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Lack of Evidence for Onshore Sediment Transport from Deep Water at Decadal Time Scales: Fire Island, New York

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ABSTRACT

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Fire Island, New York, is a 50-kilometer-long barrier island that has remained positionally stable without any formation of breach inlets for nearly 200 years. Some researchers have attributed its stability to a major supply of sand moving onshore from relatively deep water (*i.e.*, >10 m depths). Others have demonstrated via sediment budgets that the principal sand sources at decadal to century time scales are littoral sediments derived from eroding beaches, bluffs, and cannibalization of inlet shoals in shallower depths (*i.e.,* ≤10 m). Published sediment budgets indicate that the quantity in question is of the order 10^5 m^3/yr. The possibility that this deep-water source of sand is significant, active, and persistent at decadal to century time scales has led to reluctance to mine deep-water shoals for beach nourishment of Fire Island. Herein, the authors review five factors related to the potential for a significant deep-water sand source in this setting: (1) spatial and temporal frames of reference necessary for this flux of sand; (2) studies of scour and sediment transport over offshore features; (3) sediment size distribution across the foreshore; (4) depth of closure (DOC); and (5) contribution of abandoned inlet shoals. The authors conclude that evidence for an onshore flux of sediment (*i.e.,* order of 10^5 m^3/yr) is lacking and suggest that reluctance to mine the offshore for beach nourishment is unfounded.

ADDITIONAL INDEX WORDS: C*oastal erosion, sediment budget, Fire Island, depth of closure, cross-shore transport, longshore transport, sediment source, offshore shoals, beach profile, littoral sediment, tidal inlets, ebb tidal delta, mesoscale.*

INTRODUCTION

Fire Island is the centerpiece of a series of barrier islands that define much of the south shore of Long Island, New York (Figure 1). Unlike its neighbors to the east (Westhampton Beach) and to the west (Oak Island and Jones Beach), Fire Island has been relatively stable for nearly 200 years. Since 1830, when an inlet off Bellport closed (Leatherman, 1985), there have been no breach events and the island has remained in position, with moderate to low erosion rates impacting the oceanfront (Leatherman and Allen, 1985; RPI, 1985a; USACE, 1958). This is in contrast to the shoreline east of Moriches Inlet, which has experienced numerous breaches throughout the 20th century. There were as many as ten incipient inlets (Figure 2a) along Westhampton Beach immediately after the hurricane of record on 21 September 1938 (Leatherman and Allen, 1985; Panuzio, 1968; USACE, 1958). Much of Westhampton Beach is now stabilized by groins and nourishment (Nersessian *et al.*, 1993). Similarly, Oak Island and Jones Beach to the west were low barrier islands (Caro, 1974) that likely overwashed or breached. However, the islands were merged and built up via nourishment and land reclamation between 1927 and 1933. In one of the largest beach projects ever, upward of 30 million cubic meters (m³) were dredged from Great South Bay and placed on Jones Beach (NY State Dept. of Parks, unpublished records; Caro, 1974).

Why Fire Island, unlike its neighbors, has remained positionally stable for at least two centuries is uncertain. Studies have confirmed there is a net longshore transport from east to west. Given its location within the New York Bight (defined by the Long Island and New Jersey coastline), Fire Island receives highest wave energy from the east. This drives spit growth to the west at each inlet (Saville, 1961). The uncertainty about the stability of Fire Island relates to its source of sand. Some have attributed Fire Island's stability to a major supply of sand moving onshore from relatively deep water (Hapke *et al.*, 2010; Lentz *et al.*, 2008; Schwab *et al.*, 2000; Williams, 1976; Williams and Meisburger, 1987; Wolff, 1982). Taney (1961) was one of the early proponents of this theory. Others have attempted to demonstrate via sediment budgets that the principal sources at decadal to century time scales are littoral sediments derived from eroding beaches and bluffs, as well as cannibalization of inlet shoals from earlier ebb-tidal deltas

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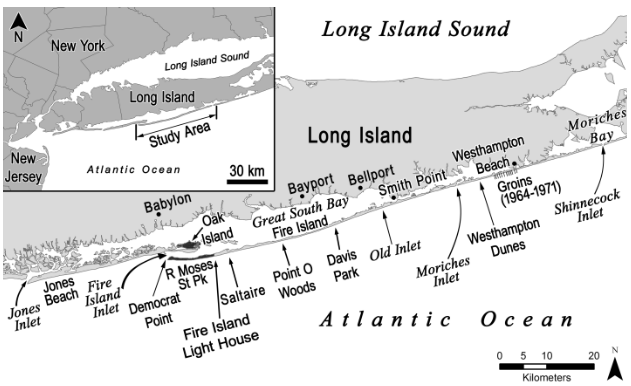

Figure 1. Vicinity map of the barrier islands along the south coast of Long Island, New York, USA.

