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A Review of Sediment Budget Imbalances along Fire Island, New York: Can Nearshore Geologic Framework and Patterns of Shoreline Change Explain the Deficit?

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ABSTRACT

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Sediment budget analyses conducted for annual to decadal timescales report variable magnitudes of littoral transport along the south shore of Long Island, New York. It is well documented that the primary transport component is directed alongshore from east to west, but relatively little information has been reported concerning the directions or magnitudes of cross-shore components. Our review of budget calculations for the Fire Island coastal compartment (between Moriches and Fire Island Inlets) indicates an average deficit of 217,700 m^3/y. Updrift shoreline erosion, redistribution of nourishment fills, and reworking of inner-shelf deposits have been proposed as the potential sources of additional sediment needed to rectify budget residuals. Each of these sources is probably relevant over various spatial and temporal scales, but previous studies of sediment texture and provenance, inner-shelf geologic mapping, and beach profile comparison indicate that reworking of inner-shelf deposits is the source most likely to resolve budget discrepancies over the broadest scales. This suggests that an onshore component of sediment transport is likely more important along Fire Island than previously thought. Our discussion focuses on relations between geomorphology, inner-shelf geologic framework, and historic shoreline change along Fire Island and the potential pathways by which reworked, inner-shelf sediments are likely transported toward the shoreline.

ADDITIONAL INDEX WORDS: *Long Island, Fire Island, sediment budget, cross-shore transport, shoreline change, nearshore bathymetry, geologic framework.*

INTRODUCTION

The south shore of Long Island (SSLI) comprises a series of barrier islands stretching from Rockaway Beach in the west to Shinnecock Inlet to the east (Figure 1A). The south shore gradually increases in relief east of Shinnecock Inlet and ends at Montauk Point, where coastal bluffs are the dominant geomorphic feature of the system. Fire Island is in the central portion of the barrier island system and extends 50 km from Moriches Inlet in the east to Fire Island Inlet. Alongshore sediment transport from east to west has been widely documented on the basis of spit growth and inlet dredging records (Leatherman, 1985; Smith *et al.*, 1999). Uncertainties and unresolved deficits in the alongshore sediment budget (Lentz, Hapke, and Schwab, 2008) have lead some researchers to suggest that an inner-shelf sediment source supplies material to the upper shoreface along the SSLI, especially along western Fire Island. According to Schwab *et al.* (2000), Williams (1975), and Williams and Meisburger (1987), the inner shelf might act as a significant sediment source, but the timescale on which it acts is unknown. Others suggest that no significant exchange occurs between the inner shelf and the shoreface (Kana, 1995; Morang, Rahoy, and Grosskopf, 1999; Rosati, Gravens, and Smith, 1999). However, most studies concur that cross-shelf transport of sediment is complex and the processes and timescales controlling this movement are not fully understood. Few studies have documented cross-shelf transport along the SSLI or Fire Island. However, numerous studies conducted in other areas show that cross-shore transport is an important coastal process, and sediment transported from the inner shelf to the shoreface is an essential component of a coastal sediment budget (Conley and Beach, 2003; Hinton and Nicholls, 2007; Park, Gayes, and Wells, 2009; Swift *et al.*, 1985; Wright *et al.,* 1991) on timescales ranging from storms to years to several decades. It is likely that similar processes are active along the SSLI as well.

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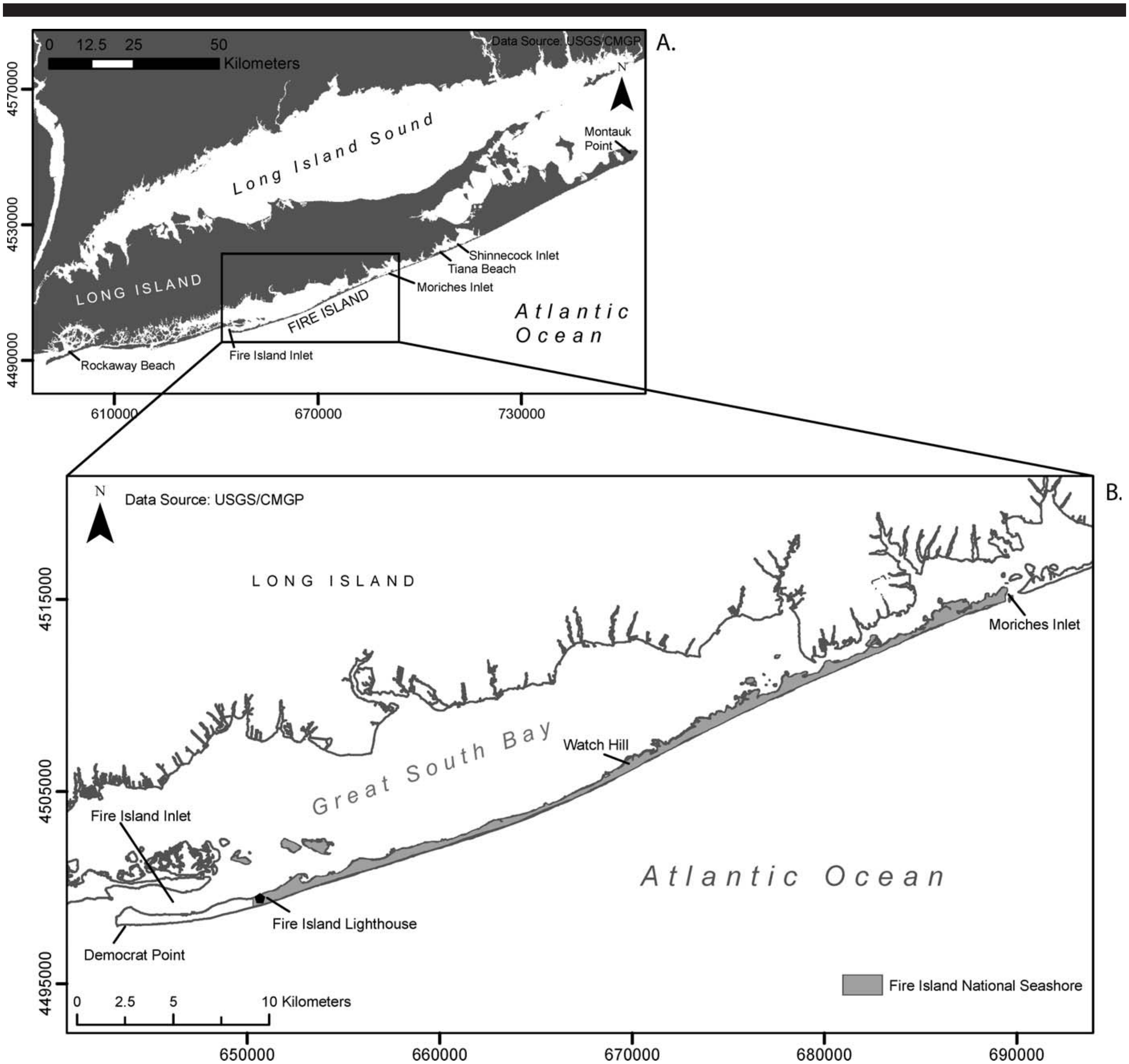

Figure 1. (A) Regional map of the south shore of Long Island, New York, showing place names discussed in the text; (B) location map of Fire Island.

Understanding the regional sediment budget and the processes governing it are crucial for the effective management of the SSLI. Coastal managers, especially in the federally managed lands (*i.e.*, Fire Island National Seashore; Figure 1B), rely on science to better understand coastal processes and better manage and protect coastal resources. In this paper, we present a review of the current knowledge base of coastal sediment budgets and sediment transport mechanisms along the SSLI, with a focus on Fire Island; examine problematic assumptions in currently applied engineering models; and present new information that demonstrates the influence of the nearshore geologic framework on shoreline behavior and provides evidence of a physical linkage between the offshore and the beach system.

