A COMPARISON OF A Seawall-Constrained and Unconstrained Beach In Groton, Connecticut

Katherine A. Serafin
Oregon State University

Catherine Campbell
University of Wyoming

Douglas Thompson
Connecticut College

ABSTRACT

Four profiles were measured on two barrier beaches in Groton, Connecticut to compare the affects of storms, seasonality and time on beach erosion for the unconstrained versus the seawall-constrained systems. Paired sets of profiles at the two beaches were collected with autolevels and tape measures on ten different days in 2003 and 2007 during the spring, late summer and fall seasons. Limited sediment sampling was also conducted to evaluate particle-size variations at the two sites. The two transects at the unconstrained beach follow a typical cut and fill seasonal cycle, display removal of a berm from higher wave energies present during storms, and show net accretion over the four year period. Two transects beginning at the beach with the seawall display little change in beach morphology in response to changes in seasons and storm activity, and exhibit considerable variability in long-term accretion and erosion. Although different degrees of recovery from previous storm erosion create challenges in predicting beach behavior in the long term, there is evidence of reduced sand availability on the beach constrained by the seawall compared to the unconstrained beach over the four-year period. *Keywords: hard stabilization, seawall, beach retreat, barrier beach, coastal erosion, coastal protection.*

Introduction

The 2007 Intergovernmental Panel on Climate Change (IPCC) report predicts that global sea level could rise 0.6 m or more by 2100 (Nicholls et al. 2007), putting the 55 percent of Americans living within fifty miles of the coast (Marlowe 1999) at risk from coastal erosion. Barrier islands and spits are common features along the eastern coast of the United States that provide protection from storm surge and waves. With adequate sediment supply, barrier islands can persist for thousands of years, adjusting to sea-level rise and high wave conditions via the deposition of overwash sediment on to dunes and washover fans located in the backshore. While sediment may be lost from the nearshore and foreshore zones, the overwash contributes enough sediment to allow the beach to migrate landward. However, when backed by bedrock, consolidated sediment, or hard structures such as seawalls and buildings, the beach system becomes spatially-constrained and runs out of room to migrate. Seawalls are usually built in place of dunes, but can actually increase erosion rates along the foreshore (Komar 1998). To assess long-term trends in sand volume change for an unconstrained beach and a beach constrained with a concrete seawall, topographic measurements were collected on beach profiles at adjacent barrier beaches in Connecticut. We hypothesize that the artificially-stabilized beach will undergo net volume loss, while the unconstrained beach will be dynamically stable. Wave reflection off of the seawall can create a loss of sand on the foreshore and potentially move sediment out of the littoral zone past the depth of closure at the constrained beach. The results highlight the importance of considering the long-term impact of seawalls, which in this study exacerbated the erosion of the shoreline the seawall was meant to protect.

Previous Research

Barrier beaches make up about 15 percent of the world's coastline and occur in areas with an abundant sediment supply (Davis and Fitzgerald 2004). Beaches consist of the offshore, nearshore, foreshore, and backshore areas, which are collectively referred to as the littoral zone. This zone encompasses the entire beach system, as well as an area below the waterline to the depth of closure. At water depths below the depth of closure, typically greater than 10 to 20 meters, net sediment transport due to waves becomes insignificant (Komar 1998). Within the littoral system, the nearshore zone often includes submerged longshore bars and troughs (Komar 1998). The foreshore includes the beachface and is the most dynamic area, where sediment is constantly moved by wind and wave energy. The backshore extends from any vegetation or change in physiography, like dunes, seaward to the limit of wave runup, often defined by a wrackline or berm. Sand dunes, found in the backshore zone, typically form through aeolian processes above the extreme high tide line. The resilient nature of sand dunes makes them a valuable and effective natural barrier of protection from coastal storm surges (Davis and Fitzgerald 2004).

Shoreline erosion is usually associated with wave activity. Wave strength is influenced by three principal storm related factors, wind speed, storm duration, and fetch (Ritter, Kochel, and Miller 2002). Stronger more persistent winds create stronger waves. Fetch is the distance of water over which the wind blows in a generally constant direction providing energy for the production of waves (Ritter, Kochel, and Miller 2002; Komar and Moore 1983). Wave activity also varies with the seasons and is associated changes in storm frequency.

Storm waves move sand among the nearshore, foreshore and backshore over a short period of time and are an integral component of barrier island processes. The beach profile is essentially a topographic representation of how the beach responds to wave energy flux (Ritter, Kochel and Miller 2002). When swash runs up the foreshore, it will either carry sediment back from the backshore or percolate into pores in the sediments. During calmer wave conditions typical of summer weather, the beach usually displays a larger width and steeper beachface slope due to the breaking of individual waves with a substantial amount of time between breaks. This allows the processes of swash to dominate over those of backwash (Haslett 2000). Such repetitive and well spaced movement produces a prominent ridge, called the berm, where the swash repeatedly breaks and deposits sediment high on the beachface (Haslett 2000). The result is a steeper foreshore that ends in a berm and then levels off in the backshore. However, larger sediments permit more percolation of swash, which diminishes the effectiveness of the wave energy, leaving a steep foreshore. Therefore, foreshore slope also typically increases with sediment size (Komar 1998).

High energy wave conditions prominent during storms and in the winter months create a narrower beach and gentler beachface slope. During a storm, waves arrive in rapid succession causing backwash to move down the beach as the swash moves up the beach. This produces a net seaward movement of sediment, which creates a terrace around the low-tide level, as well as longshore bars close to the shore composed of sediment eroded from the foreshore (Haslett 2000). During the winter months, a wrack line, a deposit of mostly organic material, may develop on the foreshore or backshore depending on wave energy (Davis and Fitzgerald 2004). The location of the wrack line is a function of the swash uprush associated with wave breaking and water level elevation (Thornton and Jackson 1998). Therefore, the position of the wrack line gives a good estimate of the height of the wave runup.

Influence of seawalls

A seawall is a shore-parallel structure built to prevent landward retreat of the shoreline and to reduce the effects of strong waves on infrastructure located behind the wall by reflecting wave energy (Kraus and McDougal 1996). Seawalls can enhance erosion and reduce the width of a beach by a series of mechanisms that include placement loss, passive erosion, active erosion, or a combination of the three. Placement losses occur when a seawall is constructed on beaches between high and low tide lines, and immediately impacts the beach sediment budget by leaving little to no beachface during high tide (Griggs et al. 1991; Pilkey and Wright 1988). Seawalls can passively cause the beach to erode by cutting off sand supply to the system and inhibiting longshore sediment transport (Pilkey and Wright 1988). For example, down-drift of a seawall in India, massive erosion occurred due to the loss of the longshore component of the sediment budget (Jayappa, Kumar, and Subrahmnya 2003). Furthermore, seawalls may inhibit the ability of a beach to respond to storm waves because there is no longer a frontal dune as a reservoir of sand (Fitzgerald, Van Heteren, and Montello 1994; Morton 1988; Pilkey and Wright 1988).

Active erosion involves a mechanism of accelerated erosion initiated by wave reflection and storm surf zone narrowing by the wall (Griggs et al. 1991; Pilkey and Wright 1988). The energy of a wave reflected from a seawall is similar to that of the incoming wave, and may cause scouring along the toe of the wall (Komar 1998; Kraus 1988). Wave refraction is strongest with vertical and impermeable seawalls (Davis and Fitzgerald 2004). The growth of multiple bars can result from standing waves that are developed in front of seawalls (Komar 1998). Although seawalls prevent waves from directly reaching structures landward of the wall, beach scouring associated with their presence may prevent the redeposition of sand following storm and seasonal erosion (Komar 1998; Dean 1999). However, scouring may not be a significant contributor to broader scale beach morphology changes in all cases (Griggs et al. 1991; Kraus and McDougal 1996).

The impact of seawalls on beach dynamics varies with location. Some literature describes the seawall-wave interaction as contributing to altered beach profiles (Griggs et al. 1991; Kraus and McDougal 1996; Morton 1988), but other studies show that seawalls do not adversely influence beach morphology (Basco et al. 1997; Griggs, Tait, and Corona 1994; Nelson 1991). Basco et al. (1997) found that erosion rates in front of seawalls were not higher than those on a beach without the control structure. However, the seawall influenced the seasonal variability with increased accretion in the summer months and increased erosion during the winter. Basco et al. (1997) also found that immediately after wall construction, erosion rates increased, versus what was observed prior to the construction of the wall. Ruggiero and McDougal (2001) created a model to look at wave setup, longshore currents, and sediment transport on beaches with seawalls to try to eliminate some of the contradictions found within seawall studies. Their findings indicated that a wave approaching a beach with a seawall will break farther seaward than on an unconstrained beach, resulting in a smaller surf zone. Subsequent longshore sediment transport either increased or decreased depending upon the proximity of the seawall to the surf zone (Ruggiero and McDougal 2001).