(Kana, 1995; McBride and Moslow, 1991; RPI, 1985a; Rosati *et al*., 1999). The quantities in question are of the order 200,000 cubic meters per year (m^3/yr) impacting a portion of the ~50-kilometer(km)-long island. Schwab *et al*. (2000), reiterated by Allen *et al*. (2002), Batten (2003), Lentz *et al*. (2008), and Hapke *et al*. (2010), have promoted the case for a "deep-water" source of sand entering the littoral system along central Fire Island, thereby accounting for the island's long-term stability. Some researchers (*e.g*., Lentz *et al*., 2008) have advised the U.S. National Park Service (NPS), the federal agency that manages much of Fire Island as a national seashore, against utilizing certain deep-water deposits for nourishment because that sediment may be part of the active sand-sharing system with the beach. These deposits include certain federally designated borrow areas in water depths between 10-20 meters (m) (USACE, 2002).

The purpose of this paper is to review the evidence, or lack thereof, for a significant offshore source of sand along Fire Island at decadal to century time scales. This has implications for management and maintenance of the Fire Island beaches. The paper is organized by first presenting our hypothesis and approach, and then systematically examining five potential factors accounting for transport along Fire Island. The authors conclude that evidence for an onshore source of sediment is lacking and suggest that reluctance to mine the offshore for beach nourishment is unfounded.

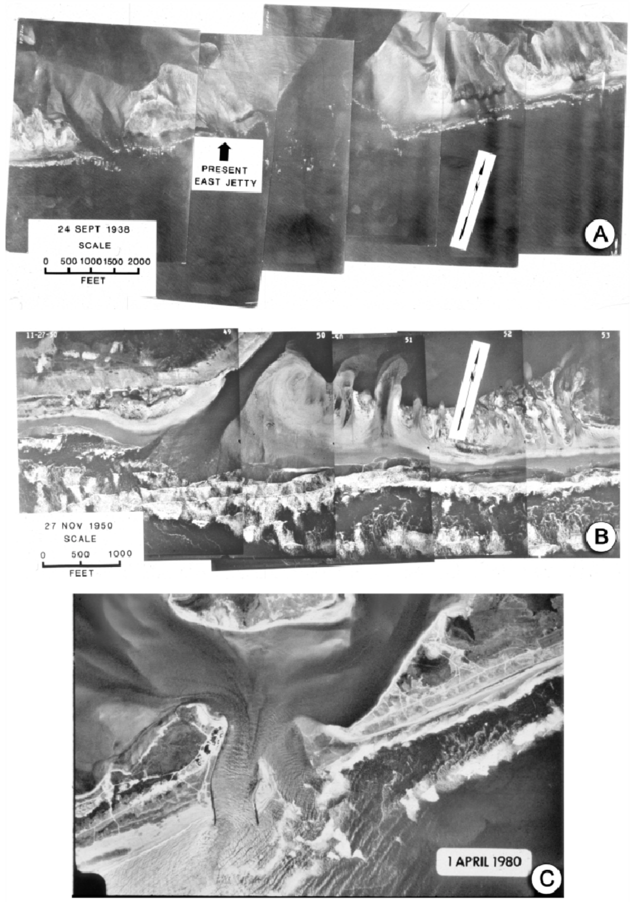

Figure 2. Mosaic of aerial photographs of Westhampton Beach and the shoreline immediately adjacent to Moriches Inlet: (a) three days after the hurricane of record on 21 September 1938 – Fire Island to the west sustained washovers but no complete breaches of the island, except the area shown just west of the present inlet; (b) Moriches Inlet on 27 November 1950, two days after a northeaster, showing fresh washovers on the Westhampton side of the inlet (prior to jetty construction); and (c) Moriches Inlet on 1 April 1980, approximately three months after channel scour east of the east jetty breached Westhampton beach (note the isolated east jetty between two adjacent inlet channels). Photos courtesy of New York District, U.S. Army Corps of Engineers.