STUDY AREA

Barrier Island Geomorphology and Geologic Setting

Long Island is an east–west oriented island in New York that marks the northern limit of the New York Bight reentrant and southern boundary of the Coastal Plain. Long Island is composed of high relief glacial deposits, and the coastal system along the south shore is composed of glaciofluvial deposits of varying thickness. The sand and gravel deposits were transported by ancestral rivers and numerous glaciofluvial streams that drained moraines to the south as the climate warmed and the glaciers retreated (Williams, 1975). As sea level rose during the Holocene, the shoreline transgressed from the shelf edge to its current position. Modern coastal landforms, dominated by barrier islands, were constructed by a combination of sand eroded from the moraine headland section of eastern Long Island and moved westward by longshore currents and sand eroded and remobilized from submerged outwash deposits on the continental shelf (Leatherman, 1985).

The SSLI barrier system is microtidal with a mean tidal range of 1.3 m (Leatherman, 1985). The predominant wave direction from the east and southeast drives net longshore transport in a westerly direction. Local reversals have been recorded (Kana, 1995; Rosati, Gravens, and Smith, 1999) and are likely due to variation in wave direction. Fire Island, one of the largest barrier islands of the SSLI system, is bounded by engineered inlets: Fire Island Inlet on the west and Moriches Inlet on the east (Figures 1A and B).

The southeast-facing shore of Long Island is directly affected by extra-tropical storms and hurricanes arriving from the south. The effects, documented as early as the 1600s, show that throughout recorded history, storms have had a substantial influence on the geomorphology of this coast. Storm-driven overwash events create surge channels through the dune system that frequently lead to inlet formation (Leatherman, 1985).

The late Holocene evolution of Fire Island has been well documented by Leatherman (1985). East of Watch Hill (Figure 1B), the island has migrated landward through inlet formation and subsequent marsh accretion on the bay side. In comparison, west of Watch Hill, the island has no historical inlets, and this portion of Fire Island does not appear to be migrating landward at the same rate as the eastern portion of the island. Although overwash events have increased island elevations, the ocean-facing beaches from Watch Hill to the Fire Island Lighthouse (Figure 1B) continue to erode with little sediment deposited into the back-bay marsh, resulting in an overall narrowing of the island (Leatherman, 1985). The western segment of the barrier island from the Fire Island Lighthouse to Democrat Point (Figure 1B) formed as a prograding spit, as evidenced from large, parallel back-dune ridges that are geomorphic evidence of relict recurved spit formation processes.

Inner-Continental Shelf

The pronounced ridge and swale morphology of the continental shelf south of Long Island, has been described by Duane *et al.* (1972) and Uchupi (1968). The ridge features consist of linear shoals that can be shoreface-attached or -detached and tend to be oriented parallel to the direction of the dominant storm wave approach (Uchupi, 1968). Linear shoals or ridges are ubiquitous features of the Mid-Atlantic Bight continental shelf. However, their origin and evolution are not well understood. A large body of literature discusses specific ways in which the ridges evolve and are maintained via oceanographic processes, including Hayes and Nairn (2004), Huthnance (1982), Snedden and Dalrymple (1999), and Trowbridge (1995). The details of these process theories will not be described herein.

Subsequent mapping of the Long Island inner shelf by Schwab *et al.* (2000) showed that the ridges extend offshore approximately 20 km, are spaced 1–3 km apart, and have a northwest–southeast azimuth of approximately 120° to 130°. West of Watch Hill, the ridges appear to be attached to the shoreface. The ridges are composed of Holocene sediment texturally similar to the sand found on the Long Island barrier island beaches. The ridges lie above the Holocene transgressive surface, a disconformity with underlying Pleistocene glacial outwash deposits composed of sand, gravel, and limited mud (Schwab *et al.*, 2000). The ridges west of Watch Hill rise as high as 6 m above the seafloor. Sand ridges above the Holocene transgressive surface are also present along the eastern half of the island, although less well formed, less continuous, and detached from the shoreface.

SEDIMENT BUDGET ESTIMATES

A sediment budget describes sediment influx, storage, loss, and transport pathways in a coastal system. The components of a sediment budget are often difficult to accurately quantify, and estimates for a given area typically have high uncertainty values. Sediment transport pathways within a littoral system comprise two primary components: longshore transport and onshore–offshore transport. Most coastal sediment budgets assume that the later is negligible, even though Wright *et al.* (1991) demonstrated that cross-shore transport gradients are much greater than alongshore gradients. Along the SSLI, longshore transport is the primary mode of sediment movement and is well documented at Fire Island on the basis of jetty infilling and pre-jetty spit growth at Fire Island Inlet.

Sediment budget fluxes are commonly estimated from jetty/groin infilling rates, spit growth rates, inlet dredging records, beach and dune erosion/accretion rates, and nourishment records. Beach profiles, collected in time series, are also used to assess how transport gradients vary alongshore through the analysis of volume changes to the profiles. A number of sediment budgets have been calculated for the Fire Island to Montauk Point barrier system over annual to decadal timescales. The system-wide estimates are formulated along smaller local cells that more accurately reflect spatial and temporal changes within the system. We focus on the stretch of coast between Moriches and Fire Island Inlets (Figure 1A and Table 1) and discuss three sediment budgets, primarily because they are published in peer-reviewed journals rather than the gray literature (Kana, 1995; Panuzio, 1969; Rosati, Gravens, and Smith, 1999). These three budgets demonstrate the differences in the assumptions and the time intervals used in the studies.

Panuzio (1969) estimates that 267,600 m^3/y of material is entering the Fire Island system at Moriches Inlet, and the rate of longshore transport at Fire Island Inlet is 458,700 m^3/yr (Table 1). His estimates are based primarily on inlet migration and variations in shoreline erosion rates along the coast. The shoreline data and inlet progradation information (historical maps) date back to the early 1800 s. The differences in the along-coast values provided by Panuzio (1969) indicate that

Table 1. *Summary of inputs, outputs, and proposed sources of material to the coastal system from existing sediment budgets for Fire Island.*

Reference	Years	Input (m^3/y)	Output (m^3/y)	Deficit (m^3/y)	Addition of Material East–West
Panuzio (1969)	1931–1933; 1873–1909	267,600*	458,700*	191,100	Beach nourishment from tidal inlet
Kana (1995)	1955–1979	45,000*†	360,000*†	315,000	Relict ebb tidal delta
Rosati, Gravens, and Smith (1999)	1979–1995	29,000*†‡	176,000*†‡	147,000	None: deficit is within the range of uncertainty (±40,000 m^3/y)

* On the basis of impoundment rates at jetties, westward migration of inlets, or both.
† On the basis of volumetric estimates from beach profiles, shoreline change, or both.
‡ From Rosati, Smith and Gravens (1999) Table 1 and Figure 5.

191,100 m^3/y is contributed to the system along the stretch of coast from Moriches Inlet to Fire Island Inlet, which he suggests could be accounted for by beach nourishment. However, the fill areas for beach nourishment are west of Fire Island Inlet and cannot account for excess material between Moriches and Fire Island Inlets. Panuzio (1969) provided no error or uncertainty estimates for his sediment budget calculations, and the budget numbers he presents are based only on subaerial changes to the coastal system.