A review of the literature highlights the uncertainty in beach morphologic response associated with the introduction of seawalls to a previously unconstrained beach system. Beaches can experience little change or net sediment loss depending on the interaction of the seawall and high surf. This study was conducted to determine how a near-vertical, impermeable seawall in a low-energy Long Island Sound beach system influenced morphologic responses to storms, changes in season and longer-term sediment availability compared to an unconstrained beach system. We anticipate less morphologic adjustment and net sediment loss in the constrained beach due to reflected wave energy during storm periods when surf reaches the seawall. In comparison, the unconstrained beach is expected to display more profile change in response to storms and seasonal change, and exhibit dynamically-stable beach profiles over the four year study period. The dynamically-stable system should show little net vertical erosion, although frequent sediment transfers among the backshore, foreshore and nearshore zones are expected.

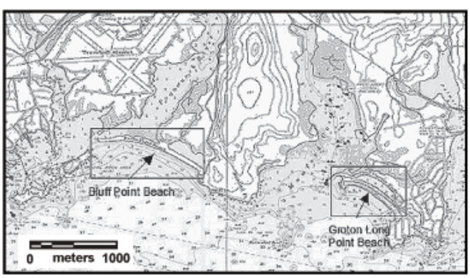

Figure 1. Study Area showing location of beaches at Bluff Point and Groton Long Point. Note the similarity in aspect and proximity of the two pocket beaches.

Study Areas

The study compared two adjacent beaches located at Groton Long Point and Bluff Point on the northeastern shore of Long Island Sound in Groton, Connecticut (Figure 1). The beaches were selected based on their proximity to one another and similarities in aspect, size and physical appearance. Long Island Sound experiences semi-diurnal tides and a mean tidal range of 0.71 m. Long Island and Fishers Island act as large breakwaters limiting fetch and therefore reducing the impacts that storms have on the Connecticut shore. The predominant winds along the coast of Connecticut are westerly, with seventy percent originating from the NNW or SSW. Because the study beaches are oriented WNW-ESE, the significant fetch is from the southwest. Winds from this direction are common during the summer months. In Long Island Sound, the strongest winds and wave action are usually associated with hurricanes and nor'easters. Hurricanes are rare but do occur during the summer and fall, while nor'easters typically occur during the winter months.

The 1.2-km long unconstrained beach at Bluff Point is a welded barrier, with the bluff acting as one headland and Bushy Point as the other (Figure 2). The low wave energy along the Connecticut shoreline on Long Island Sound preserves the sediment in these pockets between rocky headlands (Lewis and DiGiacomo-Cohen 2000). The beach has a small dune system and is backed by a marsh and lagoon. Sediment is coarser on the eastern side towards the bluff but becomes finer towards Bushy Point. The bluff that gives the area its name is located to the east of the beach and is a high bedrock gneiss headland that is mantled with glacial till. Further to the west is Bushy Point, part of the recessional moraine complex formed during the retreat of the Wisconsinian glaciers (Stone et al. 2005). Approximately 17,500 years ago as the glaciers receded, glaciofluvial sediments fed a deltaic deposit formed in a sediment-dammed lake to the north of Bluff Point (Lewis and DiGiacomo-Cohen 2000). These deltaic deposits are part of the Poquonock River deposit sequence; a large fluviodeltaic deposit associated with the ancestral Poquonock River and glacial Lake Connecticut, and subsequently supplied sediment to Bluff Point Beach (Stone et al. 2005). The water level in Lake Connecticut was at roughly the same elevation as modern sea-level (Lewis and DiGiacomo-Cohen 2000). Therefore, beaches that formed along the ancient lake were reoccupied when sea-level rose to a level that reinundated the Long Island Sound basin.

Figure 2. Photograph showing the unconstrained beach at Bluff Point and the approximate locations of the survey transects. The houses in the background are located across the cove on the far shore of the inlet not on the unconstrained beach.

Bluff Point State Park is a 684 acre coastal reserve located on the Bluff Point peninsula (Connecticut Department of Environmental Protection (CDEP) 2003). In the early 20th century, Bluff Point was a developed vacation destination with cottages lining the beach. These cottages were obliterated by the hurricane of 1938. These structures were not rebuilt and the reserve was gradually purchased by the State of Connecticut from 1965 to 1975. Bluff Point State Park officially opened in 2000 (CDEP 2003). Some plantings of dune grasses and the installation of sand fences controlled pedestrian traffic and helped trap dune sand. Currently, the beach is restricted to foot traffic.

Groton Long Point beach, to the east of Bluff Point beach, is a welded barrier between two developed headlands. The beach is backed with a near-vertical, concrete seawall completed during the summer of 1955, which was constructed to protect residential structures (Figure 3). The two headlands are armored with riprap and produce little to no sediment for the system. The beach and lagoon area at Groton Long Point is a late Holocene beach and tidal-marsh deposit (Stone et al. 2005). The glaciofluvial Poquonock River deposit has a large western outlet that supplies the beach at Bluff Point and a smaller outlet further to the east in Mumford Cove (Stone et al. 2005), and may provide an important sediment supply to the beach at Groton Long Point. The fine-to-medium sand beach is approximately 0.76 km long. Groton Long Point has slightly less fetch for southerly winds than Bluff Point because of its location northward of Fishers Island.

Figure 3. Photograph showing the seawall and homes that constrains the beach at Groton Long Point. The two lines show the approximate locations of the two survey transects.

Groton Long Point is a residential community that contains approximately 600 houses, with a year-round population of less than 1800, and summer population of greater than 5400. Prior to the seawall construction and an earlier boardwalk, the beach was backed by dunes. Currently, there is a restriction on further development of both residential and commercial buildings. The beach has not been nourished, but is reshaped every May to flatten the upper profile. A surf rake is used in the spring to remove seaweed and trash.

Methods

The study consisted of repeated topographic surveys of four beach transects perpendicular to the shore, with transects named for local landmarks (Figure 4). The most easterly transect, located at Groton Long Point beach, is called Picket Fence (PF), and extends perpendicular from the seawall at N41° 18.674’ W072 00.662’. A transect 50 m to the west is named House 32 (H32) and is located at N41° 18.697’ W072 00.689’. At Bluff Point beach, the eastern transect is called Sand Fence (SF) and is located at approximately N41° 19.000’ W072 02.227’. The most westerly transect, Orange Stake (OS), is located at N41° 19.025’ W072 02.261’ roughly 90 m from the bluff.

The paired transects at each beach were measured on the same dates to capture similar wave conditions at the two locations. Five surveys were collected from 5 September 2003 to 12 December 2003, and five additional surveys were completed from 15 May 2007 to 25 November 2007. The time period of the surveys permitted analysis of conditions at the end of the summer, autumn and winter seasons. The various surveys also enabled analysis of seasonal changes, post-storm impacts and long-term change at the two sites. Unfortunately, the location of Bluff

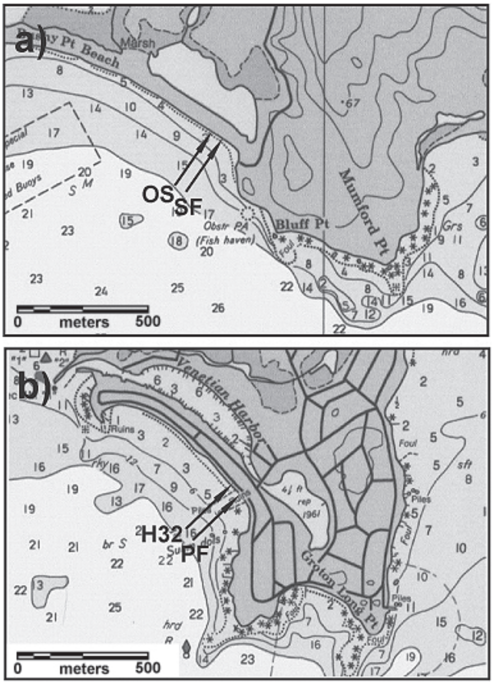

Figure 4. Location of survey transects along the beaches at a) Bluff Point and b) Groton Long Point.

Point transect SF was difficult to accurately relocate in 2007 because a fence used as a reference point was knocked down sometime after 2003. Therefore, this transect is thought to be in the same position in 2007 as in 2003, but may be displaced along the shore +/– 0.5 m.