SEDIMENT BUDGET

Hypothesis

Our hypothesis is that beyond some offshore depth (order of ~10 m), there will be little measurable advection of sand from deeper depths into the active littoral zone along Fire Island. This is not to say sediment transport stops beyond the 10-m contour in this setting, but rather, the potential contribution from offshore or to offshore is insignificant over time frames applicable for planning and management of this island. The depth limit of significant net sand transport between offshore and onshore areas is considered at decadal to century time scales, appropriate for management of the coastline.

The principal quantities in question are: (1) gradients and absolute values of net westerly longshore transport along Fire Island; and (2) average annual contributions of sediment from "deep water," well beyond the outer bar. Other volumes of interest are nourishment associated with dredge and fill projects, the net volumetric erosion rate along the coast, volumes of sediment lost to washovers and breach inlets, and the potential volumes "lost" within the littoral profile due to historical rises in sea level. These quantities are the basic elements of a sediment budget which can be expressed generally as (Rosati *et al*., 1999):

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

where all terms are volumes into or out of a control volume or sediment budget cell, having prescribed limits within the active beach zone between the foredune and a defined offshore contour, with ΔV equaling the net volume change within the cell. Q_{source} includes net longshore transport, net onshore transport, and contributions from bluff or dune erosion. Beach nourishment volumes (P) are an artificial source placed into the control volume. Q_{sink} includes net longshore transport out of the control volume, losses to washovers (landward of the foredune), losses to inlets, and losses to deep water in response to sea-level rise or storms. Artificial removal within a cell is indicated by R, and accounts for dredging or sand mining. The residual volume, *res*, will be zero for a balanced control volume.

Focus herein is on gradients in longshore transport along Fire Island and the average annual contribution from deep water. Other quantities are either small (*e.g.,* annual losses to washovers; *c.f.,* Kana, 1995; Leatherman, 1985; Leatherman and Allen, 1985; RPI, 1985a) or are not applicable along the Fire Island beaches (*e.g.,* losses to inlets, excavations, and mechanical removal of sand from the littoral zone).

Beach nourishment has been a significant source of littoral sediment along Fire Island from the 1940s to 1990s. Kana (1999) estimated the average annual additions to be ~1.8 cubic meter per meter per year ($m^3/m/yr$) (reference period 1920-2000) applied over a length of 44.4 km (omits ~3 km at each end of the island). This would equate to ~80,000 m^3/yr. Rosati *et al*. (1999) reported nourishment additions of ~100,000 m^3/yr for the periods 1933-1979 and 1979-1995. During the latter period, nearly all beach fills were placed along the western 20 km (~40 percent) of the island. Based on the general agreement of average annual nourishment volumes, the authors conclude that a representative magnitude and associated uncertainty for average annual beach nourishment placed along Fire Island is of the order $10^5 \pm 10^4$ m^3/yr.

Leatherman (1985) reported numerous historical washovers along Westhampton Beach but few along Fire Island with almost none reaching Great South Bay in historic times. RPI (1985a) documented littoral budget losses to washovers on Fire Island at <0.4 $m^3/m/yr$ (~15,000 m^3/yr) for the period 1955-1979. This period included the March 1962 northeaster of record (USACE, 1963). There were no sand losses to breach inlets along present-day Fire Island during the 20th century, and only one breach inlet updrift along Westhampton Beach between 1955 and 1979. The 1962 breach was estimated to remove the equivalent of ~3,500 m^3/yr from the south shore littoral system (1955-1979 period; Kana, 1995). Moriches Inlet (at Fire Island's eastern end) opened naturally in 1931, migrated west, then shoaled and closed in 1951. It was reopened by dredging on 18 September 1953, then stabilized with the present jetty system in 1954 (Czerniak, 1976; USACE, 1958; Vogel and Kana, 1985). Thus, the loss to Fire Island beaches through washover and inlet breaches is of the order $10^4 \pm 10^4$ m^3/yr.

