National Park Service
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Northeast Region
Boston, Massachusetts

A Review of Sediment Budget Estimations at Fire Island National Seashore, New York

Technical Report NPS/NER/NRTR--2008/114

ON THE COVER
Fire Island dunes and beaches west of Kismet
Photograph by: Cheryl J. Hapke

A Review of Sediment Budget Estimations at Fire Island National Seashore, New York

Technical Report NPS/NER/NRTR--2008/114

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NPS D-133 March 2008

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report presents a review of the existing body of scientific literature, as it pertains to issues relevant to coastal sediment budgets, both at Fire Island National Seashore (FIIS) and in general, in order to provide the National Park Service (NPS) with the information they need to best manage park resources at FIIS. The review outlines the state of knowledge on processes of sediment transport, and addresses the relationship of the nearshore with the shoreface and beach. Few studies of sediment budget processes exist for Fire Island and the south shore of Long Island, and as such, this review includes the current knowledge base of studies conducted world-wide.

Due to the large potential uncertainties associated with calculating sediment budgets, they are inherently difficult to quantify. A number of detailed estimates of sediment budgets exist for Fire Island and the entire south shore of Long Island. However, very few of these have been published in the peer-reviewed literature or as gray literature (e.g., conference proceedings, Ph.D. theses). For the purposes of this report, we are only citing the aforementioned body of literature and are not considering agency technical or administative reports in the review. This is not to discount the integrity of these reports; instead it is to assure that the science we are summarizing for the NPS has passed through the peer-review process that is standard for scientific advancement of information and ideas.

A variety of beach nourishment projects have been conducted over the last 50 years to mitigate coastal erosion for privately owned lands on Fire Island, a partially developed barrier island along the south shore of Long Island, New York. The inner continental shelf closest to the project sites has typically been the source of the nourishment material. Additional nourishment projects are being planned and more are anticipated in order to protect property and development from predicted sea-level rise and increased storminess due to climate warming. Currently proposed dredging areas are located in inner shelf and nearshore regions immediately adjacent to the boundary of Fire Island National Seashore (FIIS). Removal of sediment from nearshore regions has the potential to alter wave refraction and diffraction patterns, and result in changes in the wave energy reaching the beach.

Sediment budget assessments for the Long Island south shore, which have been estimated over a variety of timescales, document variable volumes of littoral transport, with the primary component being longshore transport from east to west. However, published sediment budgets indicate that an addition of approximately 200,000 m^3/yr of sediment is needed to account for the calculated longshore transport volumes for the coastal system. The source of additional sediment has not been unequivocally identified, although geophysical mapping and sediment analyses suggest that a series of shoreface-attached sand ridges could be a conduit for the onshore transport of inner shelf sediment to the system. There is a growing body of literature that documents the contribution of inner shelf sediments to sediment budget estimates of coastal areas, though little data exist on this subject at Fire Island. However, results of shelf mapping, beach profile comparisons, and sediment budget calculations indicate that onshore sediment transport at Fire Island is likely an important process, on time scales ranging from single storms to decades and longer.

INTRODUCTION

Fire Island is a northeast-southwest trending barrier island, part of a barrier-island chain that stretches approximately 135 km along the south shore of Long Island (Figures 1a,b). The island supports a population of 400 year-round residents that swells to 50,000 during the summer months. Continued development on Fire Island and on the southern shore of mainland Long Island has put mounting pressure on coastal managers to consider stabilizing the shoreline to mitigate the effects of erosion.

Forty-two of the 55 km of Fire Island lie within the boundaries of a National Seashore. FIIS was established in 1964 by the National Park Service (NPS). Private property ownership within the Seashore boundary, which also extends 304.8 m (1000 feet) offshore, has continued, although community members are required to abide by National Park regulations governing the use and modification of the beaches. At the eastern boundary of the National Seashore are Smith Point County Park and the adjacent Otis Pike Federal Wilderness Area (Figure 1b). While the federal wilderness area is managed by NPS and Smith Point County Park is owned and maintained by Suffolk County, both areas fall within the jurisdictional boundary of the National Seashore. Smith Point County Park is a public recreational area immediately west of Moriches Inlet and faces continual erosion problems due to interruptions in westward littoral transport from the jetties stabilizing Moriches Inlet. Although exceptions do exist, Federal Wilderness Areas must be left unimpaired by human activities for future protection of wilderness habitat and resources. Managers of each of these public lands must ensure that all coastal hazard mitigation strategies and ensuing regulations are also consistent with the NPS policies.

One strategy utilized to mitigate erosion is to nourish beaches with material dredged from the adjacent inner shelf. However, some controversy exists as to the long-term (decades and longer) effects of offshore dredging. The dredging and placement of inner shelf sediment onshore for nourishment may be viewed by some as merely an acceleration of natural processes. Others suggest that there is no significant exchange between the inner shelf and the shoreface (Kana, 1995; Morang *et al.,* 1999; Rosati *et al.,* 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. According to Williams and Meisburger (1987) and Schwab

