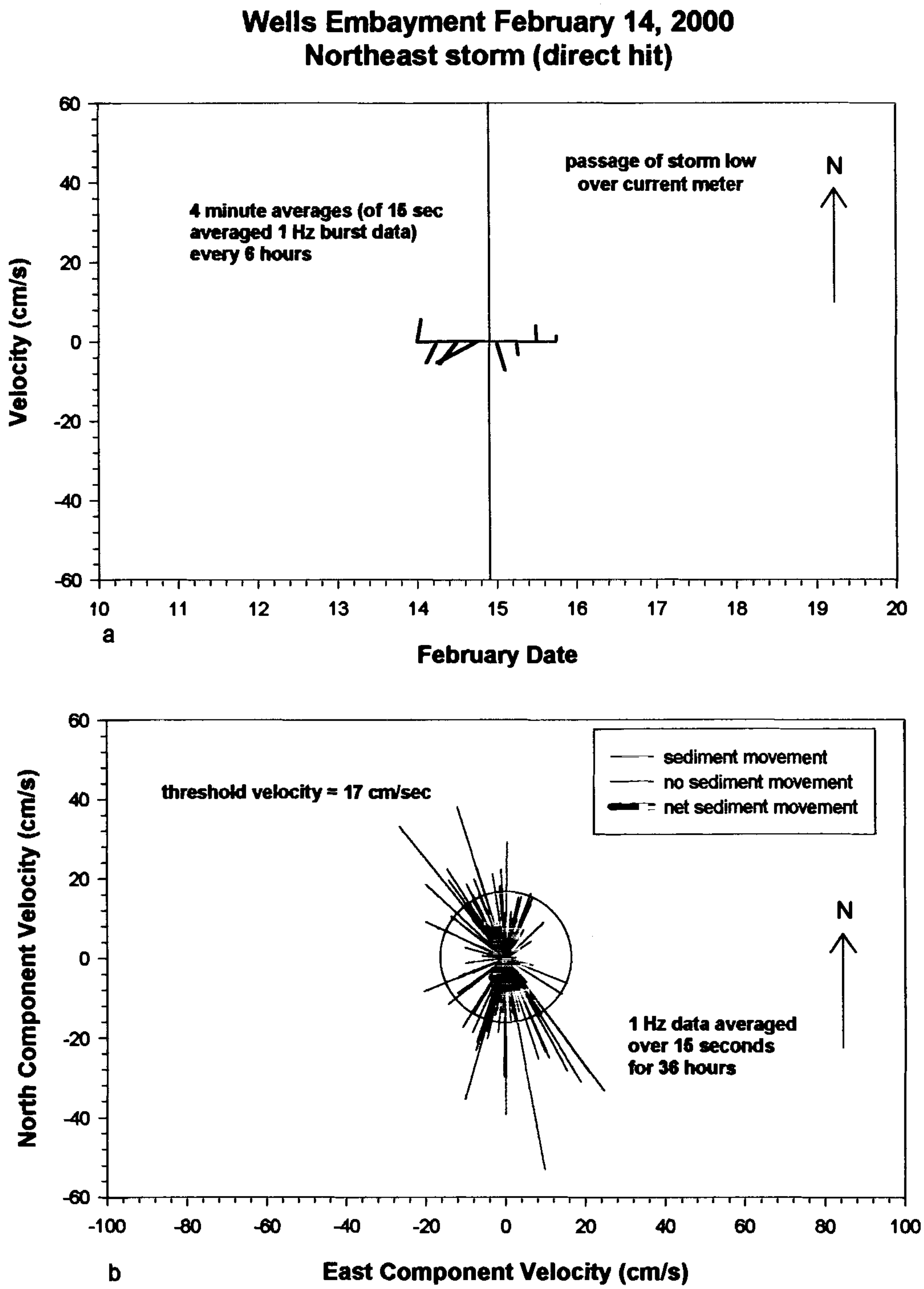
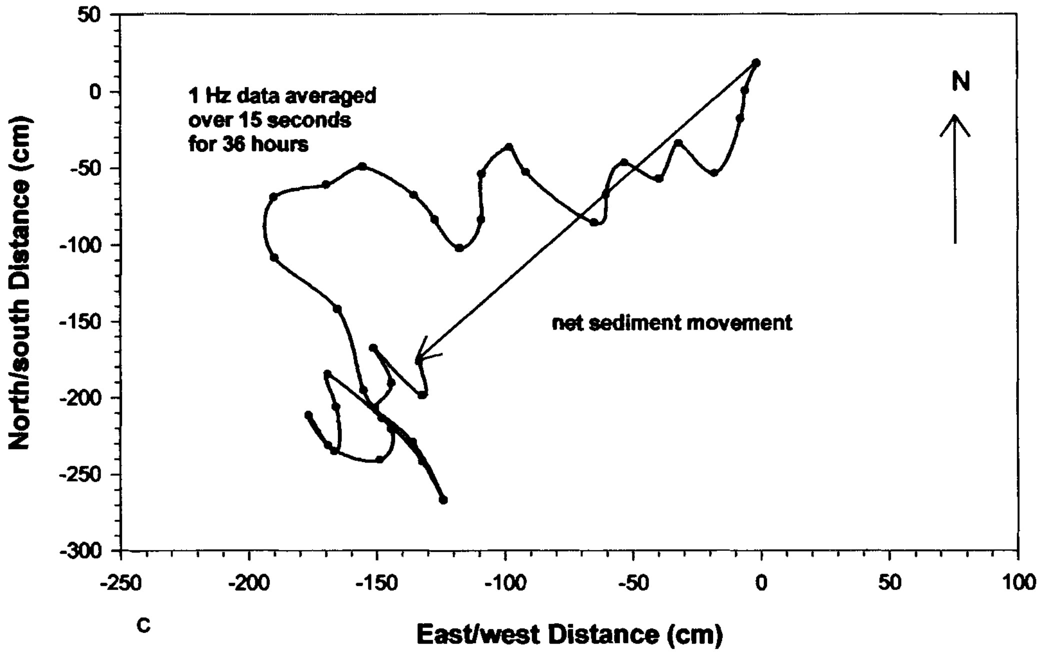
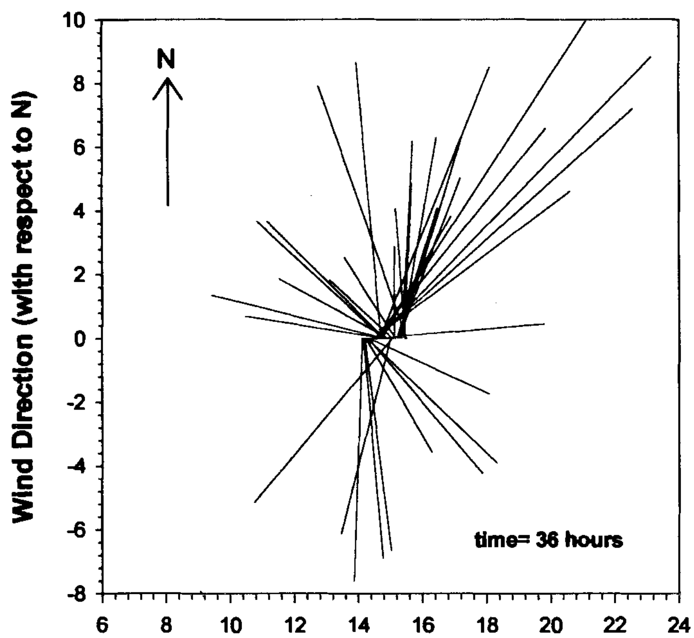