Previous sediment budgets (RPI, 1985a; Rosati *et al*., 1999; USACE, 1980) have assumed losses due to profile adjustment in response to sea-level rise. The term, Q_{SL}, as applied in the Rosati *et al*. sediment budget, was based on sea-level rise of 3 millimeters (mm) per year (from 90 years of tide gauge records at the Battery, New York City) and application of the Bruun (1962) Rule. (The authors acknowledge the limitation of the Bruun Rule where longshore transport gradients are present.) For profiles at Fire Island, the translation under the observed sea-level rise was estimated to be ~0.19 m/yr, which Rosati *et al.* (1999) converted to a volumetric loss into deep water (>7 m) of ~2.0 $m^3/m/yr$. RPI (1985a) applied a similar term which averaged ~2.5 $m^3/m/yr$ along Fire Island. Kana (1995) used a deeper profile calculation depth (~9.1 m) and omitted the sea-level rise adjustment. When applied over the length of the island in certain previous sediment budgets, Q_{SL} is in the range 100,000-125,000 m^3/yr. Uncertainty in Q_{SL} approximates its magnitude which, for Fire Island, gives $10^5 \pm 10^5$ m^3/yr.

Another relevant event that impacted the regional supply of sand in the latter half of the 20th century was construction of 15 groins at Westhampton Beach, beginning ~6 km east of Moriches Inlet. Constructed between 1964 and 1971 without concomitant nourishment (USACE, 1980), the groins produced a total littoral trap during the 1970s (Kana, 1995) and possibly into the 1980s (Rosati *et al*., 1999). It is generally acknowledged that the presence of groins reduced the supply of sand to Moriches Inlet. Since the 1990s, when a lawsuit resulted in restoration of the downcoast beach at Westhampton Dunes (Daley *et al*., 2000; Terchunian and Merkert, 1994) and after the Westhampton groin field was filled to capacity, there has been an apparent resumption of sand supply updrift of Moriches Inlet. Uncertainty associated with sand trapping by the groin field is discussed in the next section.

For purposes of this paper, the authors will assume all sediment volumes in question have a degree of uncertainty equal to their magnitude unless otherwise noted (*c.f.,* Kraus and Rosati, 1998; Rosati, 2005; Rosati and Kraus, 1998), whether as a result of insufficient historical records (beach fills), extrapolation of volumes from vertical aerial photography (*e.g.,* washovers), or lack of precision and consistency in offshore profile surveys (*e.g*., error inherent with bathymetric surveys obtained via different acoustic recording devices). Yet, this summary of quantities applicable to Fire Island suggests the uncertainty associated with some elements of the sediment budget is relatively unimportant. Washover volumes and beach nourishment volumes appear to have errors of the order 10^4 m^3/yr. These volume contributions or differences among various researchers are an order of magnitude less than the quantities in question — gradients in longshore transport along the island or potential contributions from a deep-water source (order of 10^5 m^3/yr).

Gradients in Longshore Transport Along Fire Island

Some of the earliest estimates of longshore transport along the U.S. coast were made at Fire Island Inlet (Taney, 1961). Its prolonged westerly migration produced the prototypical "overlapping offset inlet" (Galvin, 1971). Between 1825 and 1940, Fire Island Inlet migrated 7.5 km (65 m/yr) to the west (Figure 3), overlapping adjacent Oak Island (Saville, 1961; USACE, 1958). This migration was stopped in 1940 by construction of a ~1,500-m-long jetty at Democrat Point, the

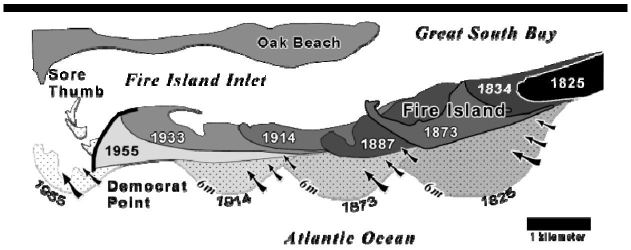

Figure 3. Historical migration of western Fire Island based on comparative shorelines prepared by U.S. Army Corps of Engineers (Saville, 1961). Dotted lines are inferred locations of ebb-tidal deltas associated with representative shorelines. As the inlet migrates along with its delta, trailing shoals feed spit growth. Walton and Adams (1976) and Moffatt and Nichol (2002) have estimated the ebb-tidal delta shoals contain ~38 million and ~31 million cubic meters (respectively).