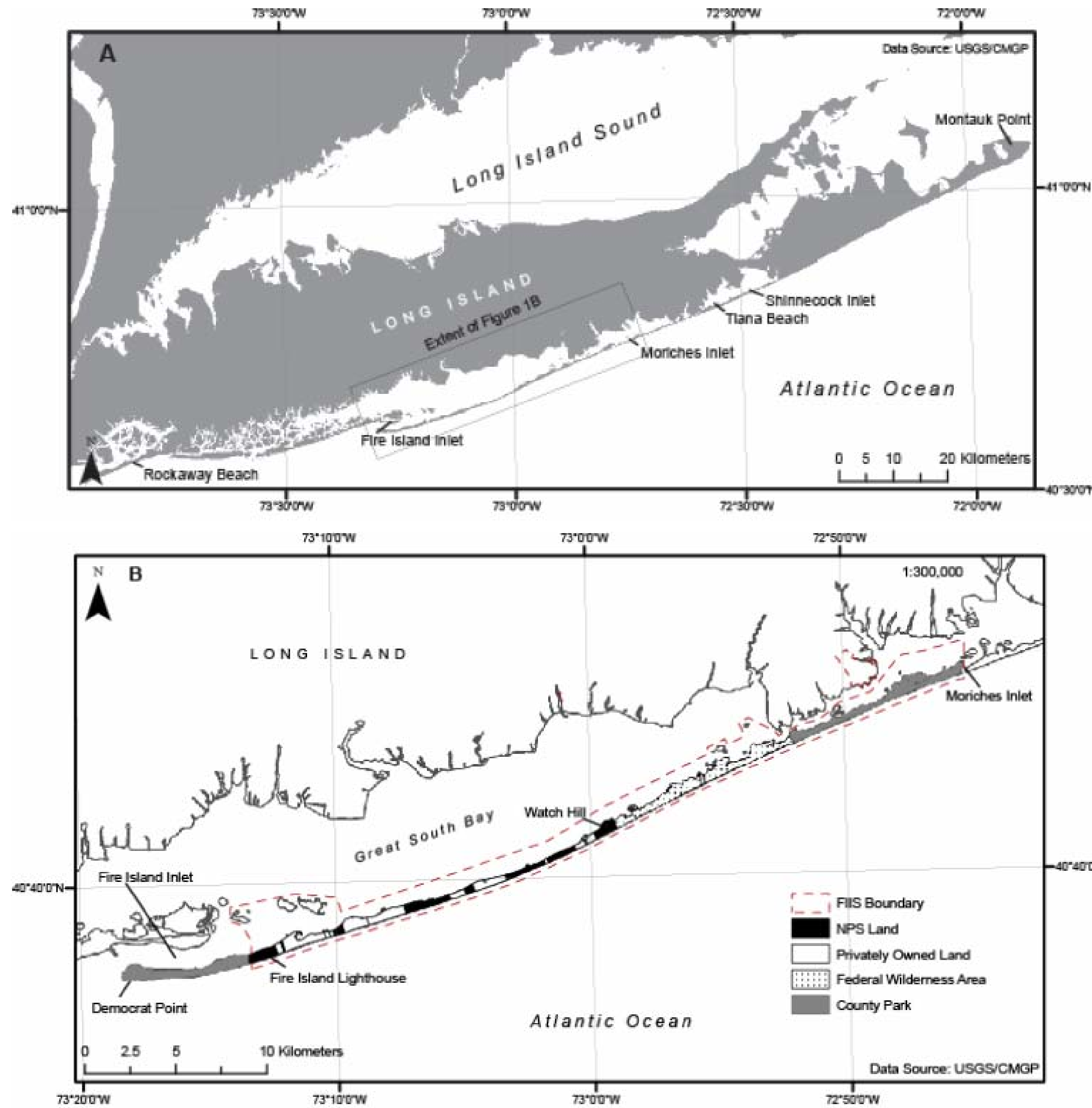

Figure 1. A) Regional map of south shore of Long Island, New York and B) Location map and management boundaries at Fire Island National Seashore.

et al. (2000), the inner shelf of Long Island may act as a significant offshore sediment source, naturally supplying beaches as sediment is transported onshore. Few studies have been undertaken to document the processes controlling cross-shelf transport along Fire Island or the south shore of Long 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 the coastal sediment budget (Swift *et al.*, 1985; Wright et al., 1991; Conley and Beach, 2003; Hinton and Nicholls, 2007; Gayes et al., *in press*), on time scales ranging from storms to years to several decades. It is likely that similar processes are active along the Fire Island coast as well (Williams and Meisburger, 1987; Schwab *et al,* 2000; Batten, 2003).

Understanding the regional sediment budget and the processes governing it are crucial for the effective management of Fire Island. Coastal managers have committed to rely on best-available science to better understand coastal processes and better manage and protect island resources of the over the long term. This report reviews the current knowledge base of coastal sediment budgets and sediment-transport mechanisms, examines assumptions in currently applied engineering models, and explores additional research needed to better understand the dynamics of sediment transport in the inner shelf setting. No new data are presented herein, and only literature that has undergone external peer-review (journal articles, conference proceedings, PhD dissertations) will be considered in the discussions given below. Numerous technical reports and planning documents have addressed issues related to Long Island sediment budgets. However, because the data contained in agency reports have not undergone external peer-evaluation, they are not considered in the discussions presented in this report.

STUDY AREA

Fire Island is centrally located within a barrier system lying along the south shore of Long Island (Figure 1b). This wave-dominated barrier island system is microtidal with a mean tidal range of 1.3 m (Leatherman, 1985). Fire Island ranges in width from 0.5 to 1 km and is bounded by two engineered inlets: Moriches Inlet to the east, and Fire Island Inlet to the west. 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 *et al.,* 1999) and are likely due to variation in wave direction but the predominant long-term transport direction is westward. Democrat Point lies at the western end of Fire Island and has historically been prograding, accreting at a rate of approximately 68 m/yr prior to the construction of the Fire Island Inlet jetty in 1941 (Leatherman, 1985; Smith *et al.*, 1999). The jetty filled to capacity 20 years after construction, and the inlet is now dredged every two years on average to provide navigational access by the U.S. Army Corps of Engineers (USACE).

The eastern segment of the island has migrated landward through inlet formation and subsequent marsh accretion on the bay-side (Leatherman, 1985). Here, overwash events, such as the widespread events that occurred during the 1938 hurricane, have served to elevate back-barrier segments of the island and make corresponding areas in the bay more shallow (Leatherman, 1985). In comparison, the central and western segments of the island have 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 in the central segment continue to erode and little sediment is deposited into the back bay marsh, resulting in an overall narrowing of the island (Figure 2) (Leatherman, 1985). The western segment of the barrier island from the Watch Hill to the west formed as a prograding spit (Leatherman, 1985) as evidenced from large, parallel backdune ridges that are geomorphic evidence of relict recurved spit formation processes.

The south-facing shore of Fire Island is directly impacted by extra-tropical storms and hurricanes arriving from the south. Impacts documented as early as the 1600s show that throughout recorded history, storms have had a substantial influence on geomorphology of Fire Island. Storm driven overwash events create surge channels through the dune system that frequently lead to the inlet formation. Twenty-six relict inlet sites have been identified between

Fire Island Inlet and Shinnecock Inlet, and gaps in the foredune indicate general instability east of Watch Hill (Leatherman, 1985).

Erosional cells along the western portion of the island, 1-2 km in wavelength alongshore were suggested to be created by breaks in the nearshore bars that expose beaches to active scouring from higher energy waves (Schwab *et al.*, 2000). These cells have been observed to erode the berm, as well as back beach and foredune (Gravens, 1999). Spatial and temporal progression of these erosional cells is poorly understood; however, they do seem to reappear in specific areas with limited alongshore migration (Gravens, 1999, Seaver *et al.*, 2007).