Figure D.2. Wells Embayment February 14, 2000 direct hit northeast storm: a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.



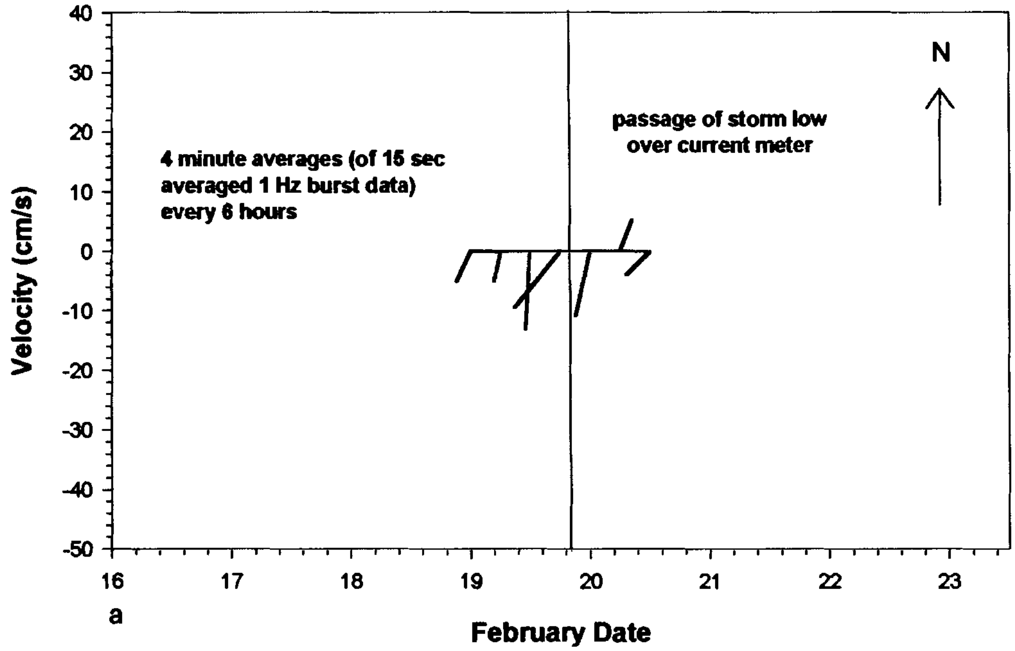
c



d

Figure D.2 (cont) c. Progressive vector plot of combined flow and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