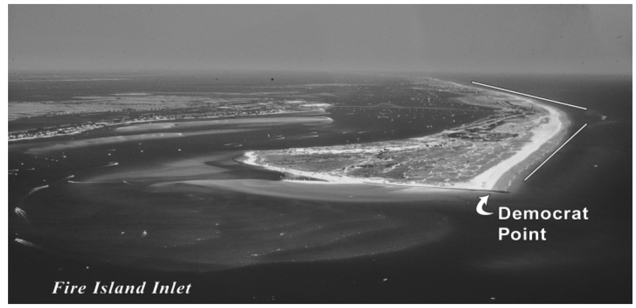

Figure 4. Oblique aerial photograph at low tide in August 1981 looking east at Fire Island Inlet. The ~1,500-m-long jetty at Democrat Point was constructed in 1940 and filled to capacity by the mid-1950s (Saville, 1961). The 2-km-long fillet associated with the jetty is oriented east-west, a difference of ~17º from the azimuth of central Fire Island. (Photo by T.W. Kana)

western terminus of the spit. After the jetty was completed, it impounded sand gradually over its entire length, serving as a near-total littoral barrier for over a decade. Surveys in the mid 1950s by USACE (1958) confirmed complete fillet development within ~10 years and the onset of jetty bypassing and shoaling in the navigation channel (authorized depth ~4.3 m MLLW). The resultant fillet at Democrat Point produced a straight segment of beach (~2 km long) oriented east-west at an azimuth of ~90ºTrue. The average azimuth of western Fire Island (7–20 km east of the inlet) is ~73ºTrue, a 17º difference, with implications for longshore transport accelerations from east to west (Figure 4).

Growth of Fire Island spit (1825-1940) and development of a fillet at the jetty after construction in 1940 provided an opportunity to estimate net longshore sediment transport (LST, summarized in Figure 5). Unpublished records of the New York District USACE indicate there were estimates back in the 1940s of net LST of the order 0.5 million cubic yards per year (cy/yr, ~380,000 m^3/yr) based on spit growth. One such estimate was prepared for the District by the Beach Erosion Board (BEB, 1946) and Professor Morrough P. O'Brien, a pioneer of coastal engineering in the U.S. (M.P. O'Brien, pers comm, June, 1983). USACE (1963) published an estimate of 480,000 cy/yr (367,000 m^3/yr) moving west at Fire Island Inlet. Panuzio (1968) reviewed federal dredging records for Fire Island Inlet and reported an average annual volume of ~600,000 cy/yr (~460,000 m^3/yr) excavated. The source of material was assumed to be littoral transport originating along Fire Island (*i.e.*, no inputs from Oak Island or Jones Beach). Therefore, Panuzio's estimated net LST rate apparently equaled the inlet dredge volumes.

Since the early work of the Beach Erosion Board and U.S. Army Corps of Engineers, there have been several estimates of LST at Fire Island Inlet and Moriches Inlet derived from: dredging records (*e.g.,* RPI, 1982, 1985b); wave energy flux (*e.g.,* Czerniak, 1976); and regional sediment budgets (*e.g.,* Kana, 1995; RPI 1985a; Rosati *et al*., 1999). RPI and Kana developed sediment budgets for the period June 1955 to December 1979. Rosati *et al*. formulated a regional budget for the period 1979 to 1995. The LST rates associated with regional

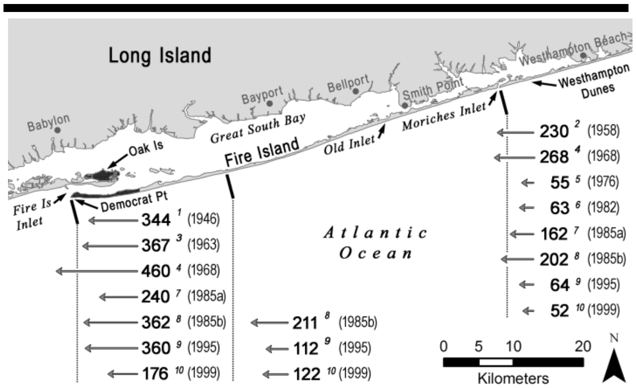

Figure 5. Gradients and variation in net longshore transport along Fire Island based on published estimates, as noted. Rates in 1,000s m^3/yr. Values for west-central Fire Island are for a point ~18 km east of Democrat Point.
[Note: References RPI, 1985a (Appendix G – based on dredging records); RPI, 1985b (Summary & Final Budget – based on accumulated volume changes).]