Kana (1995) developed a detailed sediment budget for the SSLI, in which he estimated that the sediment transport rate at Moriches Inlet is 45,000 m^3/y but increases to 360,000 m^3/y at Fire Island Inlet (Table 1). The numbers he presents are based on profile data from two time periods, 1955 and 1979, spanning 24 years. The profiles used by Kana (1995) extended to an offshore closure depth (9–12 m), and his budget estimates also included data from dredging and fill activities. The difference in the estimate of longshore sediment transport is 315,000 m^3/y. Kana (1995) suggested that the increase in the sediment transport rates between Moriches and Fire Island Inlets was due to sediment input from erosion along the eastern portions of the island and possibly erosion of a relict ebb-tidal delta of Fire Island Inlet.

Kana's 1995 sediment budget provided the most detailed and accurate sediment budget to date and greatly improved upon studies such as that of Panuzio (1969) by including nearshore profile data and attempting to quantify and incorporate the effects of beach nourishment. Weaknesses of Kana's model include the reliance on endpoint profile changes and the lack of an uncertainty estimate. Additionally, the suggestion that the sediment budget deficit can be explained by contributions from up-coast erosion and a relict ebb tidal delta are not supported by either the long-term (century) shoreline change rates or the nearshore bathymetry (which shows no evidence of a delta-type deposit).

Rosati, Gravens, and Smith (1999) used 10 historical shoreline data sets from 1830 to 1995 to formulate a sediment budget for Fire Island to Montauk Point, focusing on the time period from 1979 to 1995 (a 16-y time period). Shoreline change rates were determined from transects spaced 25 m alongshore. Beach profile data supplemented the shoreline position data and were used in volumetric change calculations, which were determined by assuming cross-shore profile translation over an active depth. Their results estimated that 29,000 m^3/y entered the system at Moriches Inlet in the 16-year time period of their study, and 176,000 m^3/y left the system west of Fire Island Inlet (Table 1). Uncertainties in the estimate were calculated from the standard deviation of the net longshore transport rate for the region (Montauk Point to Fire Island Inlet), providing an estimated average uncertainty of 40,000 m^3/y. The net deficit associated with the Rosati, Gravens, and Smith (1999) sediment budget within the Moriches Inlet to Fire Island Inlet stretch of coast totals 147,000 $\pm$ 40,000 m^3/y.

The sediment budget provided by Rosati, Gravens, and Smith (1999) is thorough and is the first to include estimates of uncertainties associated with sediment budgets for this area. Their estimates are likely the most accurate available, although the time span of the estimate is only 16 years. A net sediment budget deficit is apparent in the values presented, but Rosati, Gravens, and Smith (1999) suggest that the deficit can be accounted for by sediment contributions from erosion along the eastern portion of the island and beach nourishment volumes. The contribution of beach nourishment volumes to sediment budgets are difficult to estimate accurately. If material for beach nourishment is dredged from ebb or flood tidal deltas, inlets, or the nearshore, this material is actually part of the coastal system and should be accounted for in the regional sediment budget estimate. Finally, Rosati, Gravens, and Smith (1999) state that it is possible that a source of offshore sediment might be a contributing factor to the nearshore sediment budget but do not identify the nature of the possible sediment source.

Existing sediment budgets estimated over a variety of timescales for Fire Island require an along-cell contribution (between Moriches Inlet and Fire Island Inlet) ranging from 147,000 to 315,000 m^3/y in order to balance (Table 1 and Figure 3). On timescales of decades to centuries, it is important to note that sediment budgets estimated over shorter timescales might not be representative of the future environment. Sediment budgets do provide useful estimates of the transport of material through approximations of the fluxes, sources, and sinks in coastal systems. However, high levels of uncertainty are associated with these estimates. The sediment budget of Rosati, Gravens, and Smith (1999), as noted earlier, is the only SSLI budget to attempt to quantify the uncertainty in their estimates.

A review of the sediment budget estimates for Fire Island provides several potential and substantial sources of uncertainty. Sediment budgets generally use inlet migration, jetty impoundment, and volumetric estimates from repeat beach profiles, some of which are widely spaced, in conjunction with shoreline change rates. Estimates based on profile changes will have spatial uncertainty associated with between-profile interpolation, as well as the offshore profile distance—shorter profiles might not capture the entire active profile. In addition to spatial uncertainty, temporal variations affect profiles depending on the day and conditions under which the profile was collected. Profiles also might not be accurate enough to capture volumes of material that are transported in thin layers over large areas. Finally, profile and shoreline change rates often incorporate historical data, which could have undetermined high error. Although the various sediment budget estimates for the SSLI and, more specifically, Fire Island have errors and uncertainties, all of the studies yield relatively similar estimates before the incorporation of intracell inputs, which themselves have errors associated with them and that in some cases are speculative.

DISCUSSION

The longshore component of the sediment budget along the SSLI is fairly well constrained despite uncertainties, and the processes driving longshore transport (prevailing wind and dominant swell directions) are generally understood. However, little is known or understood about the cross-shore component of the regional sediment budget, although a number of studies along the SSLI suggest that an inner-shelf source supplies some of the sediment to the beach and that the sediment budget deficit discussed herein might be resolved by including an inner-shelf source. Although cross-shore (especially onshore) transport processes have not been directly studied at Fire Island, numerous studies from other coastal systems indicate that cross-shore transport is common. This discussion provides a synthesis of existing evidence for an inner-shelf sediment source at Fire Island and a review of some of the key studies that support the existence of cross-shore transport as a mechanism to move sediment from the inner shelf to the beach. Additionally, we present new data that strengthens the argument for a connection between the inner shelf and the beach system and postulate that cross-shore processes are active and important along the Fire Island barrier system.

Inner-shelf Sediment Source

Several studies along the SSLI coast provide evidence in support of inner-shelf sediment as a source for beach sand (Williams, 1975; Williams and Meisburger, 1987; Williams and Morgan, 1988, 1993). These studies include an analysis of a glauconite mineral tracer whose source is the Cretaceous headland off central Fire Island and indicate that the inner shelf has been an important source of sediment to Fire Island (Williams and Meisburger, 1987). In another study, a scanning electron microscope analysis was used to compare surface textures of quartz grains from beach and offshore samples (Williams and Morgan, 1993). The analysis showed strong similarities in the textural variability of offshore samples, with samples collected from beaches, and Williams and Morgan (1993) used this as an indication that inner-shelf sediments are supplying sediment to the beaches of Fire Island. Williams and Morgan (1988) used euhedral quartz grains as tracers to tie the composition of beach sediments on the western segment of the island to glacial outwash lobes offshore.

In more indirect studies, inner-shelf sediment sources have been proposed on the basis of the stability of the central portion of Fire Island, the rapid spit growth at Democrat Point, and detailed geologic and geophysical mapping of the inner shelf. Proposed sources include a relict ebb tidal delta from a historical Fire Island Inlet (Kana, 1995) and erosion of a submerged Cretaceous headland offshore of Watch Hill during sea level rise (Schwab *et al.*, 2000). Schwab *et al.* (2000) argue that a relict ebb tidal delta, as suggested by Kana (1995), would not provide sufficient source material because of the characteristic small size of such features on wave-dominated coasts (Hayes, 1979). Such features could not yield sufficient material to support the prograding spit at Democrat Point over the last 300–500 years. Additionally, the suggestion that an offshore sediment supply from relict ebb tidal delta deposits could account for a portion of the high accretion rates at western Fire Island (Kana and Stevens, 1992) is not supported by more recent offshore data (Schwab *et al.*, 2000) that find no evidence of large ebb tidal deposits in this region.