Beach profiles were obtained by a two-person team using an autolevel, stadia rod and tape measure. Measurements were collected at 1m intervals along each transect and extended different distances into the water based on the given wave conditions. Positions of the berm, wrack line, and shoreline were noted. A survey was considered of satisfactory precision if the vertical elevation of a surveyed reference point was within 0.5 cm at the beginning and end of each survey. At Bluff Point an orange stake at the end of one cross-section provided the only stable reference point along the beach. At Groton Long Point a reference point along a concrete stairway was also surveyed to a fire hydrant to provide two fixed-elevation datums. Differences in elevation were measured relative to the reference points at each beach, not Mean Sea Level (MSL) because of the lack of surveyed elevation benchmarks in the areas.

Particle-size analyses of grab samples collected along the measured profiles were analyzed to assess differences in sediments at the four transects because sediment size impacts the slope of the beachface. In 2003, two samples were taken from the berm at each of the four transects approximately one meter on either side of the transect line. In 2007, two additional samples were gathered at each transect line on the two beaches. The first sample was taken in the vicinity of the berm crest for comparison to the 2003 data while the second sample was collected on the foreshore to compare sediment sorting among the four transects for the current wave conditions. Dry sieve analysis was used to examine the particle size of all samples to the whole phi interval (ϕ). The median particle sizes, d_{50} values, are reported to indicate general differences in the size of material among different samples. Sorting indices were also calculated to determine the degree of internal variation in sediment size using the formula:

$$\text{Sorting Index} = \tfrac{1}{2}\{(d_{84}/d_{50}) + (d_{50}/d_{16})\} \qquad [1]$$

where d_{50} (mm) is the median particle size, and d_{16} (mm) and d_{84} (mm) are equal to the 16 percent and 84 percent finer than values. The values for the sorting index increase with decreasing sorting of the sediment samples.

To assess storm intensity and erosion potential, significant wave heights were downloaded from the National Oceanic and Atmospheric Administration's National Data Buoy Center. Station 44039 was the closest buoy in Central Long Island Sound, located at 41.14 °N 72.66 °W, approximately 56 km SW of Groton, CT. The buoy was in almost continuous operation during the entire study period and records wave height conditions in fifteen minute intervals. It is assumed that maximum wave height at the buoy provides at least a rough estimate of possible energy conditions at the two beaches. The maximum wave height between survey dates was used as an estimate of the largest potential energy condition for the survey interval.

Results

Storm activity was generally higher in the fall of 2003 than during the fall of 2007 based on wave height data and wrack line evidence. In 2003, wrack line positions at three of the five surveys indicated that waves had reached the base of the wall at Groton Long Point. Hurricane Isabel struck the region on 19 September 2003 with wave heights less than 1.8 m at the buoy (Table 1). Residents reported seeing water overtop the seawall on more than one occasion during October of 2003. In comparison, Tropical Storm Noel and two subsequent nor'easters appeared to create high enough waves to reach but not overtop the wall during the fall of 2007. On 3 November 2007, Tropical Storm Noel crossed New England, creating wave conditions

Survey date	Maximum wave height from last survey (m)	Date of most recent maximum wave height	Days since most recent maximum wave height
05/09/2003	1.2*	08/08/2003	28
19/09/2003	1.8	19/09/2003	0
03/10/2003	1.4	24/09/2003	14
07/11/2003	2.6	15/10/2003	23
05/12/2003	2.8	15/11/2003	20**
15/05/2007	2.1	16/04/2007	29
28/09/2007	1.4	10/08/2007	49
21/10/2007	1.6	12/10/2007	9
08/11/2007	1.6	07/11/2007	1
25/11/2007	1.7	16/11/2007	9

* maximum wave heights reached during the period from 01/06/2003 to 05/09/2003.

** a storm with a maximum wave height of 2.7 m also occurred on 01/12/2007, four days before the survey.

reaching 1.6 m. The three largest storms in 2007 produced maximum wave heights in central Long Island Sound that were less than the three largest storms in 2003. Waves did not appear to overtop the dunes at Bluff Point in any of the observed storms of 2003 or 2007.

Wave conditions in 2003 and 2007 were generally lower in the summer and increased during October and November both years (Table 1). In 2003, maximum wave heights from June to the first transect survey on 5 September, only exceeded 1.0 m on two occasions. Four subsequent storms produced maximum wave heights over 1.5 m. Between 2003 and the beginning of 2007, waves reached but did not exceed 2.0 m. In 2007, wave heights exceeded 2.0 m on six dates in February, March and April.

Morphological response to 2003 storms

Bluff Point beach had a pronounced berm on 5 September 2003. Survey data then show that

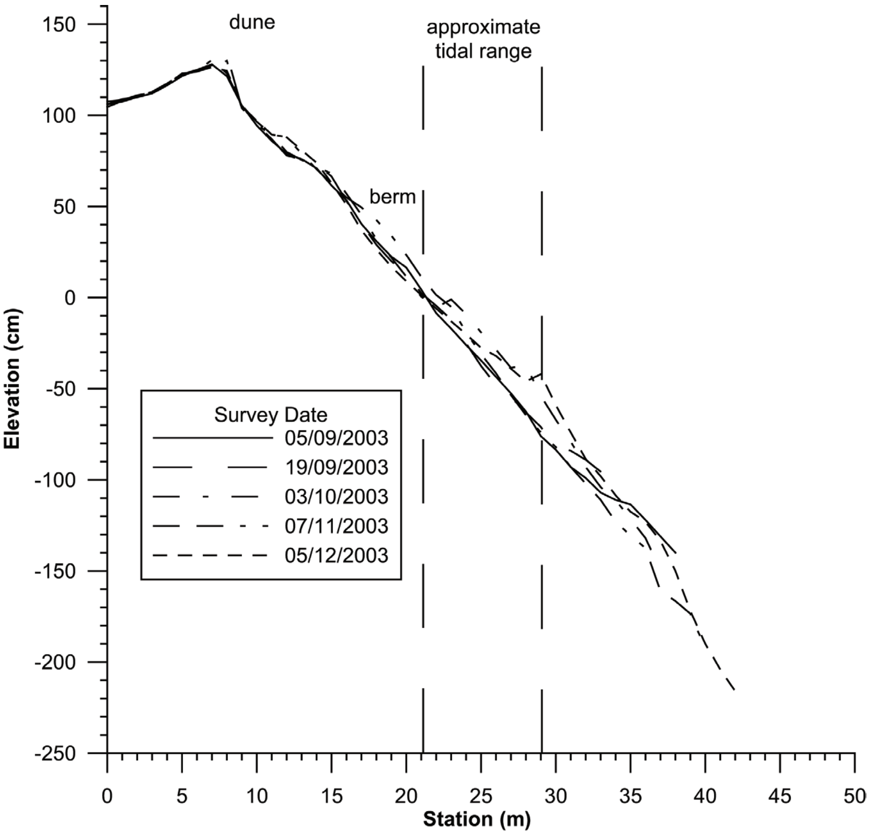

Figure 5. Surveyed profiles for transect OS on ten dates from 5 September 2003 to 5 December 2003.

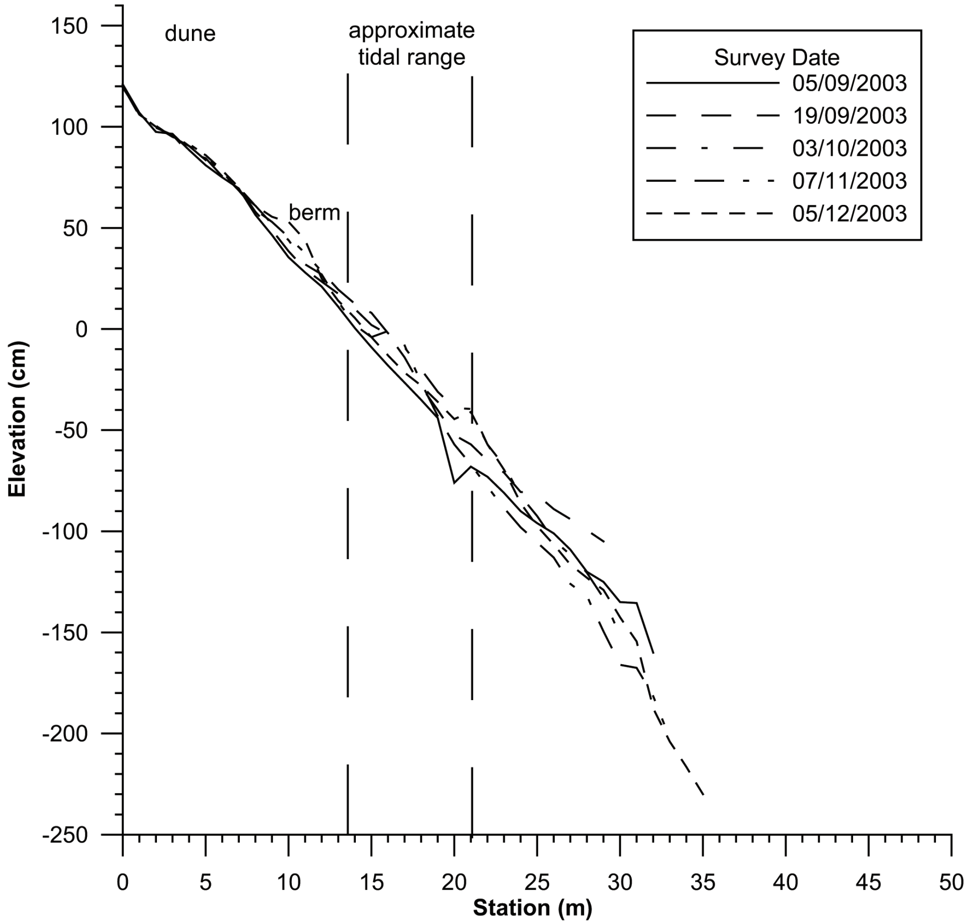

Figure 6. Surveyed profiles for transect SF on ten dates from 5 September 2003 to 5 December 2003.