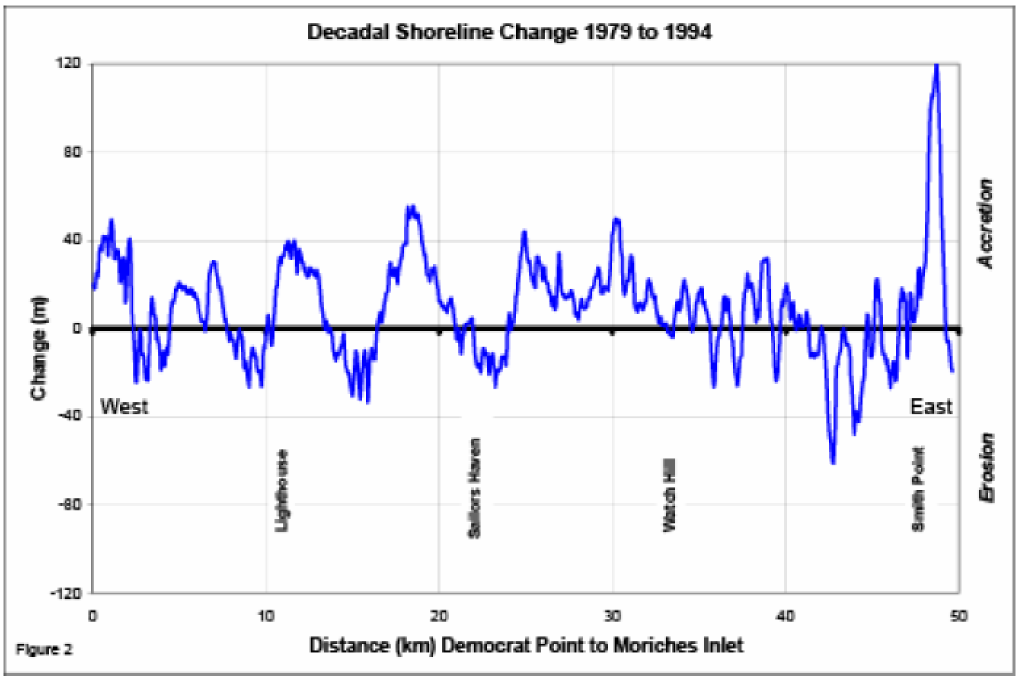

Figure 2. Erosion and accretion at Fire Island over a 25-year period. Note the more predominant erosional trend in the eastern segment of the island as compared with periodic accretional cells west of Watch Hill. From J. Allen (USGS).

Offshore Sand Ridges

The pronounced ridge and swale morphology of the continental shelf south of Long Island, was first described by Uchupi (1968) and Duane *et al.* (1972). The ridge features consist of linear shoals that may 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.

McBride and Moslow (1991), Snedden *et al.* (1999), and Hayes and Nairn (2004) provide thorough reviews of the origin hypotheses and characteristics of sand ridges. Inner shelf and ridges are common features not only along the Mid-Atlantic Bight, but have been mapped in the northern Gulf of Mexico (McBride *et al.*, 1999) and eastern Canada (Hoogondoorn and Dalrymple, 1986). Theories of the source of sediment required for ridge formation vary (e.g., Swift *et al.*, 1973; McBride and Moslow, 1991), however all recognize the importance of providing a means for placing a large volume of sediment onto the inner shelf which is then modified into sand ridges. A large body of literature discusses specific ways in which the ridges evolve and are maintained via oceanographic processes, including Huthnance (1982), Trowbridge (1995), Snedden and Dalrymple (1999), Hayes and Nairn (2004). The details of these process theories will not be described herein.

Offshore of Fire Island, the inner shelf, including shoreface-attached ridges off the western portion of Fire Island, were mapped in detail by Schwab *et al.* (2000). The ridges in this area extend offshore approximately 20 km, are spaced 1-2 km apart, and have a northwest-southeast azimuth of approximately 120° to 130°. 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 (an erosional unconformity), and rise as high as 6 m high 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. This unconformity eroded underlying Pleistocene glacial outwash deposits (glaciofluvial deposits) composed of sand, gravel, and limited mud (Schwab *et al.,* 2000).

The sand ridges located off the western portion of Fire Island, from Watch Hill to Democrat Point, appear to be connected to the nearshore bar system (Figure 3). Schwab *et al.* (2000) suggest that these shoreface-attached ridges likely influence the local wave regime by focusing wave energy along some segments of the island, and are potentially tied to mapped coastal erosional cells. Additionally, Schwab *et al.* (2000) speculate that the ridges may potentially serve as an offshore sediment source or sediment conduit for the inner shoreface system, following previous suggestions of Williams (1976) and Williams and Meisburger (1987) that inner shelf sand may contribute significant sediment to the Long Island barrier-island system sediment budget. Due to the textural compatibility to beach sand, and the proximity to the coast,

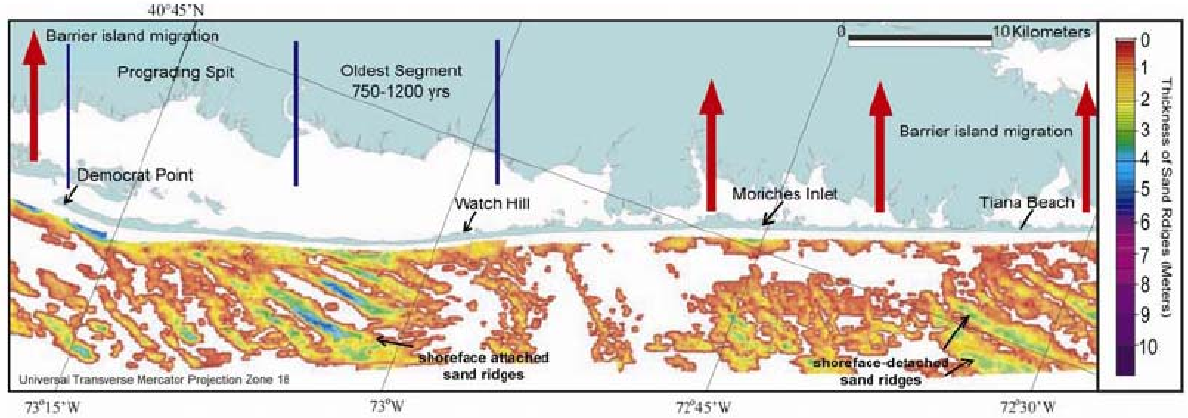

Figure 3. Isopach map showing offshore shoreface-attached and -detached ridges. The map does not depict bathymetry, only thickness of sediment contained in the ridges. Note the landward migration of Fire Island east of Watch Hill, with the section west of Watch Hill remaining relatively fixed. The oldest segment is noticeably narrower. Modified from Schwab *et al.* (2000).

the shoreface-attached ridges off western Fire Island have been proposed by the USACE as the primary borrow sites for material for beach replenishment along Fire Island.

Sand ridges have increasingly become the borrow areas for sand used to replenish nearby beaches, yet little is understood about the potential physical and biological impacts (Hayes and Nairn, 2004). According to Snedden and Dalrymple (1999), ridges in water depths of under 20 m are maintained by modern hydrodynamic processes. 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.