Wells Embayment February 19, 2000
Northeast Offshore Storm



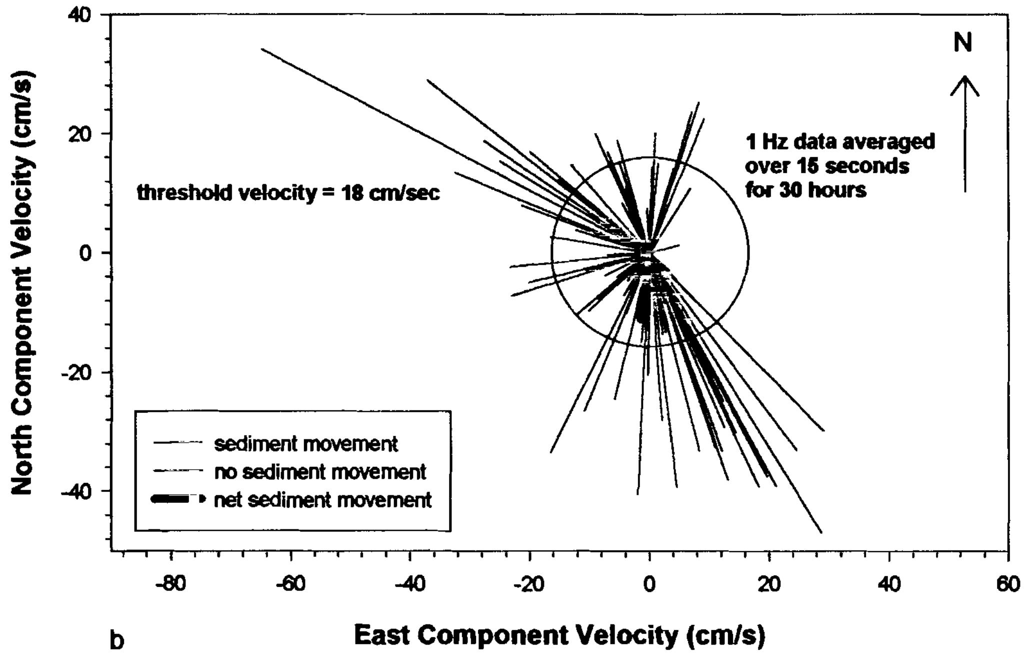
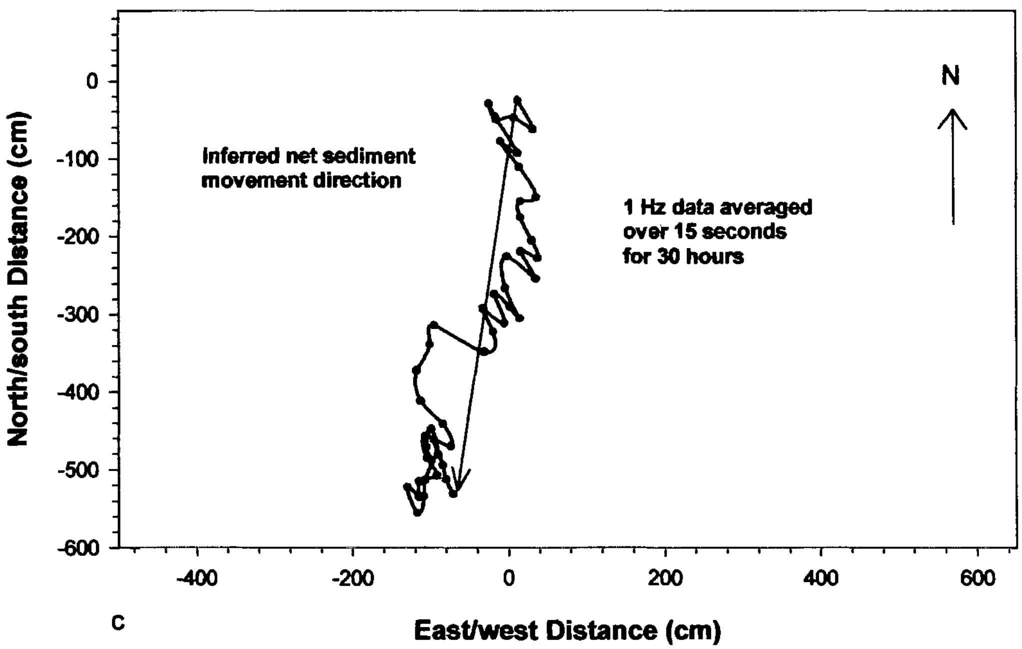


Figure D.3. Wells Embayment February 19, 2000 offshore northeast storm: a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.



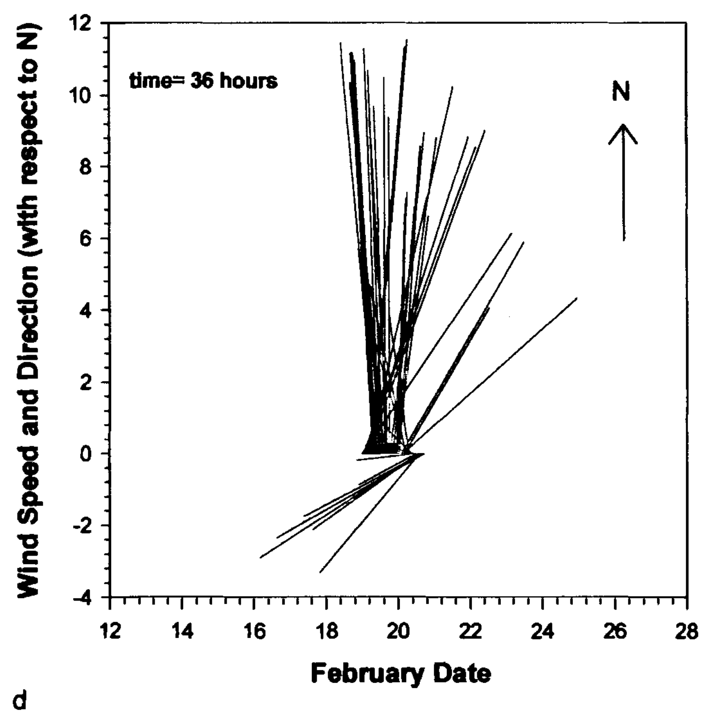


Figure D.3 (cont). c. Progressive vector plot of combined flow and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