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a series of fall storms in 2003 created changes in the slope of the foreshore at Bluff Point. The dune system at Bluff Point, an area that should have little change unless overwash occurs, generally showed consistent elevations. The transect lines tended to separate only in the foreshore where wave activity is expected to reshape the beach more frequently. The first storm flattened the profile and deposited sediment below the low-tide level at both transects (Figures 5 and 6). The foreshore recovered following a period of low wave heights for the 3 October 2003 survey with simultaneous volume loss below the waterline at both transects. Despite one strong storm in the middle of the next interval, the previous trend continued for the 7 November 2003 survey, with erosion on the foreshore and deposition near the top of the tidal range in the area of the berm. Two strong storms eroded the foreshore and deposited sediments in the nearshore as observed for the 5 December 2003 survey at both transects. Finally, on 12 December 2003, a large driftwood log was noted stranded only a few centimeters west of the SF transect, which created some local scour.

At Groton Long Point, foreshore cusps were present during the 5 September 2003 survey. A cusp is a curved erosional feature on the beachface usually a few meters in size with coarser sediment in the horns and finer sediments in the small embayments further up the beachface. Cusps are generally formed under normal wave incidence during the two to four days after the peak of a storm (Holland 1998), especially on coarser grained, steep beaches (Werner and Fink 1993). The 19 September 2003 survey took place the day that Hurricane Isabel made landfall, and there was wrack line evidence that the water had reached the seawall near transect PF. The beach directly seaward of a staircase on the seawall had a large scarp cut into it. No other similar features were noted along the foreshore. Hurricane Isabel created more initial volume loss with scour near the high tide line and deposition seaward (Figures 7 and 8). On 3 October 2003,

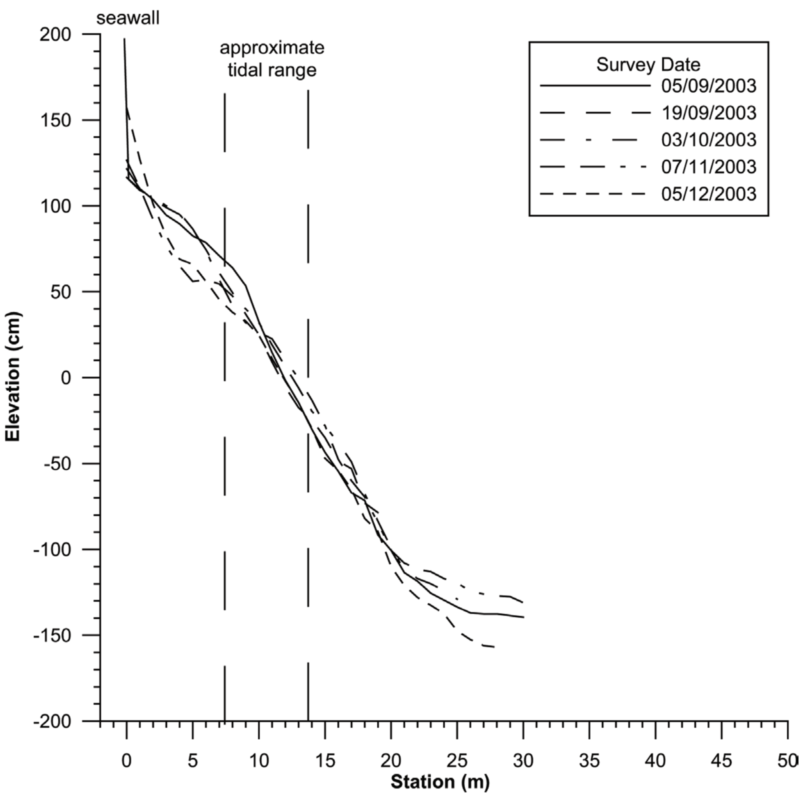

Figure 7. Surveyed profiles for transect PF on ten dates from 5 September 2003 to 5 December 2003.

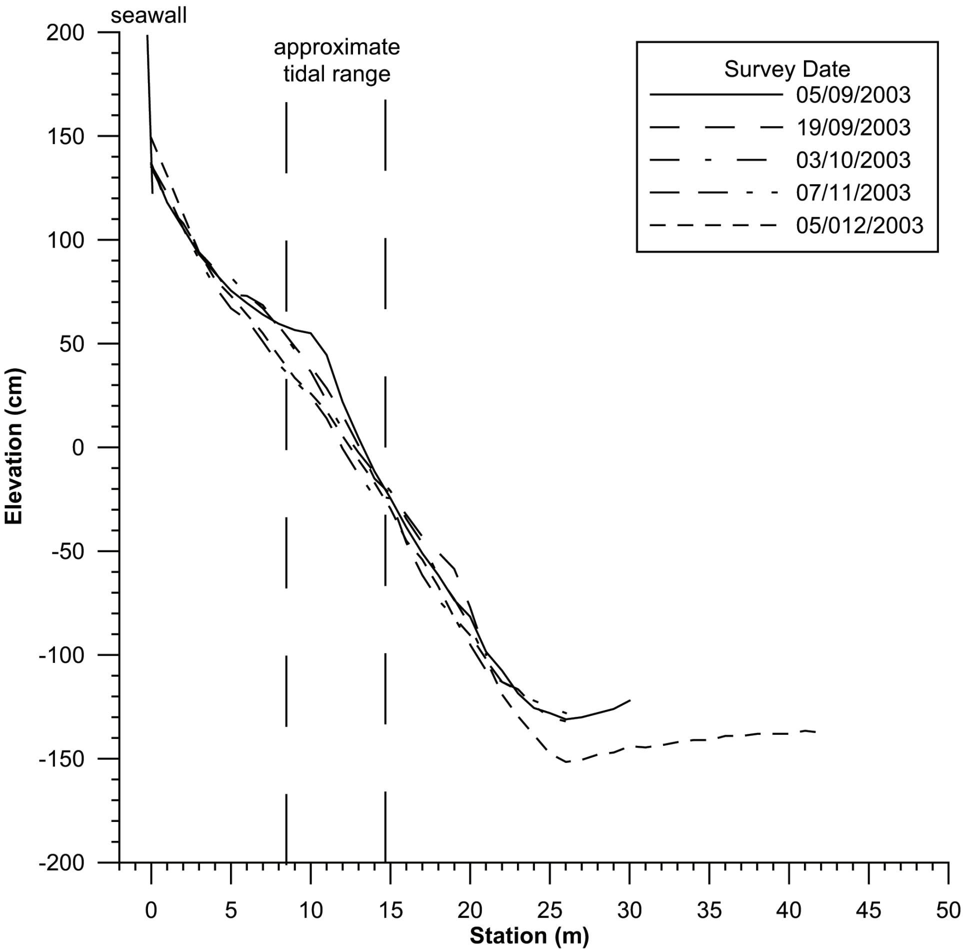

Figure 8. Surveyed profiles for transect H32 on ten dates from 5 September 2003 to 5 December 2003.

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sand along Groton Long Point Beach was visibly piled higher against the seawall along the entire beach than noted in previous transect surveys. The wrack line showed that at some point high water had reached the wall a second time. Deposition on the foreshore with some slight erosion of the berm was evident in the 3 October 2003 survey at transect PF, while volume loss dominated at transect H32. Volume loss was evident along most of the foreshore during the 7 November 2003 survey. However, a small area of deposition was noted directly at the seawall. The only exception was a small zone near the berm and the furthest offshore area measured for transect PF. The relative degree of erosion reversed somewhat for the next survey interval with slightly more volume loss for transect PF than H32 seen on the 5 December 2003 survey. Larger deposits formed near the seawall along transect PF than in the previous survey interval, but erosion characterized all other areas. Conversely, minor deposition was noted above most of the landward portion of the foreshore for transect H32, while volume loss dominated the nearshore. On 12 December 2003, Groton Long Point Beach had a significant amount of sand piled on stairs near the Picket Fence transect.