sediment budgets are based on residual volumes for various compartments (control volumes) encompassing nearly 130 km of shoreline from Montauk Point (eastern terminus of Long Island) to Fire Island Inlet. Rates estimated for Moriches Inlet and Democrat Point (east and west ends of Fire Island, respectively) are derived from changes to updrift compartments. Thus, residual volumes accumulate from east to west according to the degree of updrift erosion, artificial nourishment, sand bypassing at inlets and groin fields, and estimated losses to washovers or equilibrium profile adjustment. Certainly, any systematic errors between comparative surveys within the control volumes will also have a cumulative effect on regional sediment budgets. Not surprisingly, estimates of LST have

Table 1. *Estimates of net longshore sediment transport (LST) at Fire Island, central Fire Island, and Moriches Inlet (in 1,000s m^3/yr). All directions are westerly.*

Reference	Source	Fire Island Inlet	Central FI	Moriches Inlet	Difference: Moriches to FI Inlet	Notes on Differences
			LST in 1000s m^3/yr			
1	USACE (1946)	344				
2	USACE (1958)			230		
3	USACE (1963)	367			137	(compared with USACE 1958)
4	Panuzio (1968)	460		268	192	
5	Czerniak (1976)			55		
6	RPI (1982)			63	177	(compared with RPI 1985b)
7	RPI (1985b)	240		162	78	
8	RPI (1985a)	362	211	202	160	
9	Kana (1995)	360	112	64	296	
10	Rosati et al. (1999)	176	122	52	124	
	Mean (all sources)	330	148	137	166	
	Std Dev	93	55	89	68	
	Mean (Sources 8, 9, & 10)	299	148	106	193	
	Std Dev	107	55	83	91	

Notes: USACE did not publish a contemporaneous estimate for Moriches Inlet and Fire Island Inlet, but the 1958 and 1963 studies were related to a regional assessment of erosion and plan for hurricane protection.

RPI (1982) published an estimate for Moriches Inlet based on dredging records and other factors prior to finalization of the regional sediment budget. This is comparable to RPI's (1985b) preliminary estimate for Fire Island Inlet based on dredging records.

varied considerably depending on the methodology, researcher, and time period considered.

Figure 5 and Table 1 summarize the published estimates of net longshore transport at Moriches Inlet, Fire Island Inlet (Democrat Point), and a locality in west central Fire Island, ~18 km from Fire Island Inlet. As the data show, there is a cluster of LST estimates for Moriches Inlet around 200,000 m^3/yr and another cluster around 50,000 m^3/yr. Similarly, LST estimates for Fire Island Inlet cluster around a high of ~400,000 m^3/yr to a low of ~200,000 m^3/yr. The mean difference between LST estimates at Moriches Inlet and Fire Island Inlet is ~193,000 m^3/yr. There seems to be consensus that a significant gradient, in the order 2×10^5 m^3/yr, exists between LST at Moriches Inlet and Fire Island Inlet.

Only the RPI (1985a), Kana (1995), and Rosati *et al.* (1999) sediment budgets provide estimates of LST at intermediate points along the Fire Island shoreline. Table 1 lists their estimates at a point ~18 km east of Democrat Point. The average rates for west-central Fire Island are ~50 percent greater in magnitude than the average for Moriches Inlet, but only half the mean estimate for Democrat Point. This suggests there is a distinct acceleration of LST along the western third of Fire Island.

The difference in net longshore transport rates from Moriches Inlet to Fire Island Inlet implies that there must be a source of sediment entering the littoral transport system along Fire Island. Three sediment sources are possible:

- Erosion of the beach and inshore littoral zone.
- Beach nourishment adding volume to the littoral zone.
- Onshore transport of sediment from deep water, beyond the active littoral zone.

Of course, other factors that could contribute to differences between the estimated net transport at Moriches Inlet and Fire Island Inlet are errors in the survey data and the adopted offshore boundary for sediment budget calculations.