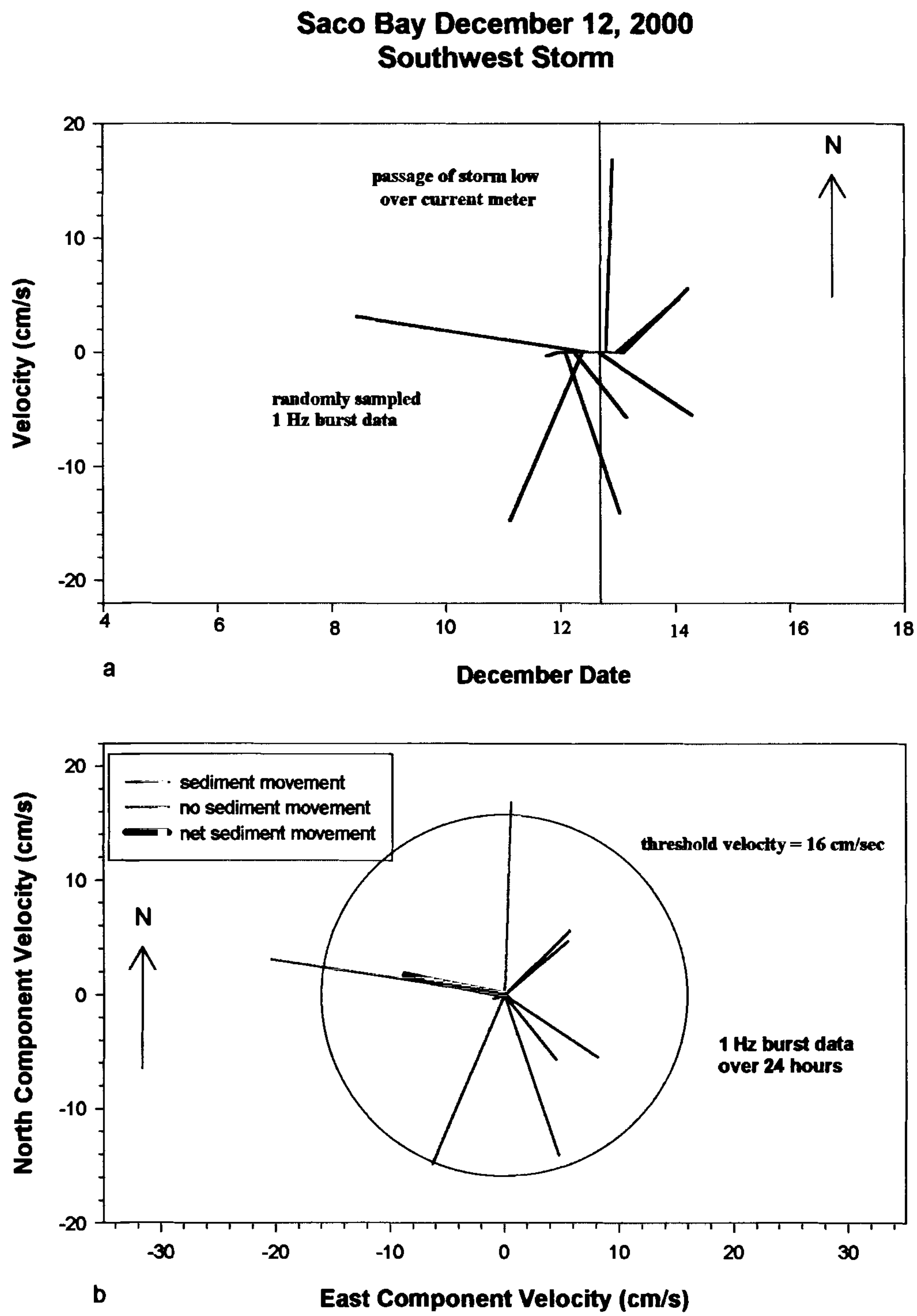
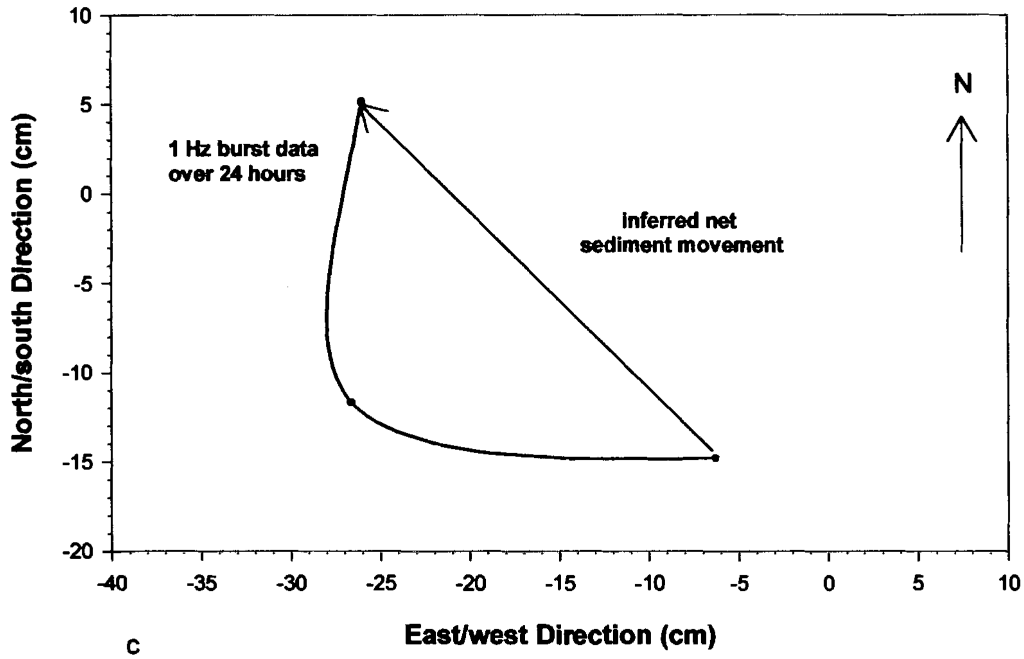


Figure D.4. Saco Bay December 12, 2000 southwest storm: a.Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.