SEDIMENT BUDGETS

A sediment budget describes the influx, storage, and loss of sediment in a coastal system, as well as the transport pathways. The components of a sediment budget are generally difficult to accurately quantify, and thus sediments budgets typically are nothing more than estimates for a given area, with high uncertainty values. Ideally, a sediment budget identifies sources of material and areas where the largest amounts of loss are occurring. The sediment transport pathways within a littoral system are composed of two primary components, longshore transport and onshore-offshore transport, although most coastal sediment budgets assume that cross-shore transport is negligible. At Fire Island, longshore transport is the primary mode of sediment movement, and is well-documented based on jetty infilling and pre-jetty spit growth at Fire Island Inlet. Although there is very little information on the onshore-offshore rates of sediment transport at Fire Island, studies along the south shore of Long Island (Swift et al. 1985; Batten, 2003) as well as a number of studies in other, similar coastal systems (Wright et al., 1991; Conley and Beach, 2003; Hinton and Nicholls, 2007; Gayes et al., *in press*) suggest that onshore-offshore transport is likely an important, albeit unaccounted for, component of the sediment budget at Fire Island.

Sediment budget fluxes are commonly estimated utilizing 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 commonly used to assess how transport gradients vary along shore through the analysis of volume changes to the profiles. Historically, sediment budget derivations have relied on the application of a set depth of closure (DoC). DoC is the depth offshore that is the limit of cross-shore exchange of sediment. Application of DoC thereby minimizes the consideration of cross-shore transport when estimating sediment budgets.

A number of sediment budgets have been estimated for the Fire Island to Montauk Point barrier system (Figure 1b), all of which have been determined over a range of different timescales (Table 1). Sediment budgets were compiled for the USACE Beach Erosion Board in 1961, for the Beach Erosion Control and Hurricane Protection Project, in 1985, and in several more recent USACE technical reports. However, because the intent of this report is to provide a review of peer-reviewed and gray literature, the information from the technical reports are not included. Only published data from Panuzio (1968), Kana (1985), Rosati et al. (1999) and Batten (2003) will be outlined.

Panuzio (1968) provides little information on the formulation of his budget, but estimates that 267,600 m^3/yr of material are 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). The difference in these values indicates that 191,100 m3/yr is contributed to the system along the stretch of coast from Moriches Inlet to Fire Island Inlet, which Panuzio offers may be accounted for by beach nourishment.

Kana (1995) estimated that the sediment transport rate at Montauk Point is 45,000 m^3/yr, and increases to 360,000 m^3/yr at Fire Island Inlet (Figure 1b). Kana (1995) used profiles that extended to the DoC (9-12 m depth or 600-800 m offshore) as well as including data from dredging and fill activities. He identified three lenses within each profile defined as dune to MLW; MLW to -7.3 m MSL; and -7.3 m to DoC, using profiles collected at two time periods (1955 and 1979). Kana (1995) defined DoC as the seaward limit of "the principal zone of cross-shore and longshore transport over decadal intervals for this coast" determined from profiles by the inclusion of the longshore bar. Alongshore profile lenses were further divided into compartments averaging 7.6 km in length. Kana (1995) suggested that the increase in the sediment transport rates between Moriches and Fire Island Inlet is due to erosion occurring in the eastern portions of the island, as well as possible contributions from erosion of a Fire Island Inlet relict ebb-tidal delta. Historical shoreline change rates are relatively high along the eastern portion of Fire Island, yet the width and morphology of this portion of the island do not support sustained (over decades to a century) erosion rates high enough to produce the volumes of material in flux at Fire Island Inlet.

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/yr	Output m^3/yr	Deficit m^3/yr	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 *et al.* (1999)	1979-1995	29,000*†‡	176,000[8]†‡	147,000	Beach nourishment and erosion: uncertainty ±40,000 m^3/yr
Batten (2003)	1995-2001	-	-	-	Onshore transport 372,310 m^3/yr†

* Based on impoundment rates at jetties and/or westward migration of inlets
† Based on volumetric estimates from beach profiles and/or shoreline change
‡ From Rosati et al. (1999) Table 1 and Figure 5

Rosati *et al.* (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. Shoreline change rates were determined from transects spaced 25 m alongshore. Beach profile data from 1979 to 1995 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. The active depth was calculated by using profile data to sum the elevation of the active seaward berm with an assumed DoC, over a measured alongshore distance. Their results estimated that 29,000 m^3/yr entered the system at Moriches Inlet in the time period of their study, and 176,000 m^3/yr left the system east of Fire Island Inlet. An uncertainty in these estimates was calculated using the standard deviation of the net longshore transport rate for the region (Montauk Point to Fire Island Inlet) and the number of yearly averages, resulting in an uncertainty of 40,000 m^3/yr. Rosati et al. (1999) provide a variety of additions and subtractions to the local sediment budget between Moriches Inlet and Fire Island Inlet to account for the net alongshore deficit of 147,000±40,000 m^3/yr. These include inputs 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. Regardless, nourishment numbers can be reasonably adjusted to accommodate the needed influx of sediment within the Fire Island reach. However, due to the large uncertainties associated with them, they do not preclude that another source of material, such as an offshore source, may contribute sediment to the littoral budget. Additionally, Rosati et al. (1999) state that "the source of offshore sediment to Fire Island beaches appears to be a contributing factor to the nearshore sediment budget, although the regional sediment budget presented herein indicates that it is not required".

Schwab *et al.* (2000) speculate that the reported sediment budget deficit could be balanced by an offshore contribution, possibly from the shoreface-attached ridges offshore of western Fire Island. Offshore mapping by Schwab *et al.* (2000) shows that, with the exception of the shoreface-attached ridges, there are limited amounts of Holocene sediment on the inner shelf, which suggests cross-shore transport has been a dominant process in the region over millennial timescales. In the most recent of the published sediment budget estimations, Batten (2003) describes substantial volumetric gains to the nearshore system based on 3,136 beach profiles collected between 1995 and 2001 (Jones Inlet to Montauk Point). For Fire Island, he calculated that 372,310 m^3/yr is added to the profile landward of 7.3 m water depth, and attribute this addition to an offshore source.

Offshore Sediment Source

Several studies along the Long Island coast provide evidence in support of onshore transport of offshore sediment as a source for beach sand (Williams, 1976; Williams and Meisburger, 1987; Williams and Morgan, 1988; Williams and Morgan, 1993; Schwab *et al.*, 2000; Batten, 2003). These studies include an analysis of glauconite mineral tracer supplied by the Cretaceous headland off central Fire Island that indicate that the inner shelf has been an important source of sediment to the Fire Island and alongshore points further west of the source (Williams and Meisburger, 1987). Scanning electron microscope analysis has been used to compare surface textures of quartz grains from beach and offshore samples (Williams and Morgan, 1993). Strong similarities in the textural variability of offshore samples with samples collected from beaches indicate the offshore sediments are likely supplying sediment to the beaches of Fire Island (Williams and Morgan, 1993). Euhedral quartz grains have been used as tracers to tie the composition of beach sediments on the western segment of the island to glacial outwash lobes offshore (Williams and Morgan, 1988).