Morphological response to 2007 storms

In 2007, the beach morphology at the two study sites continued to respond differently to

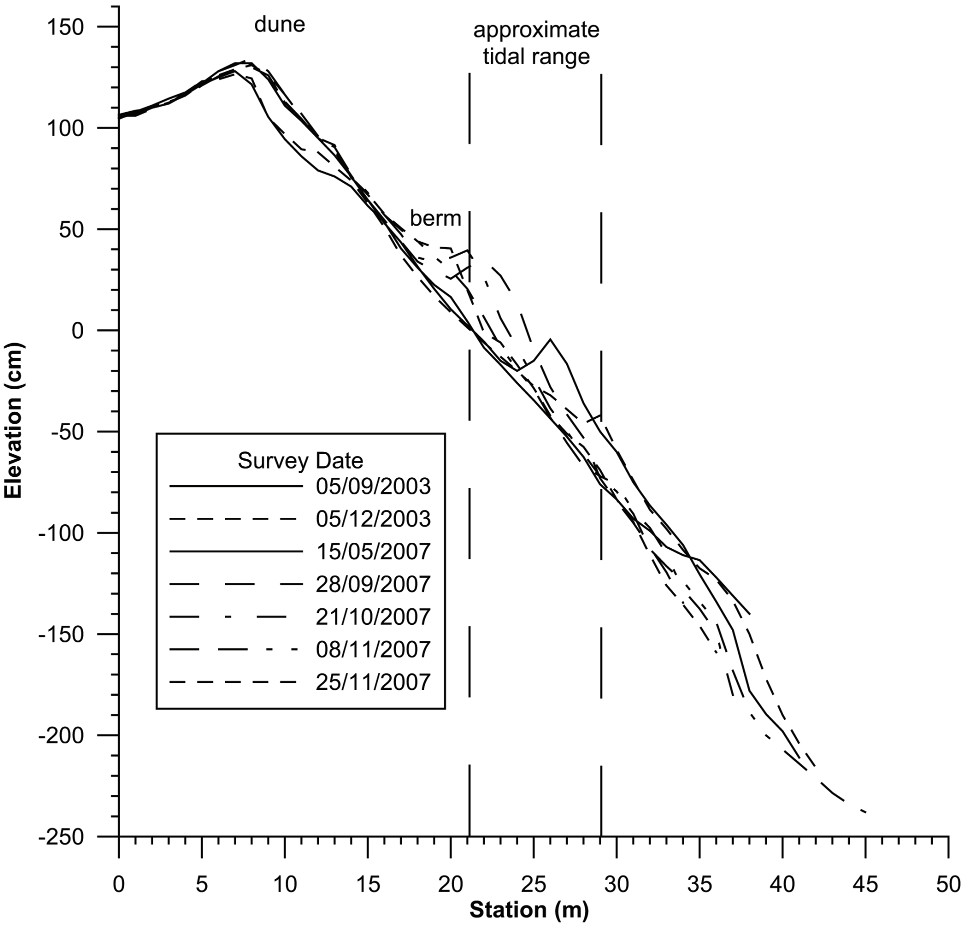

Figure 9. Surveyed profiles for transect OS on ten dates from 15 May 2007 to 25 November 2007. The 5 September and 5 December 2003 profiles provide a measure of long-term change at the site.

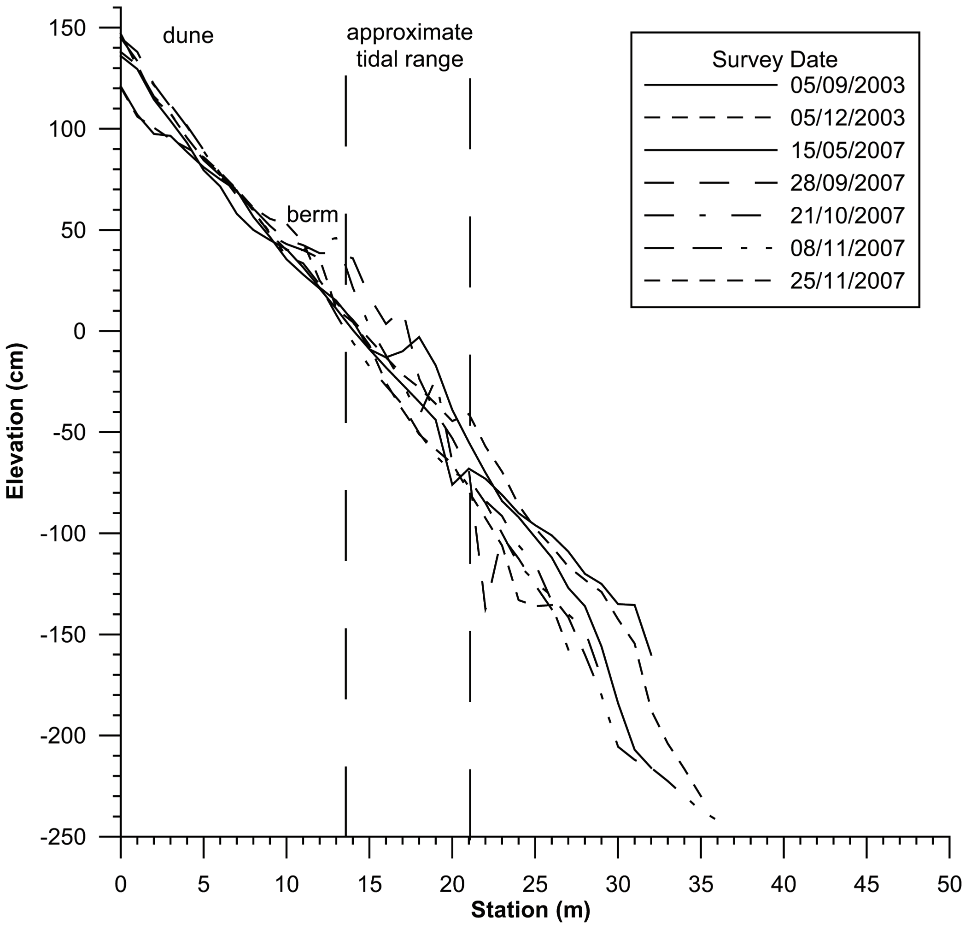

Figure 10. Surveyed profiles for transect SF on ten dates from 15 May 2007 to 25 November 2007. The 5 September and 5 December 2003 profiles provide a measure of long-term change at the site.

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the same storms. On 15 May 2007, the Bluff Point transect OS contained a bar accreted on the foreshore (Figure 9). Transects along this same profile on 28 September, 21 October and 25 November all contained distinct berms. However, on 8 November, after two storms, the profile was completely flattened. Both profiles lost sediment on the foreshore with some accumulation below the tidal zone (Figure 10). The beach was highly cuspate after the storm with a high wrack line. The pre-storm berm was removed, although a small storm berm did build at a higher elevation than the original berm. Three weeks later, on 25 November 2007, the foreshore seemed to have recovered most of the sand and had accreted a new berm. Again, the rest of the beach showed little change, except for possible trough development in the nearshore.