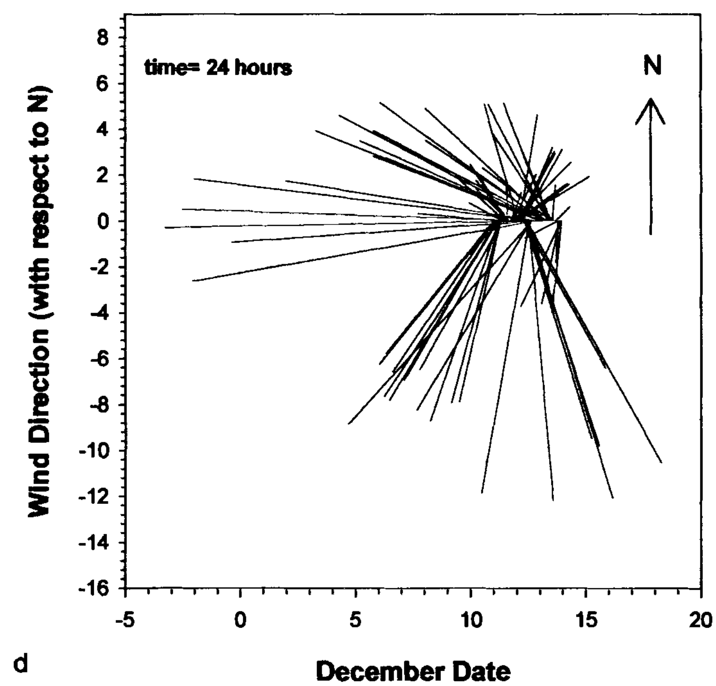


Figure D.4 (cont). c. Progressive vector plot of combined flow and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

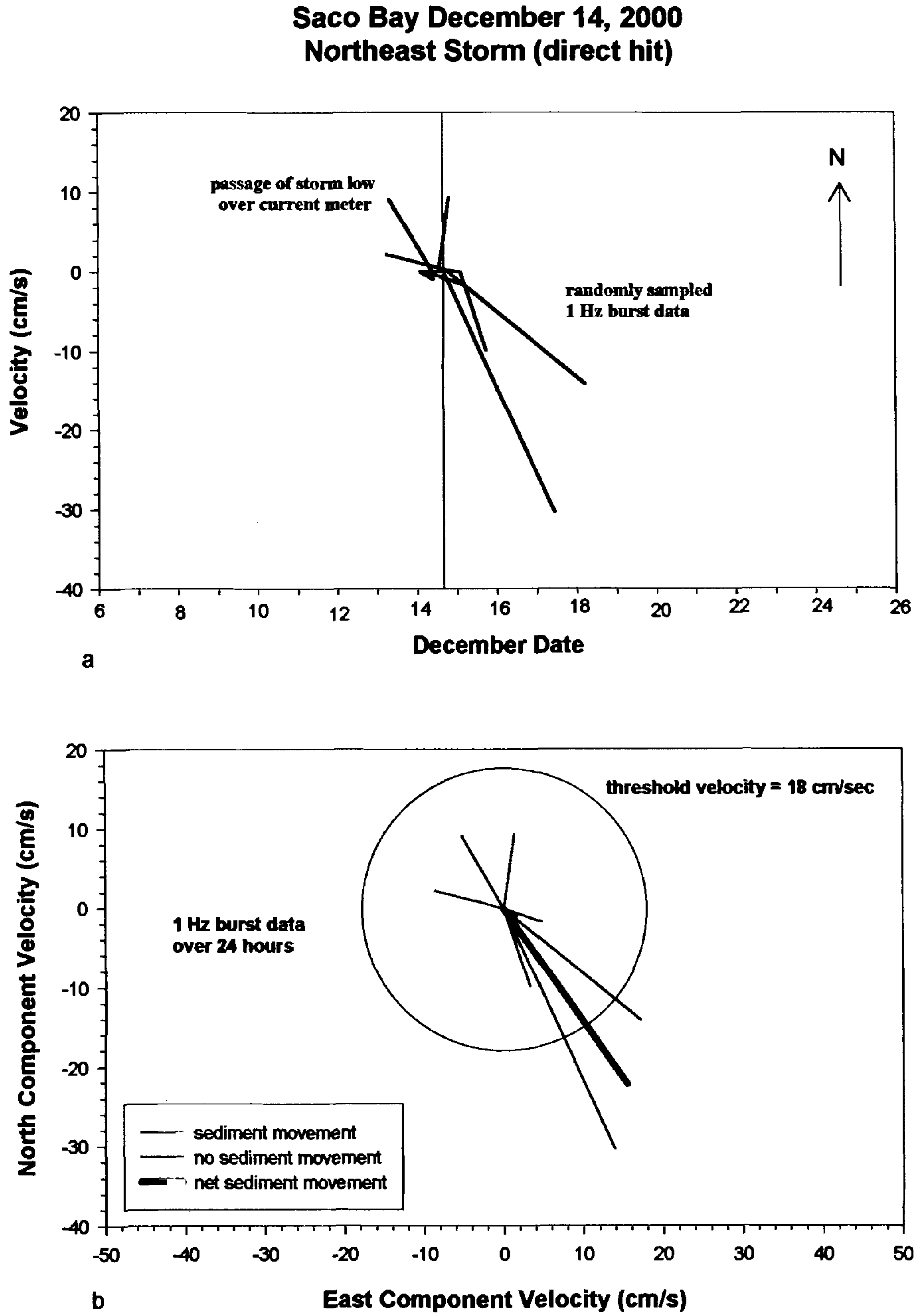


Figure D.5. Saco Bay December 14, 2000 direct hit northeast storm: a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.