Schwab *et al.* (2000) were the first to suggest that the sediment budget deficit along the SSLI could be balanced by sediment contribution from the shoreface-attached sand ridges off western Fire Island. Their offshore geological mapping shows that, with the exception of the ridges, limited amounts of Holocene sediment are seen the inner shelf, which they suggest is indirect evidence that cross-shore transport has been a dominant process in the region over millennial timescales. Schwab *et al.* (2000) also suggest that the sand ridges located off the western portion of Fire Island appear to be connected to the nearshore bar system and influence the local wave regime by focusing wave energy along some segments of the island. However, their bathymetric data did not extend far enough into the nearshore to definitively support the connection. The connection was instead explored by examining a 15-year record (1979–94) of shoreline change in which cells of erosion and accretion, roughly similar in scale to the ridge spacing offshore, were described as fixed in space. Schwab *et al.* (2000) suggested that the ridges themselves might serve as an offshore sediment source or sediment conduit for the inner shoreface system, following previous suggestions of Williams (1975) and Williams and Meisburger (1987) that inner-shelf sand might contribute significant sediment to the Long Island barrier island system sediment budget.

More recent work by Batten (2003) describes substantial volumetric gains to the nearshore system on the basis of an analysis of 3136 beach profiles collected along the SSLI over a 6-year period from 1995 and 2001. For Fire Island, he calculated that 372,310 m^3/y is added to the profile landward of 7.3 m water depth and attributed this addition to an offshore source.

If an offshore sediment source does supply the western half of Fire Island, as suggested by Schwab *et al.* (2000) and supported by the work of Batten (2003), large volumes of material on the order of 200,000 to 300,000 m^3/y could be added to the system in a cross-shore direction. If the source is the shoreface-attached sand ridges, the sediment could include inner-shelf material transported from well below estimated closure depths. Paleoshorelines (Schwab *et al.*, 2000), limited Holocene sediment on the inner shelf (Schwab *et al.*, 2000), and geomorphic evidence (Leatherman, 1985) all support a possible source of sediment offshore of the western portion of Fire Island.

Little information exists concerning the rates of onshore–offshore sediment transport at Fire Island, but studies at other

SSLI locations (Batten, 2003; Niederoda *et al.*, 1984; Swift *et al.*, 1985) and similar coastal systems (Conley and Beach, 2003; Hinton and Nicholls, 2007; Park, Gayes, and Wells, 2009; Wright *et al.*, 1991) suggest that it is a more important component of a sediment budget than previously assumed.

Cross-Shore Transport Processes

Storms from the south directly affected the SSLI because of the east–west orientation of the coast. The most damaging of these are hurricanes and extra-tropical storms because of their intensities and durations. Large storms such as hurricanes and extra-tropical storms generate waves with long periods and large wave heights, similar to those shown to transport material on the lower shoreface and inner shelf, well below established closure depths, in the Mid-Atlantic Bight and the Gulf of Mexico (Hayes, 1967; Morton, 1981; Snedden, Nummedal, and Amos, 1988; Wright *et al.*, 1991, 1994; Pilkey *et al.*, 1993). A long uninterrupted fetch distance along the SSLI only exacerbates the effects of these storms as waves form and gather energy over long distances before encountering the shoreline. Many storms have had substantial influence in shaping the geomorphology of the barrier islands by overwash, breaches, and the creation of inlets.

Downwelling currents are generated when onshore storm winds blow surface water landward. Along the SSLI, winds from the northeast create unequal movement of the surface waters, resulting in a residual, seaward-directed near-bottom current (Komar, 1998; Niederoda *et al.*, 1984.; Swift *et al.*, 1985). Upwelling can occur in the late stages of a major storm event because of a reversal in wind direction to the southwest, resulting in a near-bottom current moving in a landward direction (Komar, 1998; Niederoda *et al.*, 1984). These currents, along with tidal currents, are capable of transporting sediment already entrained in the water column.

Within the SSLI barrier system, sediment concentrations, fluid motions, and current and wave data gathered between 1974 and 1980 measured sediment transport across the shoreface during both storms and fair weather conditions. Instruments were deployed in the bottom boundary layer of the surf zone and shoreface off of Tiana Beach (Figure 1A), approximately 23 km east of Moriches Inlet (Niederoda *et al.*, 1984) in an area where shoreface-attached ridges are absent. Coastal storms caused the removal of large amounts of sediment from the beach and surf zone. Both Niederoda *et al.* (1984) and Swift *et al.* (1985) found that although this sediment was largely deposited on the shoreface of Long Island barriers, storm-enhanced wave orbital motion, which entrains sand on the shoreface, combined with downwelling currents and longshore currents to carry sediment across the shoreface to the inner shelf. Conversely, during fair weather conditions, a general trend of landward-directed cross-shore sediment migration predominated in the upper and lower shoreface, although at rates an order of magnitude lower than storm transport rates (Niederoda *et al.*, 1984; Swift *et al.*, 1985). The regional long-term trend showed longer intervals of moderate landward transport across the shoreface during fair weather conditions, disrupted by shorter, more intense storm intervals transporting large volumes of material to the shoreface and inner shelf (Niederoda *et al.*, 1984; Swift *et al.*, 1985). Although the studies at Tiana Beach did not measure substantial shoreward movement of sediment during storms, they do show that sediment is mobilized below the estimated closure depth during storms along the SSLI.

At the center of the debate over the importance of cross-shore transport to sediment budgets is the issue of closure depth and whether a definable depth exists below which no sediment is exchanged. Many engineering models rely on having a seaward limit for sediment exchange (Birkmeier, 1985; Hallermeier, 1981; Heilman *et al.*, 2006; Morang, Rahoy, and Grosskopf, 1999; Nicholls, Birkmeier, and Lee, 1998). Closure depth is important for calculations of sediment budgets that are estimated from profile data.

Along the SSLI, Batten (2003) calculated a decreasing closure depth to the west and related it to decreasing incident wave energy from east to west over a 6-year period (1995–2001). Kana (1995) estimated a closure depth of 9–12 m by identifying the limit of the nearshore bar on the basis of a break in slope from beach profiles over a 24.5-year period (1955–79). Morang, Rahoy, and Grosskopf (1999) estimate short-term (year-long) closure depths ranging from 5.6 m at western Fire Island to 6.8 m at eastern Fire Island, on the basis of 300 beach profiles from four survey dates between 1995 and 1996. No major storm events occurred in the time period of the profiles; thus, these estimates represent the sediment exchange process over a 1-year period when no large storms occurred.

Numerous studies of coastal morphodynamics and beach profiles along the SSLI have estimated a closure depth from beach profiles that precludes cross-shore transport, at least on the timescales of the analyses. Recent research by Hinton and Nicholls (2007) could resolve the apparent discrepancy between profile convergence and evidence of cross-shore transport. They examined a series of long (extending to the 16-m isobath), 1-km-spaced profiles over a temporal rage of 5–35 years along the Holland coast. The results showed that the profiles typically became inactive (*i.e.*, "closed") in water depths of 8 m or less, but then reopened further offshore. Over shorter timescales (5–10 y) the offshore zone was less active, but substantial changes were recorded in timescales of 20 or more years. It is possible that existing estimates of closure for the SSLI did not have either the spatial or temporal resolution to detect volumetric changes on the lower shoreface.