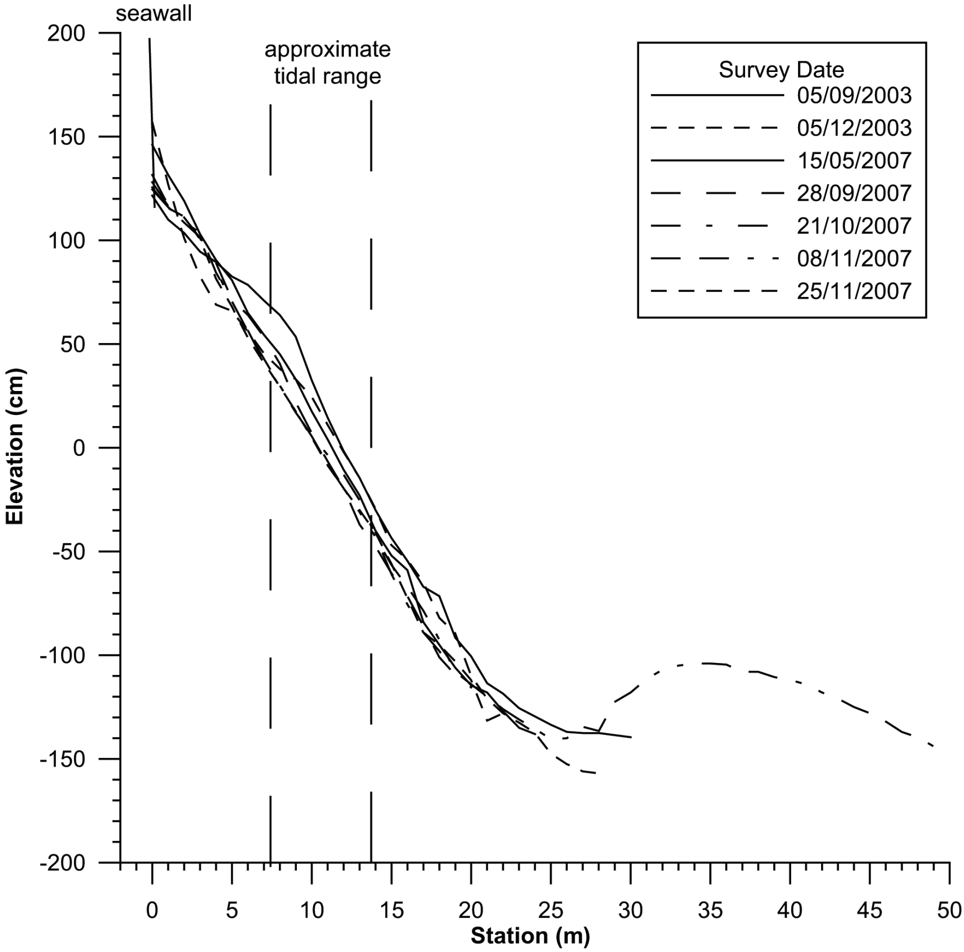

Figure 11. Surveyed profiles for transect PF on ten dates from 15 May 2007 to 25 November 2007. The 5 September and 5 December 2003 profiles provide a measure of long-term change at the site.

Groton Long Point's transects were relatively uniform with little or no berm and bar development in 2007. Furthermore, there was no cusp formation at either transect, although a flat terrace in the nearshore was noticeable. The PF profile on 15 May 2007 showed this terrace of sand near the seawall, while profiles on 21 October, 8 November and 25 November indicated the development of a small berm on the foreshore (Figure 11). Unlike Bluff Point, the beach profiles did not recover by 25 November 2007, but instead lost additional sand. Transect PF

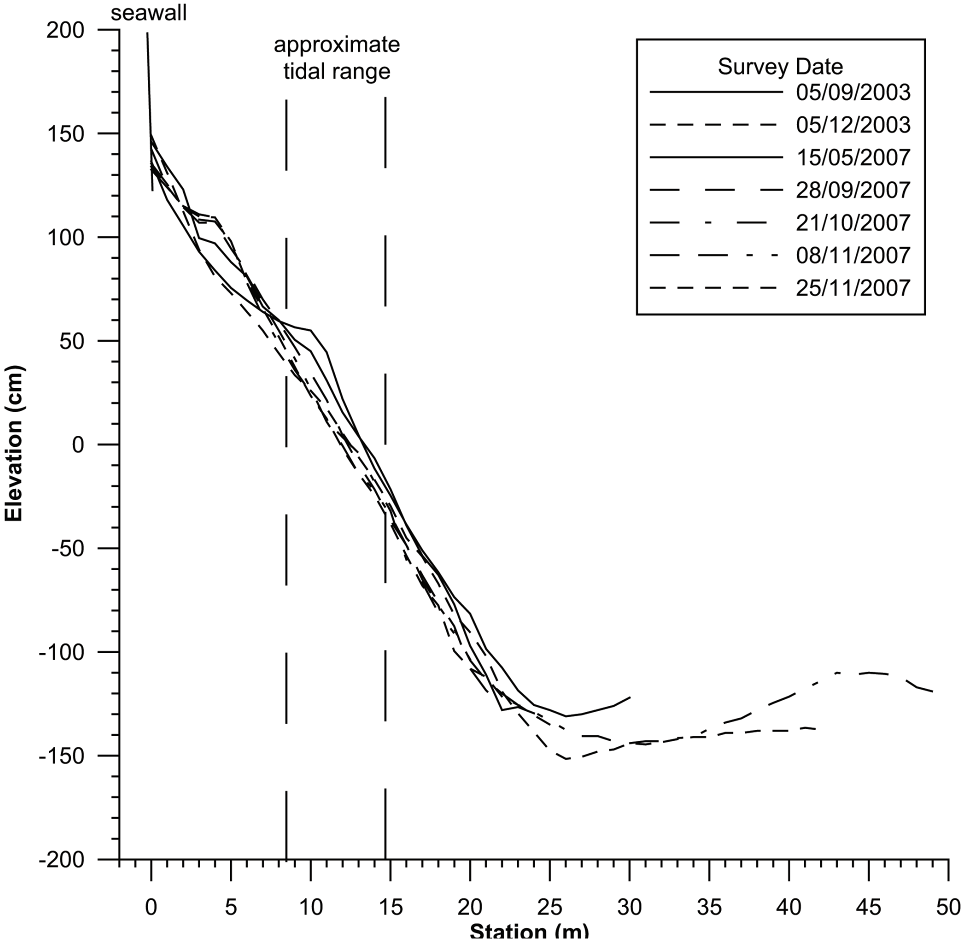

Figure 12. Surveyed profiles for transect H32 on ten dates from 15 May 2007 to 25 November 2007. The 5 September and 5 December 2003 profiles provide a measure of long-term change at the site.

behaved a little less predictably than transect H32, and zones of volume loss and deposition were smaller and more closely spaced (Figure 12). However, by 25 November 2007, both transects displayed a flat offshore bar approximately 40 m from the beach.

Seasonal trends in beach profiles

Differences in summer and winter profiles were assessed by comparing the 5 September 2003 and 5 December 2003 surveys, and the 15 May 2007 and 28 September 2007 surveys. In these comparisons, the 5 December and 15 May surveys presumably reflect typical early and late winter conditions, respectively. The September surveys represent end of summer profiles. Buoy data of wave conditions prior to the surveys support this interpretation (Table 1).

At Bluff Point in 2003, most change occurred in association with volume change below low tide. Deposition of a longshore bar with a slight trough gradually occurred from September to December along both transects. A small storm berm also developed above the high-tide level. Meanwhile at Groton Long Point small berms eroded at both transects with some deposition at the base of the seawall from September to December. Erosion of sediment in the nearshore also occurred during the fall along both transects.

Figure 9 shows the transition from a typical late season winter profile to a summer profile at Bluff Point along transect OS from 15 May 2007 to 28 September 2007. Sand stored below the low-tide level is eroded and deposited near the high-tide line to form a large berm and the steepest foreshore during this transition time. The late summer berm gradually eroded during the moderately stormy fall season from October through November to flatten the profile. A slight increase in sand storage below the low tide level formed in response to the erosion. The pattern is more complex for the adjacent SF transect with berms and bars at various cross-shore distances (Figure 10). However, a general trend of deposition below the waterline on 15 May 2007 and the steepest foreshore on 28 September 2007 is still evident. The transects in November also show a flattening of the summer profile, although elevations below the waterline did not increase considerably.

Seasonal changes at Groton Long Point were less obvious because the beach morphology lacked a backshore (Figures 11 and 12). Mechanical reworking of the beach is not a likely explanation because the 15 May 2007 survey occurred prior to raking of the beach, and the 28 September 2007 survey was over three months after raking The winter profiles at both transects tend to have more sand against the seawall than the summer profiles. Although raking activities bring this sand back to the shoreline, the summer profile still showed net erosion in the tidal zone at both transects relative to the winter profiles. The formation of a small berm is noted close to the seawall in all the fall surveys at transect H32, but appears absent for transect PF.

Long-term changes in elevation

Over the four year period, the beach transects OS and SF at Bluff Point displayed little change with minor berm and bar accretion over time. Comparisons between the last survey taken in December 2003 and the first survey taken in May 2007 show the net trend of the beach is accretion, especially in the backshore area (Figure 9 and 10). Both surveys show deposition in the area of the dune and some loss of sediment in the foreshore zone. To observe the long-term change at Bluff Point without potential complications from seasonal changes, seasonal summer transects from September 2003 and 2007 were also compared. Again, measurements taken in the dune of OS showed little to no change beyond slight berm and bar accretion lower on the profile. Conversely, data from the SF transect was more uneven with accretion in the dune area, which may be partially influenced by the difficulty in reoccupying the 2003 transect line.