Offshore sediment sources have been proposed based on the stability of the central portion of the island and growth at Democrat Point, and detailed geologic and geophysical mapping of the inner shelf. The proposed sources include a relict ebb-tidal delta from an historical Fire Island Inlet (Kana, 1995) and erosion of a submerged Cretaceous headland offshore of Watch Hill during sea level rise supplying sediment to shoreface-connected sand ridges (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 may 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.

The studies available to date provide only indirect evidence of an offshore source of sediment for Fire Island and the south shore of Long Island. The area is lacking in detailed studies of nearshore sediment transport, and therefore there is not direct evidence of this process. However, there are no studies that refute the occurrence of an offshore sediment source, and scientific evidence from other areas supports the importance of cross-shore transport in formulation of a coastal sediment budget (Swift *et al.*, 1985; Wright et al., 1991; Conley and Beach, 2003; Hinton and Nicholls, 2007; Gayes et al., *in press*). An advanced understanding of inner-shelf sediment-transport processes in the Fire Island region is necessary to identify how offshore material is delivered to the nearshore.

CROSS-SHORE SEDIMENT TRANSPORT

Upper Shoreface

The transport of material between the dunes, beach, and the upper shoreface is generally well understood on Fire Island and is driven primarily by storm activity (Niederoda *et al.*, 1985). During periods of increased storminess, material is transported from the beaches and dunes to nearshore bars where it is stored. This process tends to result in the development of a storm beach profile with little to no berm, and some erosion of the foredune. As fair-weather conditions persist, sediment is gradually transported from the nearshore bar to the beach, eventually resulting in a wide, well-defined berm and a robust foredune resupplied by eolian transport. Storm beaches and fair-weather beaches are generally attributed to seasonal conditions, as more frequent and damaging storm events tend to occur in the winter months on Fire Island. These processes are restricted to the upper shoreface (Swift *et al.*, 1985), which at Fire Island is defined as the region seaward of the shoreline to approximately 10 m water depth. The dynamics on the lower shoreface and inner shelf, however, have only recently begun to be better understood at Fire Island and other locales (Niederoda *et al.*, 1984 and 1985; Swift *et al.* 1985; Schwab *et al.*, 2000: Gayes *et al.*, 2005).

The Lower Shoreface and Depth of Closure

DoC allows estimates of depths for hydrodynamic modeling below which little impact on the system is assumed to occur, and has been useful for coastal engineering applications. However, DoC is time-specific and often event-specific and is likely to change depending on the wave climate. The use of DoC has been the target of considerable debate within the scientific community, as many studies document sediment transport between the nearshore, offshore, and inner shelf during both storms and fair-weather conditions (e.g. Gadd *et al.*, 1978; Niederoda *et al.*, 1984 and 1985; Swift *et al.*, 1985; Snedden *et al.*, 1988; Wright *et al.*, 1991; Pilkey *et al.*, 1993; Nicholls *et al.* 1998). While DoC may be accurate over the short-term (months to years), it may not be accurate after large storms or longer time periods, and any estimate of DoC should include the timescale over which it has been estimated.

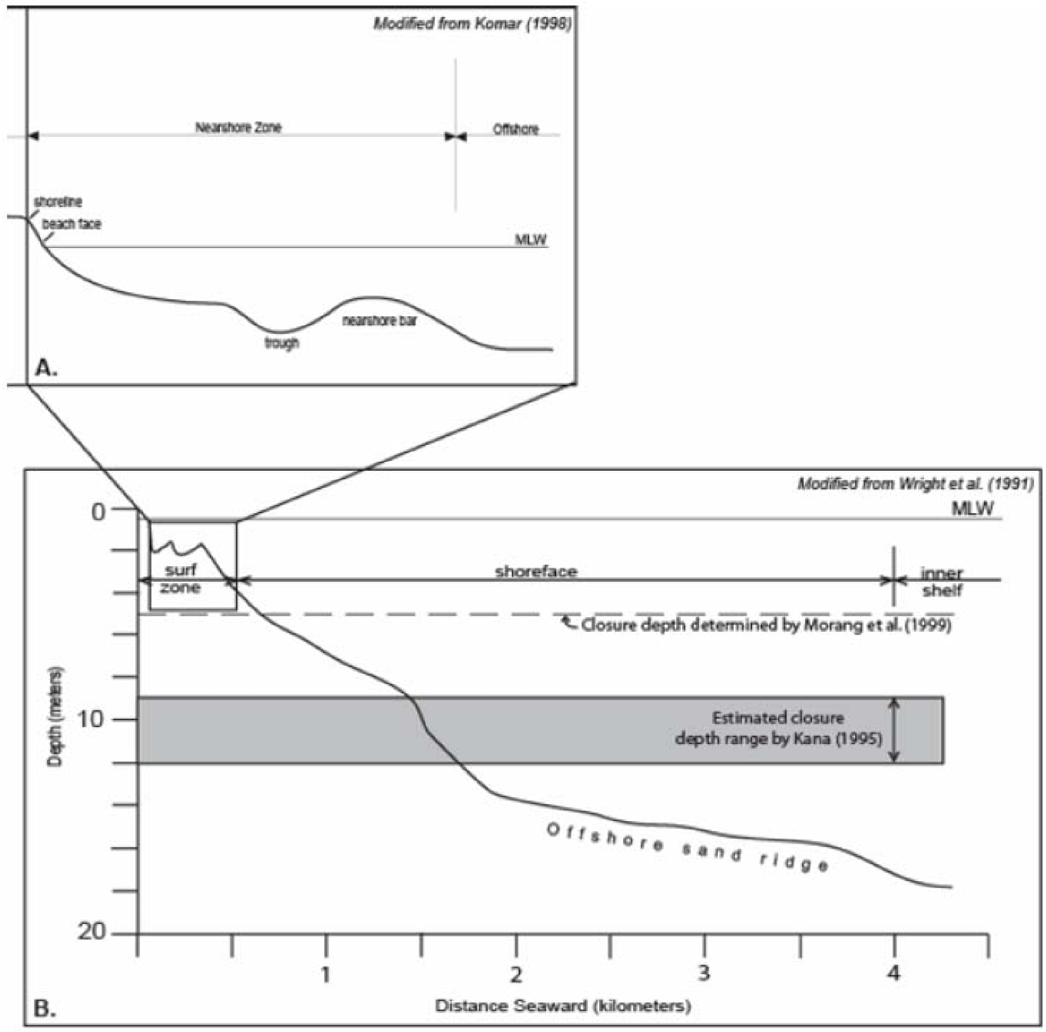

Figure 4. Schematic profile showing nearshore features and extent, as well as the start of the offshore zone (A). Extended schematic profile passing through an offshore sand ridge (B). The sand ridge in B rises a maximum of 6 m above the sea floor. Shoreface and inner shelf are denoted. Note closure depth as determined by Morang and others (1999) and estimated range by Kana 1995) where indicated.