In situ field studies that measure changes to shoreface morphology have been conducted in a variety of locations, and many show that closure depth is a time- and event-driven state. For example, studies were conducted at Duck, North Carolina, to assess the overall validity of closure depth with the use of data from high-precision shoreface profiles by Birkmeier (1985), who reasoned that an event-dependent closure depth could be determined for specific storms. Also at Duck, Nicholls, Birkmeier, and Hallermeier (1997) and Nicholls, Birkmeier, and Lee (1998) used data from 12 years of beach profiles that extended offshore to approximately 8 m water depth NGVD (National Geodetic Vertical Datum of 1929). The profiles were compared to determine erosion, seaward, and accretion, landward, of the nearshore bar and the closure depth. Nicholls, Birkmeier, and Lee (1998) found that time-dependent closure depth conditions exist at Duck and that closure depth tended to

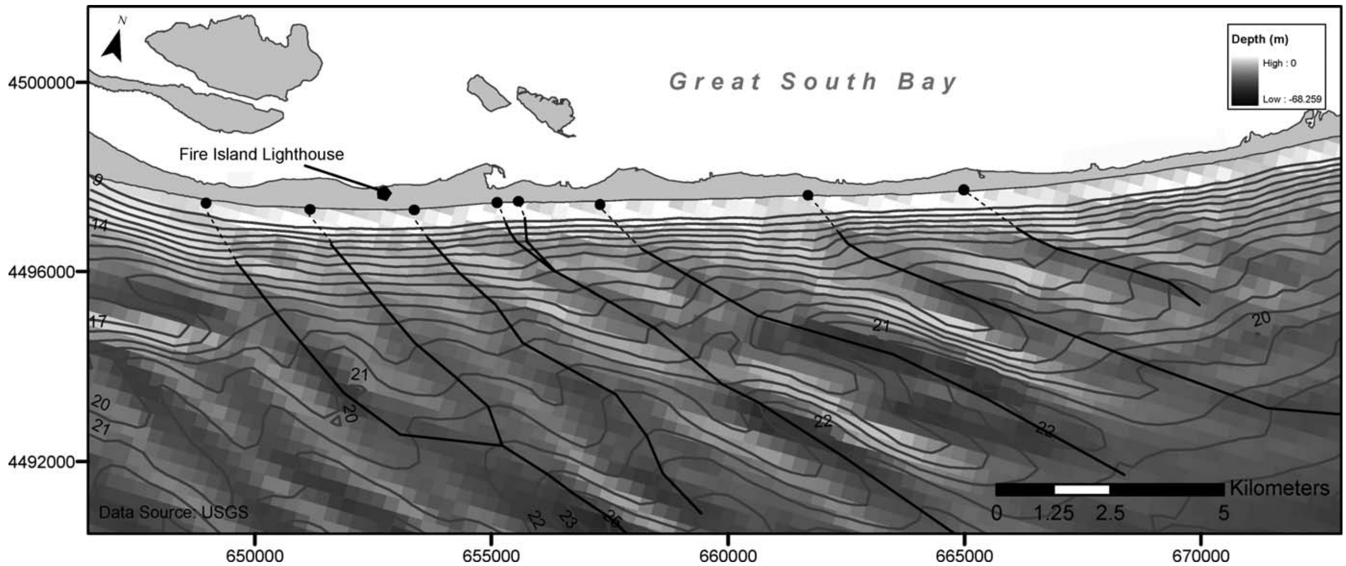

Figure 2. Bathymetric map based on data from Schwab *et al.* (2000) showing the inner-shelf ridges and troughs. The axes of the troughs are delineated and are shown as dashed lines where they are projected into the nearshore. The dots are the approximate locations of the projected trough axes where they intersect the beach.

increase (deepen) with time. Heilman *et al.* (2006) reach similar conclusions regarding changes in closure depth over time on the basis of surveys along the south Texas coast. Nicholls, Birkmeier, and Lee (1998) also observed a 40-cm net vertical change at 8 m below NGVD over a 13-year period and suggest that significant changes occurred below 8 m depth during storm events.

Wright *et al.* (1991) documented sediment transport beyond the closure depth at Duck and at Sandbridge Beach, Virginia, during both storms and fair weather conditions. Currents, wave characteristics, and suspended sediment concentrations were measured at depths ranging from 7 to 17 m depth over a 3-year period and showed that cross-shore transport occurred during both stormy and fair weather conditions, driven largely by unidirectional tide- and wind-induced currents. Pilkey *et al.* (1993) reference work in the Gulf of Mexico that finds bottom sediments move in thin sheets, large in surface area, that are difficult to resolve in even high-precision bathymetric profiles (Hayes, 1967; Morton, 1981; Snedden, Nummedal, and Amos, 1988). The authors state that the resolution of most profiles that are used for sediment budget calculations are likely too coarse to detect the changes that would occur from the transport of thin sediment sheets of sediment movement and thus might record closure when exchange of sediment between the nearshore and inner shelf is still occurring.

Although no direct measurements of onshore sediment transport of sediment exist from the inner shelf to the shoreface at Fire Island, indirect evidence exists that suggests, over decades to half centuries or more, the trend in the region is one of net onshore transport of sediment. The work of Schwab *et al.* (2000) shows the absence of Holocene sediment deposits on the inner shelf along much of southern Long Island and suggests a long-term trend of net onshore transport of eroded shelf material. The authors cite evidence from seismic and sedimentologic data documenting paleoshorelines offshore that, coupled with their own data, shows shoreface retreat of the barrier system in response to sea level rise.

Linkages between Geomorphology, Inner-shelf Framework, and Shoreline Change

To examine the connection between the inner shelf and upper shoreface and beach along Fire Island, new data in the form of nearshore bathymetry were considered and new analyses of three-dimensional shoreline change trends, morphologic behavior of the shoreline, and the relationship between inner-shelf bathymetry and shoreline behavior were conducted. These new sources of information, coupled with existing data and studies, support a linkage between the beach, nearshore, and inner shelf. This also suggests that an onshore component of sediment transport is likely more important along Fire Island than previously thought.

Previous documentations of shoreline change patterns (Allen and Labash, 1997) identified both alongshore heterogeneity and somewhat cyclical temporal behavior. Schwab *et al.* (2000) suggested that the length scale of the alongshore patterns of shoreline change (as measured over a 15-year time period) were similar to those expected by wave shoaling over the sand ridges, especially in the western reaches of Fire Island, although analysis was insufficient to assess how persistent the patterns and heterogeneities are through time. Other researchers have also identified what are termed erosional cells (Gravens, 1999; Seaver, Buoniauto, and Bokuniewicz, 2007). Spatial and temporal progression of these erosional cells is poorly understood; however, they do seem to reappear in