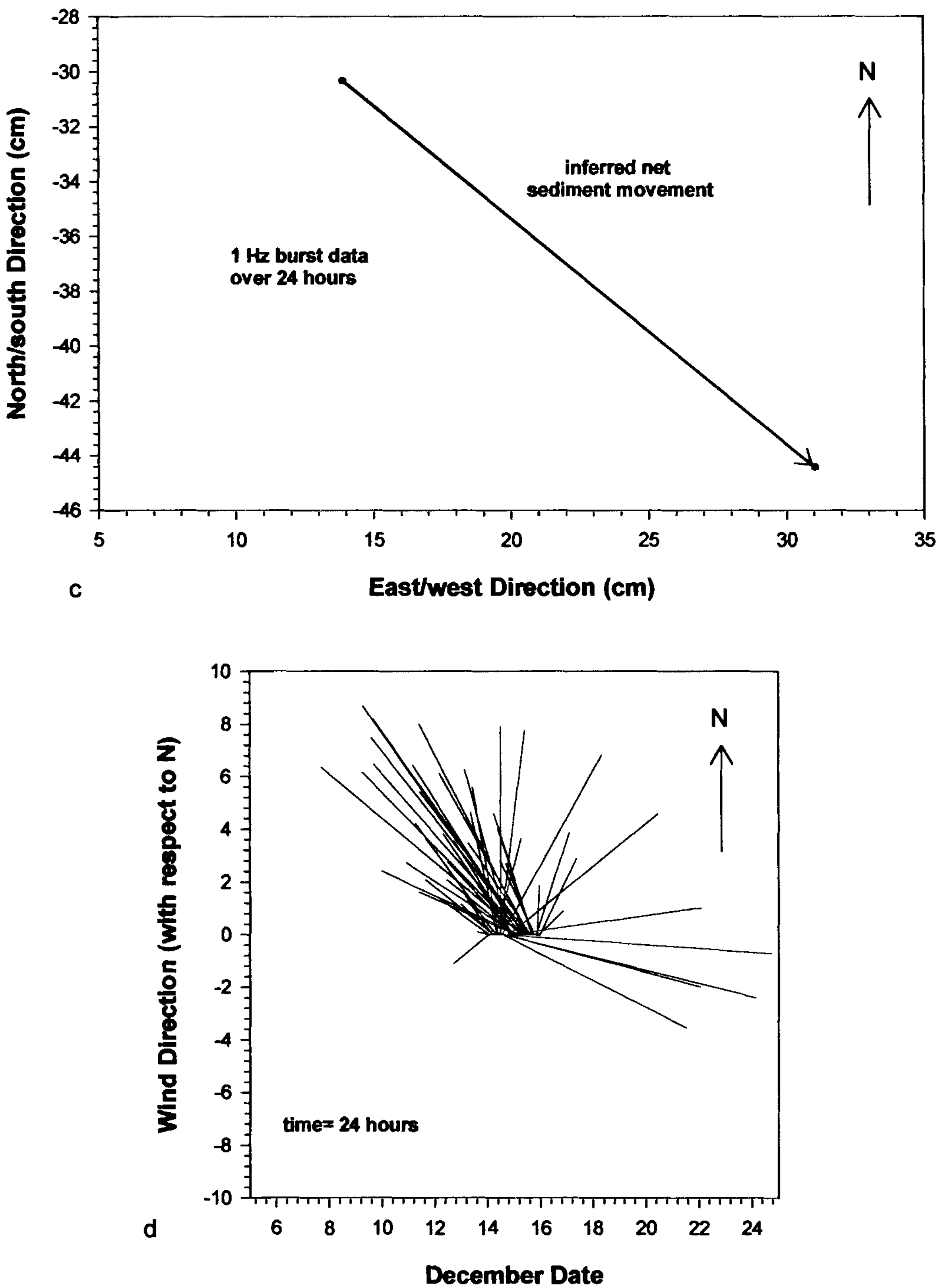


Figure D.5 (cont). c. Progressive vector plot of combined flow and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