Along the south shore of Long Island, Batten (2003) calculated a decreasing DoC to the west due to decreasing incident wave energy from east to west over a 6 year period (1995 to 2001) (Batten, 2003). Kana (1995) estimates a DoC of 9-12 m by identifying the limit of the nearshore bar based on a break in slope from beach profiles over a 24.5 year period (1955-1979) (Figure 4b). Morang *et al.* (1999) estimate short-term (year-long) DoC ranging from -5.6 m at western Fire Island to -6.8 m at eastern Fire Island (Figure 4b), based on 300 beach profiles from four survey dates between 1995 and 1996. No major storm events occurred in the time period of the profiles, and thus represent the sediment exchange process over a 1-year period when no large storms occurred.

Although two sediment transport components (longshore and cross-shore) occur simultaneously in nature, the need for simplicity in engineering applications has resulted in modeling them separately. For the most part, engineering models are 2-dimensional and employ a seaward limit for sediment exchange, the DoC (Hallermeier, 1981; Birkmeier, 1985; Nicholls *et al.,* 1998; Kraus *et al.*, 1998; Morang *et al.,* 1999, Heilman *et al.*, 2006). Methods for estimating DoC include mathematical equations, repeat beach-shoreface profile surveys, and geologic observations such as the sand to mud interface.

Understanding the concept of DoC is important for understanding the limitations of sediment budgets that are estimated using profile data. DoC assumes that any material that is gained or lost from the profile above the DoC is lost or gained in an alongshore direction and does not take cross-shore losses or gains into account. In-situ field studies that measure changes to shoreface morphology have been conducted in a variety of locations, and many show that DoC is a time- and event-driven state. For example, studies were conducted at Duck, N.C. by Birkmeier *et al.* (1985) to assess the overall validity of DoC using data from high precision shoreface profiles, and reasoned that an event-dependent DoC could be determined for specific storms. At Duck, Nicholls *et al.* (1997; 1998) use data from 12 years of beach profiles that extend offshore to approximately 8 m water depth NGVD. The profiles were compared to determine erosion seaward and accretion landward of the nearshore bar and the DoC. Nicholls *et al.* (1998) found that time-dependent DoC conditions exist at Duck, and that DoC tended to increase (deepen) with time. Heilman *et al.* (2006) reach similar conclusions regarding changes in depth of closure over time, based on surveys along the south Texas coast. Nicholls *et al.* (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 DoC at Duck, N.C., and Sandbridge Beach, VA., during both storms and fair-weather conditions. Currents, wave characteristics and suspended sediment concentrations were measured at depths ranging from 7-17 m depth over a three-year period, and found that cross-shore transport occurred during both storm 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 *et al.*, 1988). The resolution of most profiles that are used for sediment budget calculations are likely too coarse to detect the changes that would occur from thin sheets of sediment movement, and thus may record closure when there is still exchange of sediment between the nearshore and inner shelf.

In more recent studies, Gayes *et al.* (2005) monitored changes in profile slope across the along the entire South Carolina coast. Profiles were collected annually, and in some cases seasonally, at about 400 locations, extending offshore beyond the estimated DoC. Results show that in regions where the upper shoreface is artificially stabilized, the lower shoreface continues to migrate landward at a natural rate (Reynolds, *et al.*, 2007). This results in a steepening of the profile geometry on the lower shoreface. The response of the system to a steepened shoreface may result in the alteration of sediment transport and hydrodynamic patterns (Reynolds, *et al.*, 2007).

Cross-shore Transport Processes

As previously mentioned, storms from the south directly impact Fire Island due the east-west orientation of the island. The most damaging of these are hurricanes and extra-tropical storms due to 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 the established DoC, in the Middle Atlantic Bight and the Gulf of Mexico (Table 2) (Hayes, 1967; Morton, 1981; Snedden *et al.*, 1988; Wright *et al.,* 1991, 1994; Pilkey *et al.,* 1993). A long uninterrupted fetch distance at Fire Island only exacerbates the impact 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 island by overwash, breaches, and the creation of inlets.

Table 2. Comparison of storm conditions with recorded cross-shore transport rates

Storm Date	Location	Windspeed; Wave Height	Cross Shore Transport Rate	Reference
Sept. 1961	Port O'Connor, TX	43-49 m/s	200 cm/s	Hayes, 1967; Morton, 1981; Snedden *et al.*, 1988
Fall 1973	Hudson Shelf Valley, NY	5-15 m/s; minimal wave heights	40 cm/s	Gadd *et al.*, 1978
Aug. 1978	Tiana Beach, NY	4.5 m/s; 6.5 m	10 cm/s	Niederoda *et al.*, 1984
Sept. 1985	Duck, NC	10 m/s	>20 cm/s	Wright *et al.,* 1991
Oct. 1991	Duck, NC	17 m/s; 6 m	0.05-0.15 m/s	Wright *et al.*, 1994

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

No direct measurements of sediment transport during storms (or fair weather conditions) exist for Fire Island. Within the south shore of Long Island barrier system, current and wave measurements at 10 m depth were gathered from August 24-26, 1978, during which time a storm passed through the area. The instruments were deployed off of Tiana Beach, Long Island (Figure 1a), approximately 23 km east of Moriches Inlet (Niederoda *et al.*, 1984) and an area where shoreface attached ridges are absent. At the height of the storm, windspeeds of 4.5 m/s and wave heights of 6.5 m were recorded, with offshore-directed currents reaching velocities of 10 cm/s (Swift *et al.*, 1985). The rate of seaward sediment transport during storm events was observed to be an order of magnitude higher than the rate of transport landward during fair-weather conditions (Niederoda *et al.*, 1984; Swift *et al.*, 1985). Although Tiana Beach is part of the same barrier system as Fire Island, the absence of the shoreface-attached ridges in this area, as compared to western Fire Island, would be expected to affect transport somewhat differently.

Another study at Tiana Beach, over a period of six years, utilized instruments measuring sediment concentrations, fluid motions, and current and wave data, and were deployed in the bottom boundary layer of the surf zone and shoreface. This longer term analysis (years as opposed to several days) found that coastal frontal storms cause the removal of large amounts of material from the beach and surf zone, and that this material is transported across the shoreface to the inner shelf (Niederoda *et al.*, 1984; Swift *et al.*, 1985). Although the two studies at Tiana Beach did not measure substantial shoreward movement of sediment during the storms, they did show that sediment is mobilized at depth below the estimated depth of closure during storms along the south shore of Long Island. Furthermore, both Niederoda *et al.* (1984) and Swift *et al.* (1985) found that along the inner shelf of Long Island barriers a general trend of landward-directed cross-shore sediment migration predominates during fair-weather conditions in the upper and lower shoreface.