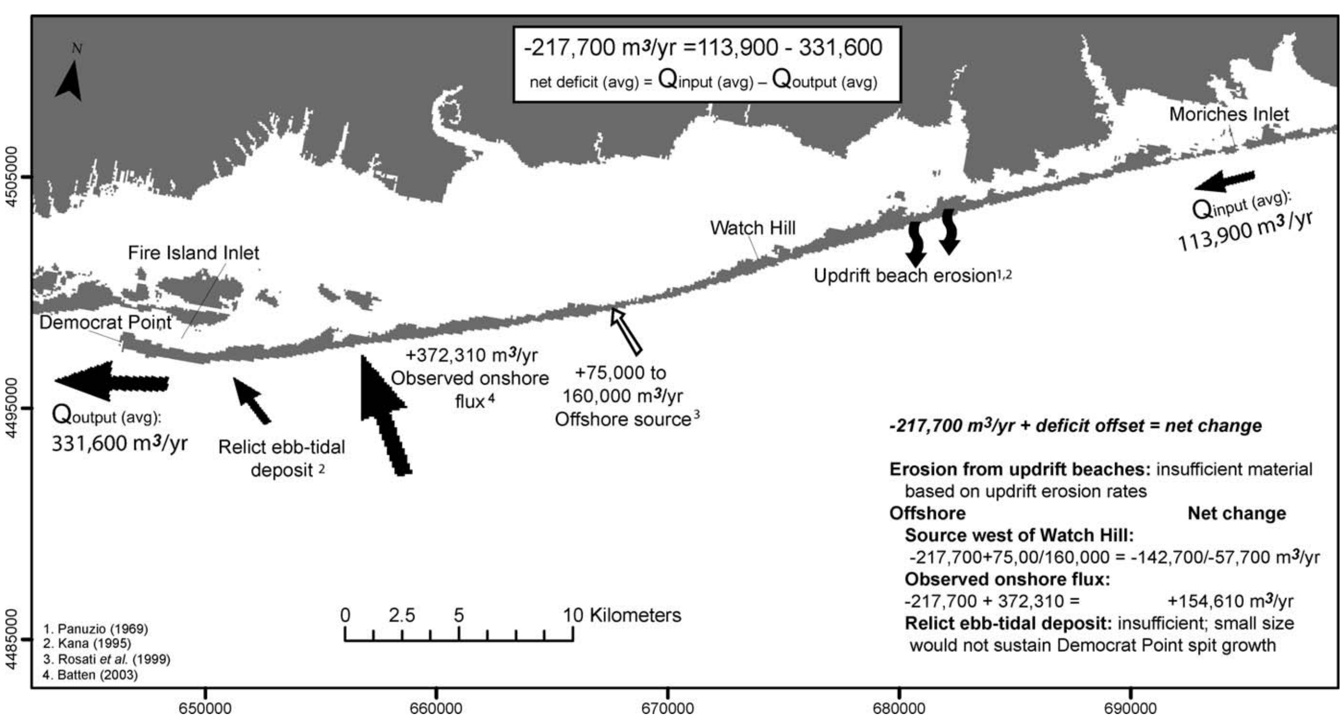

Figure 3. A conceptual model of averages of the cited sediment budget estimates for inputs to and outputs from the Fire Island system. The averages of inputs and outputs reported in Table 1 result in a net deficit (top box) that must be offset by additional sediment sources to the Fire Island coastal compartment. Proposed sources are indicated on the diagram, and their contributions of these sources, where provided, are added to the deficit residual value to show their variable potential to balance the budget. Amounts of sediment contributed to the system are schematically represented by arrow sizes.

specific areas with limited alongshore migration. If shoreline behavior is being influenced by the geologic framework of the inner shelf, as suggested by Schwab *et al.* (2000), patterns of shoreline change should maintain distinct spatial characteristics (length scales, zones of erosion or accretion) over long periods of time. Additionally, if shore-attached ridges are providing sediment to the beach system along western Fire Island, but not along eastern Fire Island, this should be reflected in the long-term shoreline change trends.

Our shoreline change analysis significantly extends the timescale over which shoreline behavior has been assessed at Fire Island. Rates of change over a 74-year time period (Figure 4) were calculated by a weighted linear regression on transects spaced 100 m apart. The Digital Shoreline Analysis System (Thieler *et al.*, 2005) was employed, and 17 shorelines ranging from 1933 to 2007 were included in the analysis.

A distinct alongshore shift in the shoreline behavior occurs at the Watch Hill location (Figure 4). To the east of Watch Hill, Fire Island is in a dominantly erosional state, the severity of which is variable alongshore. West of Watch Hill, where Schwab *et al.* (2000) maintain that sand ridges are attached to the shoreface, the long-term trend is dominantly accretional, although it is also variable alongshore. Beach replenishment along western Fire Island has been undertaken on several occasions in the past several decades, but those projects did not add sufficient material to the beach to alter the 74-year trend substantially. Persistence of the dominantly accretional long-term shoreline change signal along Western Fire Island might be related to the addition of material from the sand ridges to the beach over timescales greater than a half century. Additionally, the alongshore length scaling of peaks and valleys in the pattern of shoreline change (Figure 4) is consistent (2–4 km)

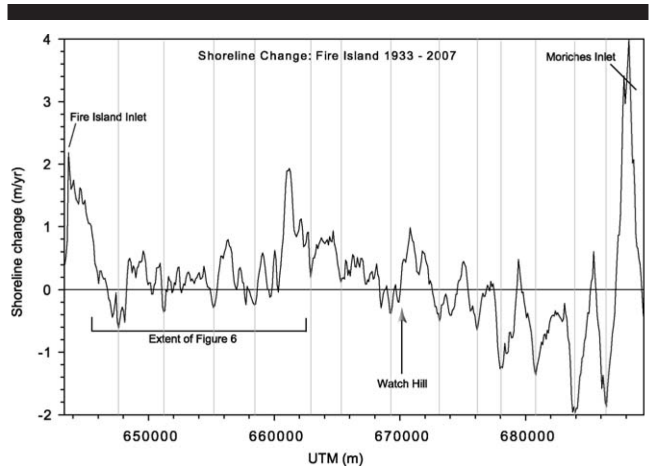

Figure 4. Shoreline change rates for Fire Island, New York, based on 17 shorelines over a period of 74 y. Note the dominant erosional signal to the east of Watch Hill and the dominant accretional signal to the west. The rates vary alongshore, but the spacing of erosional valleys and accretional peaks (vertical gray lines) is similar to the spacing of the ridge and trough system on the inner shelf.