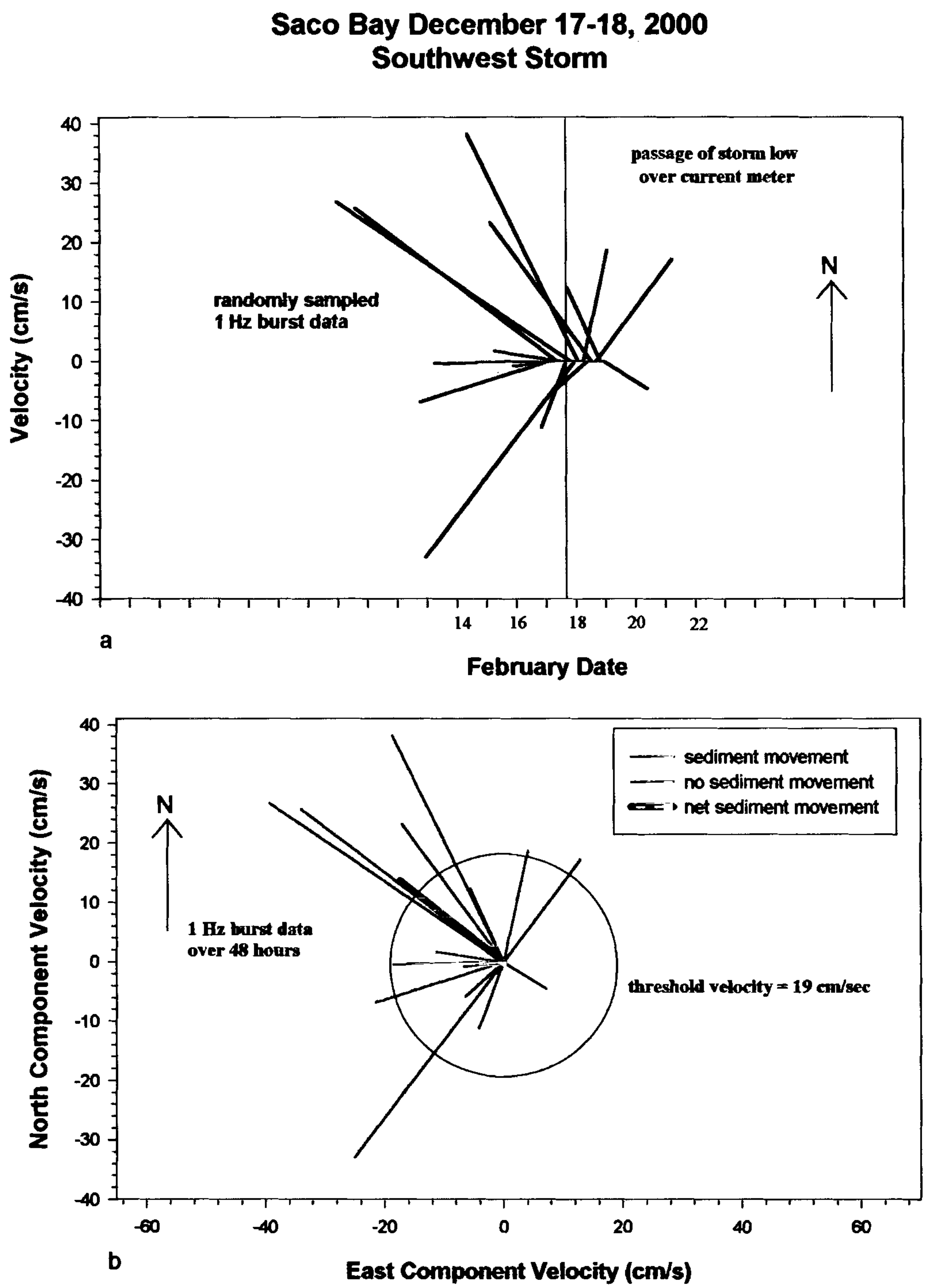
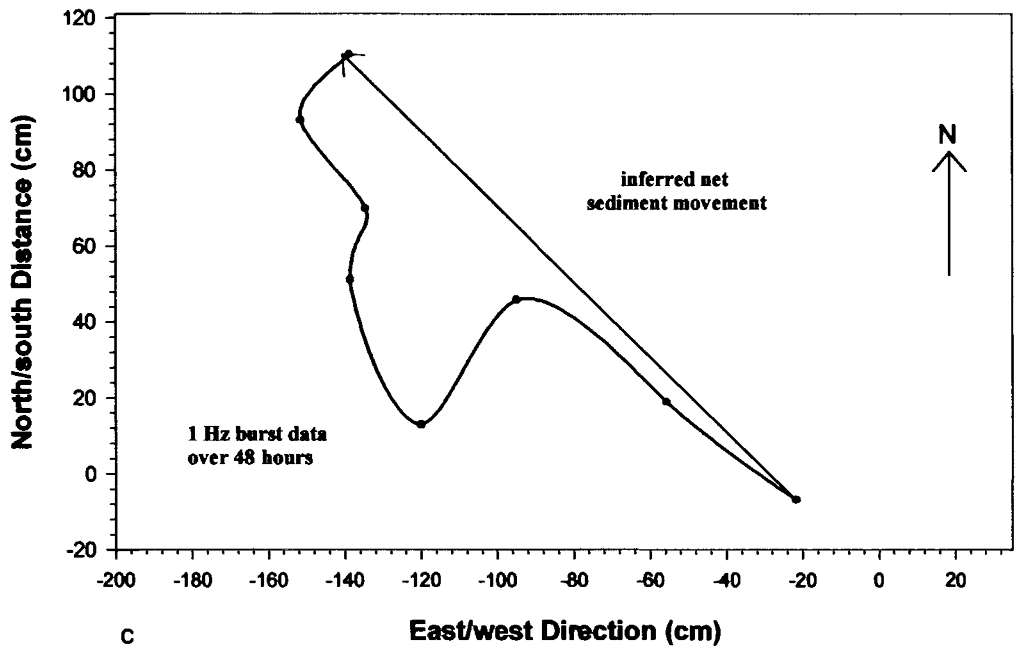


Figure D.6. Saco Bay December 17-18, 2000 southwest storm:
a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.