There was more long-term variability on Groton Long Point beach (Figures 11 and 12). From December 2003 to May 2007, both transects depicted a 20 cm elevation change to the minimal backshore. However, the foreshore behaved differently. At transect PF, the foreshore displayed a loss of sediment, there was an abundance of sand on the upper beach, and a loss of

Transect	2003 d_{50} (mm)	2007 d_{50} (mm)	2003 Sorting index	2007 Sorting index
Bluff Point (SF)	4.0	3.2	1.8	1.6
Bluff Point (OS)	5.9	4.4	1.7	1.7
Groton Long Point (PF)	0.78	0.35	1.8	1.5
Groton Long Point (H32)	0.65	0.60	1.5	1.4

Table 2. Sediment median particle sizes (d_{50}) and sorting index values for berm locations in 2003 and 2007.

Transect	Foreshore d_{50} (mm)	Berm d_{50} d_{50} (mm)	Foreshore sorting index	Berm sorting index
Bluff Point (SF)	0.47	3.2	7.7	1.6
Bluff Point (OS)	1.9	4.4	5.9	1.7
Groton Long Point (PF)	0.76	0.35	1.5	1.5
Groton Long Point (H32)	0.71	0.60	1.8	1.4

Table 3. Sediment median particle sizes (d_{50}) and sorting index values for berm and foreshore locations in 2007.

sand directly near the seawall. Transect H32 also showed a loss of sand directly at the seawall, but accretion of sand over the remaining beach areas. In comparing the September 2003 and 2007 surveys, both the foreshore and nearshore lost sand.

Sediment analysis results

Changes in the size of sediments from 2003 to 2007 were relatively small at both sites (Table 2). Sediments on the beach at Bluff Point were noticeably coarser than those at Groton Long Point beach in both 2003 and 2007. Bluff Point sediments contained sand, shells, and pebbles, while Groton Long Point sediments were mostly sand. Bluff Point berm samples were less sorted than the berm at Groton Long Point. In 2007, sediments grabbed from the vicinity of the berm at Bluff Point contained coarser sediment than the foreshore (Table 3). The beach at Groton Long Point consisted of much finer sediment and showed the reverse trend with coarser sand on the foreshore than the berm. The foreshore was considerably more sorted at Groton Long Point than at Bluff Point in 2007. The foreshore for transect SF was bimodal. This is likely due to either two different processes or two different strengths of the same process taking place. No other samples from any dates displayed a bimodal distribution.

Discussion

As described in more detail below, the beach at Bluff Point generally responded to variations in wave conditions with morphologic changes expected for normally-functioning systems. Plots of the Bluff Point transects show most change in the foreshore of the profiles, while the Groton Long Point transects tend to show most change in the top of the transect near the seawall. Bluff Point profiles flattened during high energy periods, and formed steeper foreshores with berms during quieter periods. In contrast, the beach at Groton Long Point was much more unpredictable and lacked the morphological features present at Bluff Point beach.

Storm response

Both Bluff Point beach transect locations behaved comparably in response to the storms with a net loss of sand on the lower beach after the storm (Figures 5 and 6). Each beach profile displayed a berm before the storm that disappeared after the storm, along with development of nearshore bars and troughs (Figures 9 and 10). The loss of volume on the foreshore and disappearance of pre-storm berms is a normal reaction to an increase in wave height and steepness (Boothroyd, Klinger, and Galagan 1998), while the lack of change above the wrack line verifies the vertical control of the surveys. The beach at Bluff Point also displayed the first step to beach recovery after a storm, which is rapid foreshore accretion (Morton, Paine, and Gibeaut 1994). Eventually, both transects recovered the sand lost from the foreshore and berm. Based on the sediment analysis, sediment accreted on the foreshore is smaller than that deposited in the vicinity of the berm. The pattern reflects the higher wave energy during storms that influence the berm and the lower wave energy during deposition of the foreshore. The formation of cusps on Bluff Point after the storm is also a normal response and indicates that a single dominant wave period was influencing sediment transport.

In comparison, the beach transects at Groton Long Point showed little morphologic response to the storms, and the lack of a berm was apparent (Figure 7 and 8). Storm recovery response varied between transects with accretion at one and erosion at the other. Increased morphologic variability in front of seawalls was noted in previous research (Plant and Griggs 1992). The sediment dynamics across the whole exposed beach represent just the foreshore portion of the typical unconstrained profile. If waves break close enough to the seawall during a storm, there is little room for berm development along the beach. Wrack lines were within one meter of the seawall and reached its base in some places during storms. Sediment also shows the reverse trend relative to Bluff Point with smaller sediments located further up the foreshore. This trend may reflect weakened swash further up the shore. As a result, the entire beach at Groton Long Point most likely functions as a foreshore and lacks a backshore.

Seasonal change

Beaches at Bluff Point and Groton Long Point changed in response to various conditions and follow the classic cut and fill seasonal cycle described by Komar (1998). Although a berm is not obvious in 2003, data from 2007 clearly show berm development predicted during lower wave energies in summer. In both 2003 and 2007 at each transect, Bluff Point beach profiles flatten in response to increased wave energy in the winter. The sand is shifted to the nearshore to create the bar and trough system described by Komar (1998). This winter profile serves to dissipate wave energy over a wide surf zone during storms.

In contrast, both summer and winter profiles tend to display a uniform, steep slope at Groton Long Point and neither transect showed much evidence of seasonal change (Figures 11 and 12). The only exception was on 5 September 2003 when slight berm development is apparent 10 m from the seawall along transect H32 and 9 m from the seawall along transect PF. However, the feature does not persist in the other surveys. In 2007, the smaller flat zone immediately adjacent to the seawall at transect H32 may be a result of foot traffic along the beach. The summer profile's steepness could be influenced by the human manipulation the beach undergoes before the summer season. However, these activities would seem to flatten the profile because sand is brought from the seawall back towards the shoreline. In contrast, deposition at the seawall appears to increase total relief of the beach during the winter.

Long-term trends

Bluff Point displayed little long-term change with a tendency for deposition over the four year study period. The trend of accretion is similar for the December 2003 to May 2007 survey comparisons and the September 2003 to September 2007 survey comparisons. The course sediments on Bluff Point may account for the observed deposition over the four year periods.

Coarser sediments may be eroding from the headlands to the east. The change in grain size from larger to smaller east to west on Bluff Point, is evidence of a longshore transport mechanism in the system with a potential sediment supply from the bluff. Much of the accretion was located along the dune front, presumably because a storm prior to the first survey on 5 September 2003 eroded this area. The dune front changed very little during the high wave conditions in the fall of 2003, but had recovered to some degree by 2007. There was little to no change in the dune area itself along transect OS, which helps demonstrate the accuracy of the surveys taken in 2003 and 2007. Unfortunately, the SF transect was more difficult to reoccupy because the sand fence was displaced from its original location. However, the similarity of trends for the dune front compared to the OS transect suggests it is likely that the SF transect was approximately in the original location and simply documents similar accretion along the dune front.

In comparison, long-term change on Groton Long Point was less predictable. From December 2003 to May 2007, both transects showed accretion to the upper beach. However along the foreshore one beach transect exhibited accretion of sediments over the four-year period, while the other beach transect showed volume loss. In comparing the September surveys, the foreshore and nearshore zone generally lost considerable amounts of sand. Dean (1987) discovered seawalls could be responsible for offshore bar formation, while other literature mentions sediments from the beach in front of a wall formed a relatively flat plateau extending towards the wave breaking zone (Kamphuis, Rachet, and Jul 1992). Therefore, the large bar revealed offshore during 2007 low-tide surveys could be a storage site within the littoral system. Groton Long Point's sediment size is fine and stays uniform along the length of the beach. Since the headlands in this area are armored and developed, it is unlikely sediment is actively being transported from headland to beach in this area.

Influence of the seawall and sand raking

Groton Long Point's variability suggests that the entire beach lacks an extensive backshore and behaves like a foreshore. While Bluff Point accreted sand, sediment from Groton Long Point was eroded. The observation of sand accumulating at the base of the wall suggests that the seawall is creating an obstruction to both berm and dune development. The lack of coarse sediment deposition on the beach also supports this conclusion. The difference in slope between the two beaches further accentuates that Groton Long Point is an anomaly. Usually beaches containing coarser sediments retain a steeper slope than fine grained beaches (Komar 1998). Sediment size is smaller at Groton Long Point, but the beach is steeper presumably because of the seawall. Sand is mechanically moved seasonally to reshape the beach at Groton Long Point to create a flatter foreshore conducive for recreation. However, even once the beach is flattened it is still steeper than Bluff Point beach. The data from the sediment analysis indicate that changes in beach morphology at both sites are not likely to be associated with any changes in sediment size or sorting during the study period. Sediment size and sorting along the berm were generally similar in 2003 and 2007. The minor changes in particle size probably reflect the heritage of individual storm events that impacted the area from 2003 to 2007. Similarly, minor changes in sorting values most likely represent slight changes in storm history. Therefore, the differences in morphologic behavior at the two sites are most likely due to other factors that center on the seawall and sand raking. The seasonal profile data indicate that sand raking and mechanical redistribution have only a minor impact on the area compared to the effect of the seawall. Although there is not strong evidence that Groton Long Point beach had a net loss of sediment as initially predicted, the constrained system still appeared to have less sediment availability compared to the unconstrained beach at Bluff Point which had net sediment accretion during the study period.