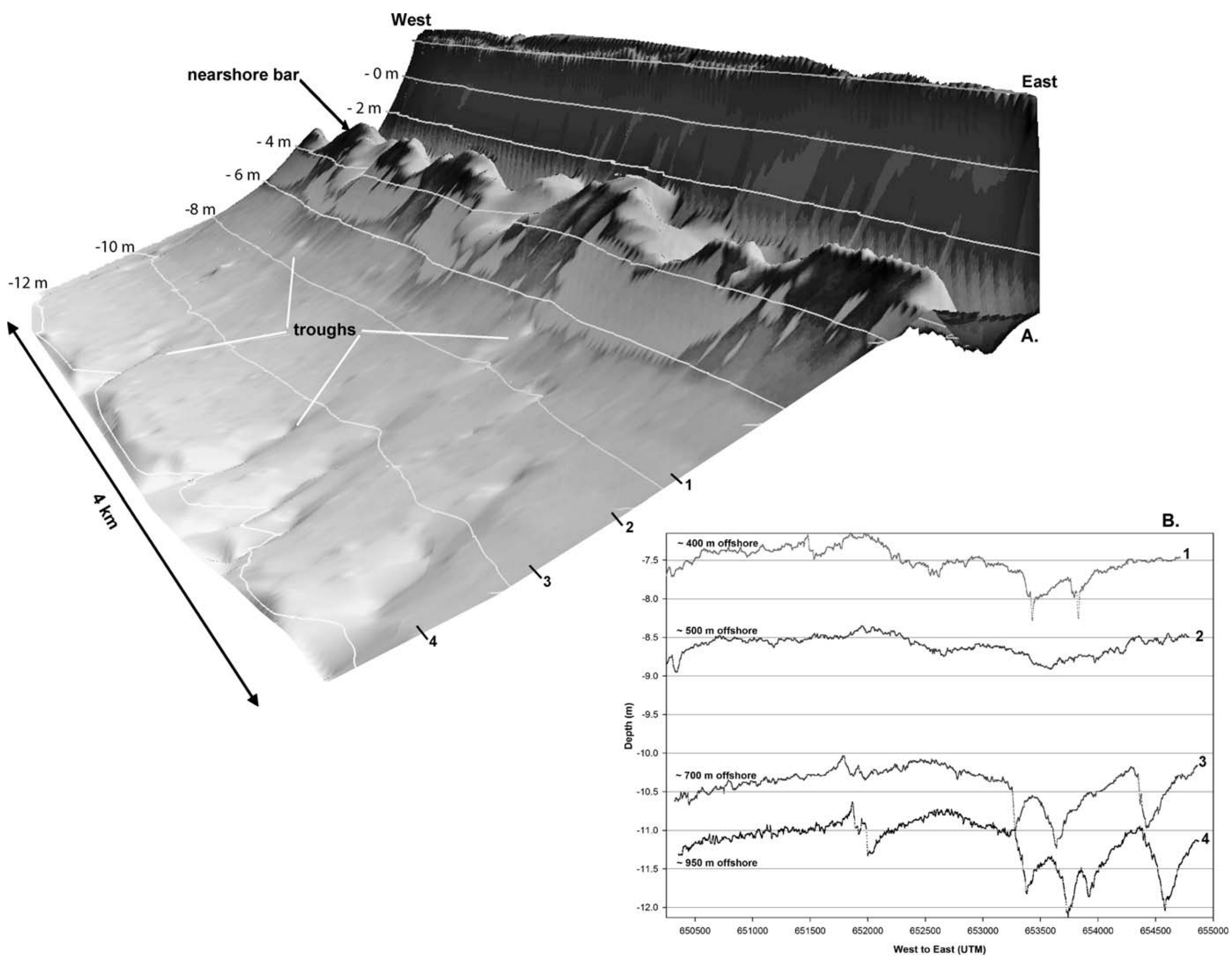

Figure 5. (A) A three-dimensional rendering of the nearshore bathymetry collected along a 4-km section of western Fire Island. The data were merged with an onshore survey to create a high-resolution surface extending from the 2-m contour to the 12-m isobath. Contour lines are shown in white. The troughs and ridges mapped previously on the inner shelf can be seen to continue to the back of the nearshore bar system, confirming that the ridges are attached to the shoreface. The numbers 1–4 correspond to the approximate locations of the alongshore profiles (B), in which the nearshore ridge and trough morphology can clearly be seen.

and is similar to the spacing of the inner-shelf troughs and ridges.

The shoreline change analysis suggests an association between beach behavior and inner-shelf geologic framework, similar to the relationship between oblique bars and shoreline change patterns documented by McNinch (2004) and Schupp, Mcninch, and List (2006). However, the specific mechanism of exchange is uncertain and understanding has been limited by a lack of nearshore bathymetry to establish that the ridges are physically connected to the shoreface. To demonstrate that the connection is likely, high-resolution bathymetric data were collected in the nearshore from 1 m of water depth to the 12-m isobath, which lies approximately 1 km offshore. These data were collected as part of a pilot study and covered 4 km^2 of the nearshore along western Fire Island. The data provide the first high-resolution surface for the nearshore region. The instrumentation for the data collection was the BERM system, which includes a rigid-hull inflatable outfitted with a precision single-beam survey fathometer interfaced with a heave, pitch, and roll sensor to remove the effects of waves. Depths are referenced to an RTK DGPS (real-time kinematic differential GPS) that provides horizontal and vertical positioning. To merge with existing bathymetry coverage on the inner shelf, a very dense grid of alongshore and cross-shore bathymetric profiles were collected along tracklines spaced between 50 and 100 m parallel to the beach and 100 m perpendicular to the beach.

The bathymetry data indicate a continuity of the offshore ridge and trough morphology mapped by Schwab *et al.* (2000) into the nearshore. Distinct alongshore undulations in the bathymetry are detectable to just seaward of the nearshore bar system (Figures 5A and B). The axes of the highs and lows are spatially consistent with the ridges and troughs mapped

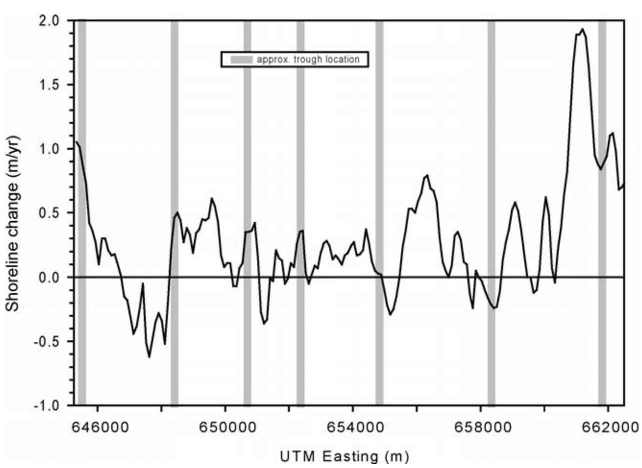

Figure 6. Seventy-four–year shoreline change rates for the western portion of Fire Island (see Figure 4 for extent). The vertical gray bars represent the approximate locations of the inner-shelf trough axes as delineated in Figure 2. The axes appear to be spatially related to zones of accretion; in all but one occurrence (UTM 658200 m), the trough axes fall in areas where accretion is the dominant signal over three-quarters of a century.

offshore, verifying a connection of the offshore linear ridges and troughs to the upper shoreface.

With the nearshore bathymetry as a guideline, the trough axes of the ridge-trough system for all of Western Fire Island were projected onto the upper shoreface (see Figure 2) to further explore the spatial relationship between patterns of shoreline change and inner-shelf geologic framework. Trough axes instead of ridge crests were used because they were much sharper and easier to identify in the data. The approximate positions of the projected axes were plotted with the 74-year shoreline change for the western portion of Fire Island (Figure 6). The resulting plot suggests a spatial correspondence of the troughs and zones of long-term accretion, as would be expected if the ridges focused wave energy in specific locations along the beach. Additional bathymetry to verify trough and ridge locations in the nearshore would allow for a more statistically robust assessment of this relationship.

The shoreline change plots shown in Figures 4 and 6 provide a long-term picture of the spatial variation in shoreline change over a set time period along Fire Island. A key question, however, is: How does the shoreline change vary through both space and time? If the inner-shelf geologic framework is exerting control on the morphologic evolution of the beach, this should be reflected in the temporal response of the system. A spatiotemporal moving regression plot of shoreline change allows this relationship to be investigated further (Figure 7). The plot was generated by calculating a weighted linear regression with the use of four shorelines for each of six time periods ranging from 1933 to 2007 and creating an interpolated surface along transects spaced at 100-m intervals.

The resulting time series plot shows the predominance of erosion over time east of Watch Hill and accretion west of Watch Hill. Zones of accretion and erosion (*i.e.*, locations a–e in Figure 7) are also temporally consistent. Heterogeneities exist, but the overall trends are spatially consistent through time. No alongshore migration of erosion or accretion cells, as has been previously suggested (Gravens, 1999, Seaver, Buoniauto, and Bokuniewicz, 2007), is evident. The temporal consistency of the spatial signal of the shoreline change zones is likely a function of the inner-shelf geologic framework, in that the focusing or dispersion of wave energy across the ridge and trough morphology consistently concentrates the energy at specific locations alongshore, given a consistent wave climate.

Management Implications

Inner-shelf sand ridges have increasingly become the borrow areas, or are proposed as borrow areas, for sand used to replenish nearby beaches at Fire Island and many other sites worldwide. However, little is understood about the potential physical and biological effects (Hayes and Nairn, 2004). According to Snedden and Dalrymple (1999), ridges in water depths of less than 20 m are maintained by modern hydrodynamic processes. Therefore, altering the morphology of sand ridges through dredging has the potential to alter wave approach and energy as well as deplete a source of sediment supply to regional sediment budgets.

Any removal of material from inner-shelf sites will change the depth or morphology of the sea floor, creating a localized increase in water depth and therefore a change in wave refraction and diffraction patterns (Komar, 1998; Reynolds, Wren, and Gayes, 2007). Removal of material from a ridge could affect the shoreline by altering the patterns of wave divergence and convergence, leading to increased wave energy in some areas. Conversely, the removal of material from a ridge could also serve to diffuse wave energy from areas of the shoreline where it was previously focused. Removing material from below the closure depth is usually proposed to minimize these effects, but given the uncertainty regarding the transport of material below a closure depth, this might not be a sound assumption. Additionally, the recent work of Hinton and Nicholls (2007) documents that the entire shoreface becomes increasingly active and moves landward through time. Thus, although continuous exchange of material between upper shoreface and inner-shelf features such as sand-ridges might not exist, documentation in the scientific literature is increasing that exchanges between the entire shoreface and inner shelf fundamentally affect the system, especially on timescales of decades to half centuries, and likely longer.