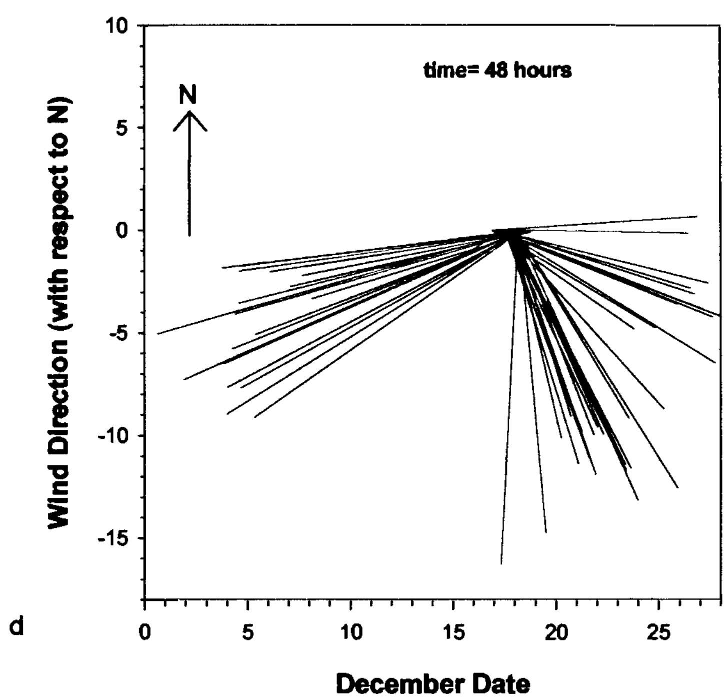


Figure D.6 (cont). c. Progressive vector plot of combined flow during the December 17, 2000 southwest storm and d. wind speed and direction during the storm at the NOAA 44007 buoy (Portland, ME). Vectors point in the direction from which the wind is coming.

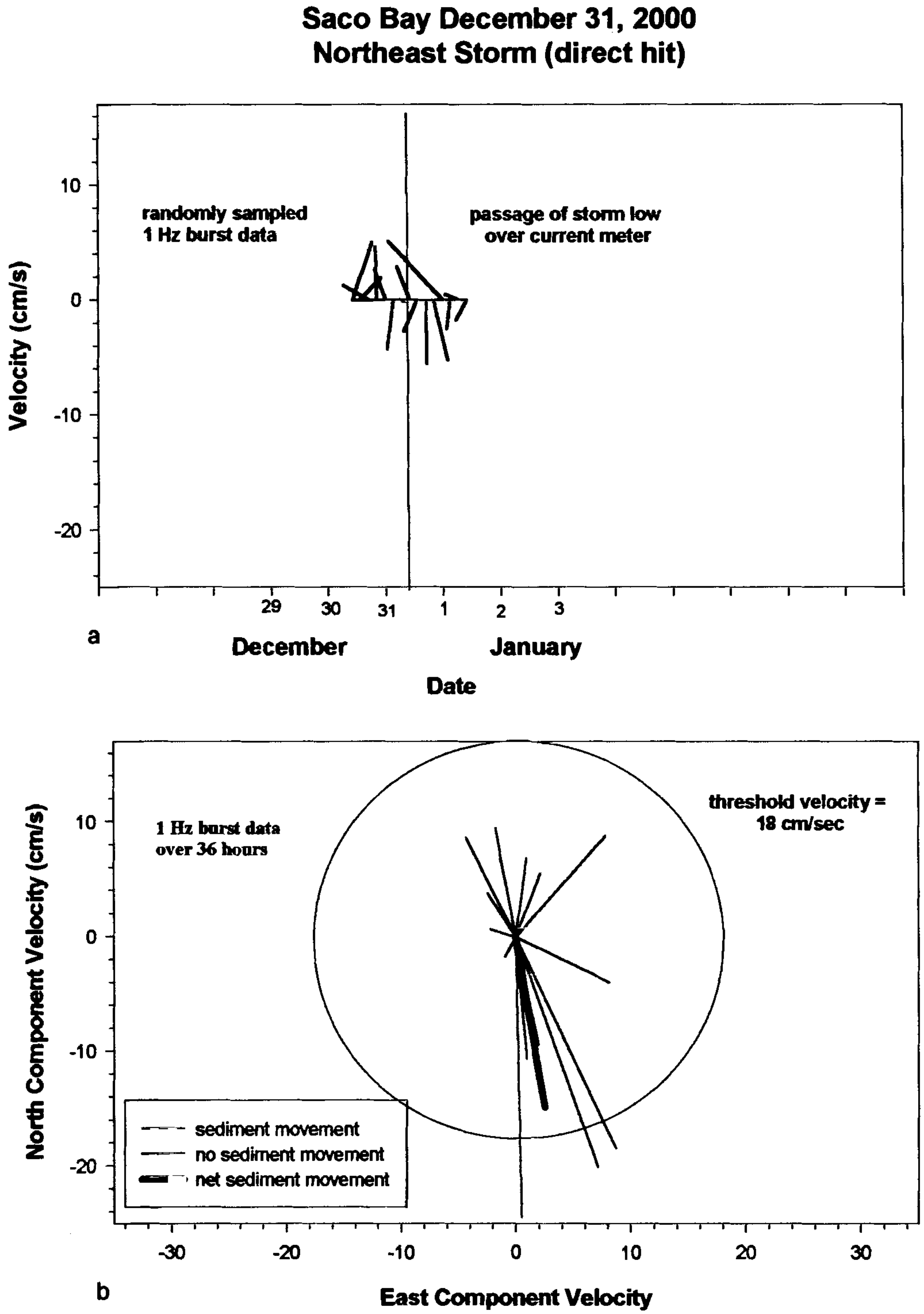


Figure D.7. Saco Bay December 31, 2000 direct hit northeast storm: a. Combined flow current magnitude and velocity and b. burst current velocities during the storm. Vectors point in the direction the current is flowing.