Shoreline Erosion

Rosati *et al.* (1999), using comparative profiles from 1979 to 1995 and an offshore boundary of ~7 m NGVD*, estimated average annual volume losses of ~203,000 m^3/yr along Fire Island (excluding ~3 km of shoreline at each end of the island). Kana (1995), using profiles from 1955 to 1979 and an offshore boundary of ~9.1 m NGVD, estimated average annual losses of ~316,000 m^3/yr within essentially the same length of shoreline. Comparative profiles necessarily incorporate any additions in the form of nourishment, backshore dune erosion added to the control volume, and overwash losses out of the control volume or losses due to equilibrium profile adjustment to sea-level rise (Bruun, 1962; Jarrett, 1977, 1991; Rosati, 2005; USACE, 1980, 1984).

When Kana's (1995) volume losses are incorporated into the regional sediment budget, net longshore transport increases to ~360,000 m^3/yr along western Fire Island (1955-1979). Rosati *et al.*'s (1999) control volume loss raises net longshore transport at Fire Island Inlet to ~175,000 m^3/yr (1979-1995 period). Rosati *et al.* assume a portion of the control volume change represents

[*NGVD – National Geodetic Vertical Datum which approximated mean sea level at certain coastal tide measurement stations in the 1920s. This fixed datum was 0.2 m below local mean sea level in the Long Island area in the 1970s–1980s. (Kana, 1995; USACE, 1980)].

losses to "deep water" (>7-m depths in this case, or depths beyond the specific calculation depth limit in other studies) in connection with equilibrium profile adjustment. Kana (1995) did not apply an adjustment in the sediment budget for equilibrium profile losses due to sea-level rise. RPI (1985a), using the same data set of Kana but an offshore control boundary limit of 7.3 m, developed an alternate estimate of longshore transport near Fire Island Inlet. Applying an adjustment for sea-level rise, the RPI (1985a) sediment budget yielded net transport of ~362,000 m³/yr at Democrat Point (1955-1979 time period). This rate is ~180,000 m³/yr higher than that of Rosati *et al.* (1999) largely because of differences in the Moriches Inlet rates for the two studies (*c.f.,* Figure 5).

Schwab *et al.* (2000) point out the inherent inaccuracies of sediment budgets, which are highly dependent on the quality and quantity of surveys. Regional sediment budgets such as those completed for the south shore of Long Island utilized surveys of limited spatial and temporal coverage. Uncertainties connected with sediment budgets are readily acknowledged by practitioners (*c.f.,* Kraus and Rosati, 1998). The RPI (1985a), Kana (1995), and Rosati *et al.* (1999) budgets are the most detailed to date for Fire Island, yet they result in differences of the order 100,000-200,000 m³/yr for net transport at the western end of the island. Schwab *et al.* (2000) express concern that Kana's (1995) estimates of ~110-180,000 m³/yr for net longshore transport along various segments of central Fire Island fall well short of the roughly 400,000 m³/yr accumulating on the spit or in the channel at the western end of the island. "If published sediment budgets . . . along the Fire Island barrier-island system are accurate, . . . an onshore sediment flux from the inner shelf of about 200,000 m³/yr is necessary to explain the spit progradation at Democrat Point" (Schwab *et al.*, 2000, *pg.* 420). Yet, this statement ignores two obvious factors that are known to produce significant gradients in longshore transport: 1) increasing erosion rates (in this case from east to west) as documented by Leatherman (1985) and Kana (1995); and 2) increasing wave energy flux along a shoreline that curves away from the predominant approach direction (Inman and Bagnold, 1963).

Somehow in the debate about a possible offshore sand source for Fire Island, a significant volume of ~200,000 m³/yr (Allen *et al*., 2002; Schwab *et al*., 2000), or 0–370,000 m³/yr (Lentz *et al*., 2008; Hapke *et al*., 2010), is now assumed by some to represent the contribution from offshore. The report by Lentz *et al.* (prepared for the NPS) speculates that "mapped linear shoals" in the offshore are "the likely source of the sediment" (Lentz *et al*., 2008, *pg.* 25). More recently, Hapke *et al.* (2010, p. 520) compare inner-shelf geologic framework and historical shoreline change and conclude that there is…"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 may be providing sediment to the nearshore and beach system." However, there is no quantification or physical basis offered to establish the relative importance of onshore transport to the regional sediment budget at decade-to-century time scales, and the comparison is primarily qualitative, with inner-shelf troughs plotted adjacent to shoreline change and discussed as "spatially related" (Hapke *et al*., 2010, their Figure 6). Points not discussed are that wave refraction and shoaling over these offshore features relative to the shoreline in western Fire Island change the location and magnitude of wave energy that mobilizes sediment, and sand is more readily mobilized over *ridges* rather than troughs.