CONCLUSIONS

Sediment budget estimations at Fire Island on the south shore of Long Island indicate an imbalance between Moriches Inlet and Fire Island Inlet, unless a substantial amount of material—greater than 370,000 m^3/y in the highest estimate—is added to the littoral system between the two inlets. It has been suggested that contributions might come from beach erosion, nourishment projects, or an offshore source. A combination of these is likely the most feasible, in that neither erosion rates nor nourishment volumes are high enough to account for the deficit Mapped linear shoals on the inner shelf along the western half of Fire Island are a likely source of the

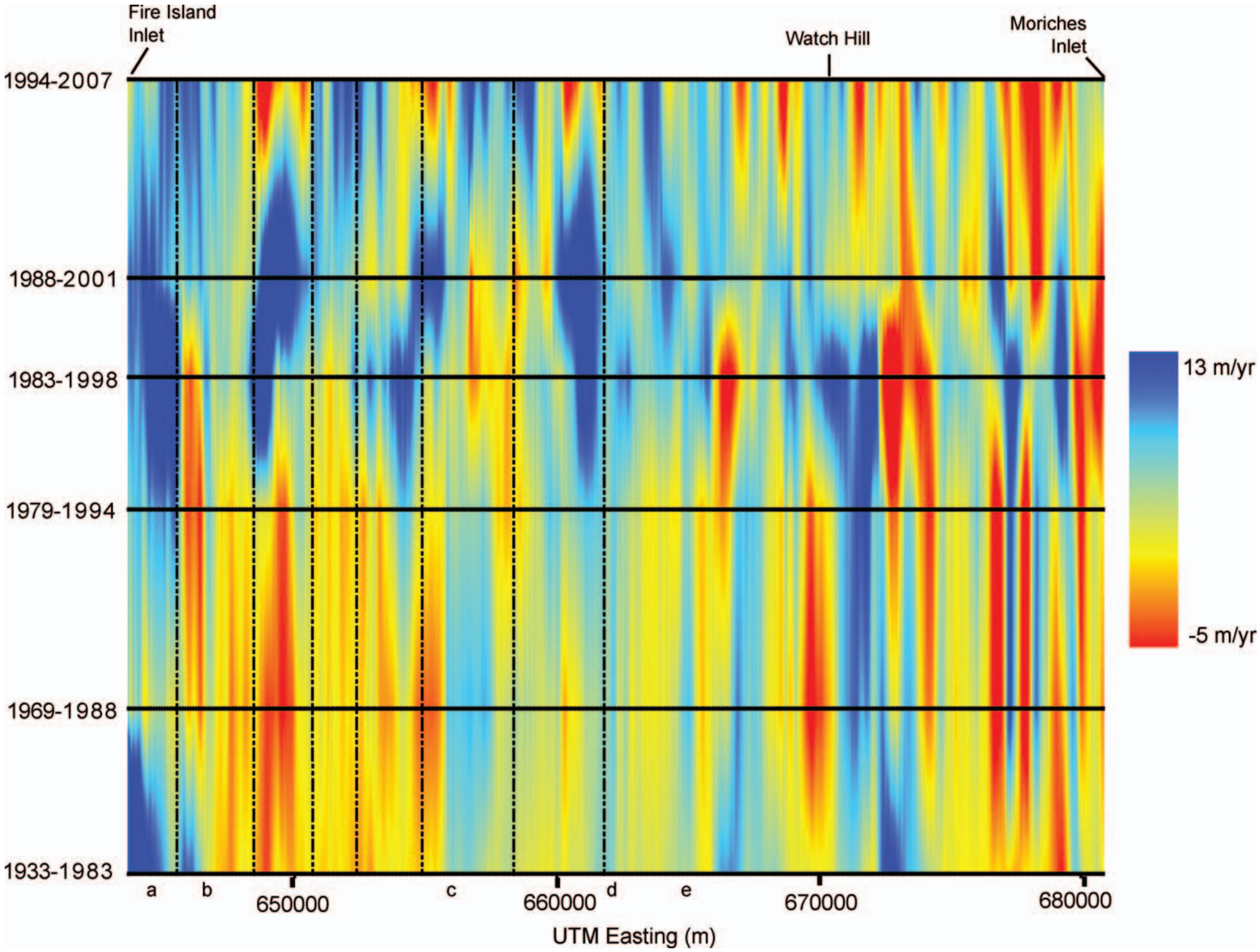

Figure 7. A spatiotemporal shoreline change plot based on a surface created by calculating a series of moving regression data points from 74 y of shoreline change data. The plot demonstrates how the shoreline changes through space and time and shows that shoreline behavior in a given location does not substantially vary through time and that there is little evidence of cells of erosion and accretion moving westward through the system.

sediment, but little data exist to provide information on the processes and pathways of cross-shore sediment transport along the SSLI. If offshore sand ridges are connected to the shoreface, as we postulate here, the presence or absence of a ridge can be expected to alter wave patterns by buffering wave energy reaching the shoreline where ridges are connected to the dominant nearshore bar and by focusing wave energy on selected segments of the adjacent beach.

We present new data in the form of high-resolution nearshore bathymetry and new shoreline change analyses that demonstrate the connection between the inner shelf, the nearshore, and the beach. The nearshore bathymetry clearly shows that the inner-shelf troughs and ridges extend landward to the back of the nearshore bar system in waters depths of less than 6 m. This provides not only evidence of a physical connection, but also a possible sediment pathway between the ridges and troughs mapped on the inner shelf and the upper shoreface along western Fire Island. Studies from other areas document both onshore and offshore sediment transport during large storms and describe the importance of cross-shore sediment transport to sediment budgets. Indirect data at Fire Island suggest cross-shore transport is also active and important and provide pathways for how material from the inner shelf might enter the nearshore system. Over longer timescales (several decades to half centuries and longer), the active shoreface could shallow and move landward, as documented in other regions.

Long-term shoreline change analyses document a distinct behavioral difference between portions of the island where the inner-shelf sand ridges are connected (western) *vs.* where they are not (eastern). The strong accretional trend where the ridges are attached to the shoreface suggests that they might be providing sediment to the nearshore and beach system. In contrast, where the ridges are not attached to the shoreface, the shoreline change trend over more than a half century is dominantly erosional. The length scaling of the peaks and valleys in the shoreline change data correspond to the length scaling of the inner-shelf morphology.

A spatiotemporal analysis of shoreline change trends also illustrates the dominance of accretion along the western portion of Fire Island. Additionally, this analysis demonstrates the temporal persistence of distinct zones of erosion and accretion, whose presence and length scaling suggest that the inner-shelf geologic framework is influencing the long-term behavior of the beach. These data, along with the continuity of the ridges and troughs from the inner shelf to the nearshore, provide evidence that these systems are linked.

Increases in storm intensity anticipated as a result of climate change are expected to affect coastal systems heavily. If the offshore bathymetry and shoreline behavior are directly connected, removing material for nourishment, as is proposed along Fire Island, has the potential to alter patterns of wave refraction and ultimately beach response (erosion and accretion), particularly with increases in storminess. Dredging might remove material that serves as a natural buffer to the coastal system, especially in areas where the sand-ridges feed the nearshore bar system. Widening beaches via replenishment will provide added buffering and protection to homes and properties from coastal storms and hazards; however, the transfer of sediment from offshore regions could cause the effects of storms to be greater on the shoreline. It is critical to understand how changes will affect the coastal system over the short and long term and what unanticipated consequences could arise as a result of such actions.

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