Measurements conducted during a 5-day storm at Duck, N.C. found that the long fetch and duration of the Halloween storm of 1991 caused a rapid downwelling of shoreface material to offshore regions (Wright *et al.*, 1994). Current and suspended sediment concentration profile data were recovered from 13 m depth, recording seaward transport along the shelf, which increased with wave height (Table 2). Following the storm, shoreward fluxes of sediment were measured in conjunction with offshore winds and a large swell (Wright *et al.* 1994).

Although there are no direct measurements of onshore sediment transport of sediment from the inner shelf to the shoreface at Fire Island, indirect evidence exist that suggest that 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) show the absence of Holocene sediment deposits on the inner shelf along much of southern Long Island, suggesting a long-term trend of net onshore transport of eroded shelf material. The authors cite evidence from seismic and sedimentologic data documenting paleoshorelines offshore, which, coupled with their own data show shoreface retreat of the barrier-system in response to sea level rise.

DISCUSSION

Local and regional sediment budgets can be estimated using the following equation (after Rosati *et al.*, 2005):

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual \qquad (1)$$

where Q_{source} and Q_{sink} represent additions and losses of material from the control volume, ΔV is the net change of the volume within the cell or system, P and R represent the respective placement or removal of material from the cell or system, and *Residual* represents the overall balance of the cell or system. Sediment budget estimates composed of many local cells can be added together to determine macrobudgets estimate on a regional scale (Rosati, 2005). However, often a *conceptual sediment budget* is used to assess all potential sources, sinks, and determine sediment pathways that can then be validated with the final estimates (Dolan *et al.*, 1987; Kana and Stevens, 1992; Rosati, 2005). For the purposes of this report, we apply the regional estimates to a conceptual sediment budget equation as a means of comparison for estimates at Fire Island. The conceptual sediment budget is represented by the following equation:

$$Q_{source} - Q_{sink} = \text{net change} \qquad (2)$$

where Q_{source} represents known additions to the system and Q_{sink} represents known losses to the system. In an equilibrium system, the difference in Equation 2 would be zero.

Existing sediment budgets estimated over a variety of timescales (ranging from 2 to 36 years) for Fire Island require an along-cell contribution (between Moriches Inlet and Fire Island Inlet) ranging from 147,000 to 315,000 m^3/yr in order to balance (Table 1 and Figure 5). Several authors have suggested sources to offset the deficit and explain the lack of landward migration on the western segment of the island. Panuzio suggests that the excess volume (191,100 m^3/yr in his estimates) is derived from beach nourishment. Kana (1995) balances his sediment budget via (proposed) trailing ebb tidal deltas associated with the migrating Fire Island Inlet. However, Schwab *et al.* (2000) point out that such relict shoals were not evident in the offshore mapping, and that ebb tidal deltas tend to be small in size on wave-dominated coasts and would therefore be an insufficient source of material to support the documented rates of spit growth at Democrat Point. Rosati *et al.* (1999) balance their sediment budget deficit by varying amounts of upcoast erosion and nourishment, which could reduce the deficit to -8,800 m^3/yr. If the onshore transport rate described by Batten (2003) is reasonably accurate at 372,310 m^3/yr, this would be a sufficient source of material to offset the loss shown in the sediment budget, and would result in a net gain of 154,710 m^3/yr of material to the system.

On coastal management timescales of decades to centuries, it is important to note that sediment budgets estimated over shorter timescales may not be representative of the future environment for which managers are trying to plan (Table 1). Sediment budgets do provide useful estimates of the transport of material through the estimations of the fluxes, sources and sinks in coastal systems. However, high levels of uncertainty are associated with these estimates. The sediment budget of Rosati *et al.* (1999), as noted earlier, is the only Fire Island budget to attempt to quantify the uncertainty in their estimates. Exploring uncertainty in sediment budgets further, Rosati (2005) differentiates between two types of uncertainty in estimates: true uncertainty and error. Sources of error are determined from instrument or measurement limitations. True uncertainty is more difficult to establish, as it is based on natural variability within the system such as spatial and temporal variations, unknowns, and how components of the system are defined (e.g., shoreline orientation).

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 uncertainty associated with between-profile interpolation. The further the spacing between the profiles, the greater this uncertainty source is likely to be. In addition to spatial uncertainty, temporal variations affect profiles depending on the day and conditions under which the profile is collected. Profiles are also generally not accurate enough to capture error associated with small-scale changes, and therefore may fail to capture large 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 there are errors and uncertainties in the various sediment budget estimates for Fire Island, all of the studies yield relatively similar estimates before the incorporation of intra-cell inputs, which themselves have errors associated with them and that in some cases are speculative.

If there is an offshore sediment source supplying 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/yr may be added to the system in a cross-shore direction. If the source is the shoreface-attached sand ridges, the sediment may include inner shelf material transported from well below the DoC. 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.

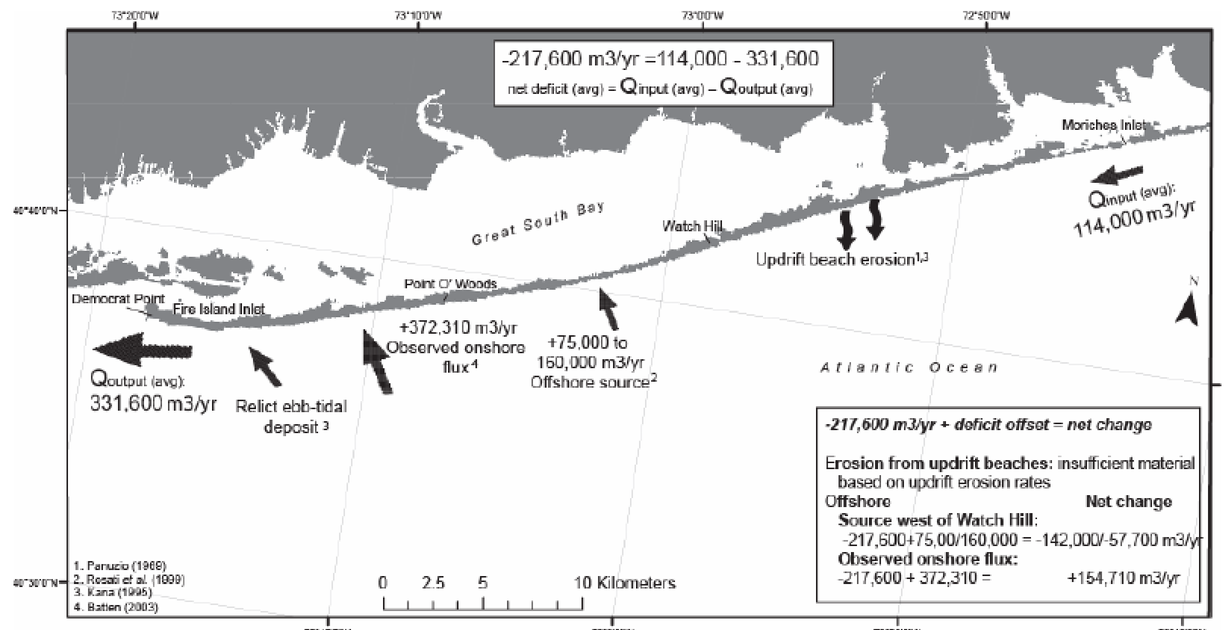

Figure 5. Diagram showing the averages of all cited sediment budget estimates for inputs to and outputs from the system. These averages result in a net deficit that is being offset by additional sources to the system. Proposed sources are indicated on the diagram, and the contributions of these sources, where provided, are added to the deficit in an attempt to balance the deficit. Amounts of sediment contributed to the system are schematically represented by arrow sizes.