Conclusions

Beach profiles measured at Bluff Point and Groton Long Point both exhibited changes due to storms, seasons, and longer term trends. The response at Bluff Point to higher energy wave conditions can be defined as a normal response for an unconstrained beach characterized by a trend of deposition over the four years, with sediment most likely supplied by the dunes and headlands bordering the beach. Periods of high wave energy removed berms and dispersed sand offshore in bars. Bluff Point also showed evidence of Komar's (1998) description of a cut and fill seasonal cycle with summer profiles characterized by large wide berms, and winter profiles that contained bar and trough systems without berms. Conversely, Groton Long Point exhibited much more variability between transects during storms and over the four year study period. In response to the storm, one beach experienced a loss in volume, the other displayed deposition. The wrack line close to the seawall indicates that there is little room for any berm development on the beach. Summer and winter profiles lack features, display a uniform slope, and show no evidence of seasonal profile change. Over a four year period the beach maintained its position, but new sediment contributions to the system are minimal. Bluff Point beach was characterized by continued accretion from 2003 to 2007, making it the more resilient beach overall. Hard stabilization methods may provide short-term benefits from storms at Groton Long Point, but once sea-level rises to the hard structures, its beach will be unable to retreat landward and will cease to exist.

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KATHERINE A. SERAFIN is a graduate student in the College of Earth, Oceanic and Atmospheric Sciences at Oregon State University, Corvallis, OR 97331. Email: kserafin@coas.oregonstate.edu. She is currently analyzing wave records throughout the Pacific Ocean. Her continued work will focus on assessing the potential impacts of extreme wave and water level events and developing approaches for evaluating coastal flood and change hazards along the U.S. West Coast.

CATHERINE CAMPBELL is a geologist with Encana Oil & Gas (USA) Inc. in Denver, CO 80202. Email: catherine.campbell@encana.com. She completed a masters at University of Wyoming evaluating strontium isotopes in coal bed natural gas produced water in the Powder River Basin, Wyoming and is currently working on development of tight gas sands in the Piceance Basin, Colorado.

DOUGLAS M. THOMPSON is Professor of Geology in the Department of Physics, Astronomy and Geophysics, and the Karla Heurich Harrison '28 Director of the Goodwin-Niering Center for the Environment at Connecticut College, New London, CT 06320. Email: dmtho@conncoll.edu. His research and interests center on geomorphology of fluvial and marine systems, and river restoration.

References

Basco, D. R., D. A. Bellomo, J. M. Hazelton, and B. N. Jones. 1997. The influence of seawalls on subareial beach volumes with receeding shorelines. *Coastal Engineering* 30: 203-233.

Boothroyd, J. C, J. P. Klinger, and C. Galagan. 1998. Coastal geologic hazards on the south shore of Rhode Island, In *Guidebook to field trips in Rhode Island and adjacent regions of Connecticut and Massachusetts*. ed. D.P. Murray, A5-1 -A5-27: New England Intercollegiate Conference Guidebook.

Davis, R. A. Jr., and D. M. Fitzgerald. 2004. *Beaches and coasts*. Malden, MA: Blackwell Publishing.

Dean, C. 1999. *Against the tide, the battle for America's beaches*. New York: Columbia University Press.

Dean, R. G. 1987. Coastal armouring: Effects, principles and mitigation. In *Proceedings twentieth coastal engineering conference*, ed. B. L. Edge, 2: 1843-57. New York: American Society of Civil Engineers(ASCE).

Connecticut Department of Environmental Protection (CDEP). 2003. *A management plan for the Bluff Point Coastal Reserve and the Bluff Point Natural Area Preserve*. State of Connecticut, Department of Environmental Protection, Hartford, CT.

Fitzgerald, D.M., S. Van Heteren, and T.M. Montello. 1994. Shoreline processes and damages resulting from the Halloween eve storm of 1991 along the north and south shores of Massachusetts Bay, USA. *Journal of Coastal Research* 10: 113-132.

Griggs, G.B, J.F. Tait, K. Scott and, N. Plant. 1991. The interaction of seawalls and beaches: Four years of field monitoring, Monterey Bay, California. *Proceedings Coastal Sediments '91*, American Society of Civil Engineers

Griggs, G.B., J.F. Tait, and W. Corona. 1994. The interaction of seawalls and beaches: seven years of field monitoring Monterary Bay, California. *Shore Beach*. 63: 21-28.

Gunton, A. 1997. Upper foreshore evolution and sea wall stability, Jersey, Channel Islands. *Journal of Coastal Research* 13: 813-821.

Hasslet, S. K. 2003. *Coastal systems*. New York: Routledge.

Holland, K. T. 1998. Beach cusp formation and spacings at Duck, USA. *Continental Shelf Research* 18: 1081-98.

Jayappa, K. S., G. T. Vijaya Kumar, and K. R. Subrahmnya. 2003. Influence of coastal structures on the beaches of southern Karnatka, India. *Journal of Coastal Research* 19: 389-408.

Kamphuis, J.W., K. Rakha and J. Jui. 1992. Hydraulic model experiments on seawalls. *Proceedings 23rd Coastal Engineering Conference*, American Society of Civil Engineers, 1272-1284.

Komar, P. D. 1998. *Beach processes and sedimentation*. 2nd Edition. Upper Saddle Ridge, NJ: Prentice Hall.

Komar, P. D. and R. J. Moore. 1983. *Handbook of coastal processes and erosion*. Boca Raton, FL: CRC Press.

Kraus, N. C. 1988. The effects of seawalls on the beach: An extended literature review. *Journal of Coastal Research: Special Edition* 4: 1-28.

Kraus, N. C. and W.G. McDougal. 1996. The effects of seawalls on the beach: Part I, an updated literature review. *Journal of Coastal Research* 12: 691-701.

Lacey, E. M., and J. A. Peck. 1998. Long-term beach profile variations along the south shore of Rhode Island, USA. *Journal of Coastal Research* 14: 1255-64.

Lewis, R. S., and DiGiacomo-Cohen, M. 2000. A review of the geologic framework of the Long Island Sound Basin, with some observations relating to postglacial sedimentation. *Journal of Coastal Research* 3: 522-32.

Marlowe, H. 1999. Assessing the economic benefits of America's coastal regions. In *Trends and future challenges for U.S. national ocean and coastal policy*, eds. Cicin-Sain, B., R. W. Knecht, and N. M. Foster, 77-80. Washington, D.C.: National Ocean Service.

Morton, R. A., J. G. Paine, and J. C. Gibeaut. 1994. Stages and duration of post-storm beach recovery, southeastern Texas coast, U.S.A. *Journal of Coastal Research* 10: 884-908.

Morton, R.A. 1988. Interactions of storms, seawalls, and beaches of the Texas coast, *Journal of Coastal Research*, SI 4: 115-136.

Nelson, D. D. 1991. Factors effecting beach morphology changes caused by Hurricane Hugo, Northern South Carolina. *Journal of Coastal Research*, SI 8: 163-179.

Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden and C. D. Woodroffe 2007: Coastal systems and low-lying areas. In Climate Change 2007: *Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Eds. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, 315-56. Cambridge: Cambridge University Press.

Pilkey, O. H., and H. L. Wright. 1988. Seawalls versus beaches. *Journal of Coastal Research: Special Edition* 4: 41-64.

Plant, N. G., and G. B. Griggs. 1992. Interactions between nearshore processes and beach morphology near a seawall. *Journal of Coastal Research* 8:183-200.

Ritter, D. F., R. C. Kochel, and J. R. Miller. 2002. *Process geomorphology*. Boston, MA: McGraw Hill.

Ruggiero P., and W. G. McDougal. 2001. An analytical model for the prediction of wave setup, longshore currents and sediment transport on beaches with seawalls. *Coastal Engineering* 43: 161-82.

Stone, J. R., J. P. Schafer, E. H. London, M. DiGiacomo-Cohen, R. S. Lewis and W. B. Thompson. 2005. Quaternary Geologic Map of Connecticut and Long Island Sound Basin. U.S. Geological Survey Scientific Investigations Map 2784.

Thornton, L., and N. L. Jackson. 1998. Spatial and temporal variations in debris accumulation and composition on an estuarine shoreline, Cliffwood Beach, New Jersey, USA. *Marine Pollution Bulletin* 36: 705-11.

Werner, B. T., and T. M. Fink. 1993. Beach cusps as self-organized patterns. *Science* 260: 599-606.