Numerous studies of coastal morphodynamics and beach profiles along the south shore of Long Island have estimated a DoC from beach profiles, which precludes cross-shore transport, at least on the time scales of the analyses. Recent research by Hinton and Nicholls (2007) may resolve the apparent discrepancy between profile convergence (DoC) and evidence of cross-shore transport. They examined a series of long (extending to the 16 m isobath), closely spaced (1 km) profiles over a temporal rage of 5 to 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 re-opened further offshore. Over shorter timescales (5-10years) the offshore zone was less active but substantial changes were recorded in time scales of twenty or more years. It is possible that existing estimates of closure for Fire Island did not have either the spatial or temporal resolution to detect volumetric changes on the lower shoreface.

Any removal of material from offshore sites for replenishment 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, *et al.*, 2007). As proposed by Schwab *et al.* (2000), if offshore sand ridges are connected to the shoreface, 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. There is also indirect evidence presented in Schwab *et al.* (2000) that the presence of offshore sand ridges is linked with documented erosional cells on along the shoreline. Removal of material from a ridge may then impact the shoreline by exposing segments previously buffered by the presence of sand ridges to increased wave energy and higher run-up, making some areas more vulnerable to overwash and breaching. Conversely, the removal of material from a ridge may also serve to diffuse wave energy from areas of the shoreline where it was previously focused. Removing material from below the DoC is usually proposed to minimize these impacts, but given the uncertainty regarding the transport of material below a DoC and the timescales for which an estimated DoC may be applicable, this may 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, while there may be a disconnect between the upper shoreface and features such as sand-ridges on time scales of years to a decade, there is increasing documentation in the scientific literature that the entire shoreface and inner shelf are connected, especially on timescales of decades to half-centuries and likely longer.

Barrier islands respond naturally to sea-level rise through overwash and the formation and closure of inlets which drive barrier migration landward. An adequate sediment supply is required for barriers to migrate naturally. Movement of material from the active lower shoreface to the upper shoreface via dredging and nourishment expedites natural processes. Material that may naturally have been transported to the upper shore from the offshore will no longer be available, unless there is infilling of the dredge site. Nourishment is a viable solution for residents concerned with the retreat of the shoreline and the diminishing widths of the beaches, but it may not provide long-term protection of homes and infrastructure unless continued in perpetuity.

FUTURE WORK

One of the most important areas of future research at Fire Island is to better understand the hydrodynamics of onshore-offshore sediment transport. Little of this work has been done in the past at Fire Island to date largely due to cost and limited technology; however, several modern techniques could be employed in a cost-effective manner to better understand the science and aid managers in difficult decision making.

Primarily, there is a need for better information on the bottom morphology of the shoreface. A better understanding of the nearshore bathymetry and antecedent geology at Fire Island is essential for providing scientists, engineers, and decision-makers with better information on the exchanges between the offshore sand ridges and the nearshore. At present, nearshore sediment transport is poorly understood because it is a difficult environment to work. However, equipment and technologies are becoming available to collect field data in such high energy and poorly accessible areas. Modern bathymetry would increase confidence in the accuracy of wave– and sediment–transport modeling that has been conducted. Furthermore, should evidence of offshore sand ridges be visible in nearshore bathymetry, this would help to verify that offshore sand ridges are indeed attached to the shoreface and provide a better conceptual understanding of the sediment transport between the offshore sand ridges and the nearshore. High-resolution swath bathymetry is more commonly being used to provide a base for sediment transport pathways, and modern technologies are improving for shallow-water data collection on open-water coasts (Gayes *et al.,* 2005; Reynolds *et al.,* 2007). A bathymetric swath survey along Fire Island would provide high resolution data measurements of sea bed morphology. If material is subsequently removed from borrow sites, a monitoring program could be established to assess impacts to the dune/beach system as well as the nearshore environment.

Obtaining bottom current velocities in the nearshore is also critical. Combined with wave gauge and suspended sediment information, these data can be used to determine movement and sediment transport rates (Komar, 1998). This information is needed seaward of the surf zone (on or just beyond the offshore ridges) and would require the deployment of instruments. These data could then be input into 3D physics-based models to determine the direction of sediment movement with and without the removal of borrow material.

CONCLUSIONS

Existing studies of sediment budgets at Fire Island indicate that there is a deficit between Q_{source} and Q_{sink} unless material is added to the littoral system between Moriches Inlet and Fire Island Inlet. It has been suggested that contributions might come from beach erosion, nourishment projects or from an offshore source. A combination of these is likely the most feasible. There is currently a large discrepancy in the relative distribution of the suggested contributions, which some estimates needing no offshore source and others suggesting more than 370,000 m3/yr is added to the system from the offshore. Mapped linear shoals in the offshore would be the likely source of the sediment, but no data currently exist to provide information on the processes and pathways of cross-shore sediment transport at Fire Island. Data from an adjacent barrier island indicate large amounts of sediment can be transported offshore during storm events and returned to the shoreface during fair weather conditions. Studies from other areas document both onshore and offshore sediment transport during large storms. This is also likely to occur at Fire Island and provides an explanation for how material from the offshore may enter the nearshore system. Over longer timescales (several decades to half centuries and longer), the active shoreface may shallow and move landward, as documented in other regions. Previously established DoC estimates would not have documented this shoreface migration due to spatial or temporal limitations.

Increases in storm intensity anticipated as a result of climate change are expected to heavily impact coastal systems. Offshore borrow sites have the potential to alter patterns of wave refraction and ultimately beach response (erosion and accretion), particularly with increases in storminess, and may remove material that serves as a natural buffer to the coastal system if the sand-ridges feed the nearshore bar system. It is not a completely safe assumption that dredging material from below the currently established DoC will have no impact. Widening the beach 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 impacts of storms to be greater on the shoreline. It is critical to understand how changes will impact the coastal system over the short and long term, and what unanticipated consequences may arise as a result of such actions.

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