Figure 6. Oblique aerial photograph at low tide on 11 January 1994 showing rhythmic shoreline features along a section of central Fire Island. The partially attached low-tide bars (center, right side of image) are estimated to contain no more than 50 m^3/m. (Photo by T.W. Kana)

Precise comparative surveys encompassing the beach, outer surf zone, and inner shelf waters to at least ~20-m depths, likely prohibitive for most studies, would be needed to ascertain decadal scale change in depth of closure. Such surveys might allow researchers to infer onshore transport and quantify its contribution. Heretofore, beach surveys along the U.S. East Coast have typically terminated in water depths <10 m because of the assumption and considerable evidence there is little measurable sand exchange with the active littoral zone beyond that depth (*c.f.,* Birkemeier, 1985; Niedoroda and Swift, 1981; USACE, 1963, 1980, 1984;). Gentle slopes of the inner shelf further complicate analyses of comparative surveys because minor vertical errors in data collection become magnified with distance offshore (*c.f.,* Kraus and Rosati, 1998). Given the lack of comparative surveys into deep water, and the potential cumulative error, researchers must resort to indirect lines of evidence regarding sediment inputs from deep water. As the authors outlined at the beginning of this paper, the question is not whether sand can move from deep water to the surf zone, but whether in this setting there is a significant, observable quantity moving onshore and adding in the order ~10^5 m^3/yr along central Fire Island. Five factors should be considered:

1) Frames of reference, scales, and time period of interest.
2) Studies of episodic scour and sediment transport over inner shelf deposits.
3) Sediment size distribution across the littoral profile.
4) Temporal and spatial estimates in the depth of closure.
5) Depletion of inlet shoals associated with earlier positions of Fire Island Inlet.

In the following sections, the authors consider each of these factors in the context of its relevance to the question of sediment sources along Fire Island.

FACTOR 1 – SPATIAL AND TEMPORAL FRAMES OF REFERENCE

To be significant at decade to century time scales along Fire Island, onshore transport from deep water must be more than a trickle of sediment moving shoreward through such conduits as "rippled scour depressions" (RSDs). First described by Cacchione *et al.* (1984), RSDs are shore-perpendicular concentrations of coarse sand, granules, pebbles, or shell hash, with bedforms indicative of sediment motion. These features have been documented off the California coast (Cacchione *et al*., 1984), South Carolina coast (Thieler *et al*., 1999), North Carolina coast (Thieler, 1997), and Long Island (Schwab *et al*., 2000)—to name several sites, by means of high resolution, shallow seismic surveys, side-scan sonar and borings. That sediment moves over U.S. East Coast RSDs in water depths >10 m is not in dispute. But given the fact that sandy sediments in deep water can only be mobilized under energetic wave and current conditions, the contribution from RSDs or other offshore deposits to the beach must be episodic in relation to storm frequencies rather than continuous. Niedoroda *et al.* (1984) and Swift *et al.* (1985) demonstrated this for Long Island's south shore. Further, to provide volumes in the range 10^5 m^3/yr along discrete segments of coastline in the lee of RSDs, there should be large, depositional signatures such as emergent bars entering the surf zone that dwarf normal ridge and runnel systems. If the contribution is large and associated with "shoreface-attached ridges" (Swift *et al*., 1973), there should be major protuberances ("salients") in the shoreline (measured in hundreds of meters relative to nearby adjacent areas) similar to those associated with inlet bar bypassing (FitzGerald, 1984).

The present authors assume for purposes of this paper that if there is a major flux of sediment added to Fire Island from deep water, it must move into shallow water over limited segments of coast, consistent with Schwab *et al*. (2000). Other researchers have concluded that the offshore of eastern Fire Island is not providing sediment because the adjacent shoreline has been rapidly eroding (Psuty *et al*., 2005; Schwab *et al*., 2000). If one assumes the central ~20 km (~40 percent) of Fire Island receives the bulk of sediment from offshore, the average annual flux would be 5-10 m^3/m/yr for volumes in the 100,000-200,000 m^3/yr range. But more realistically for this hypothetical scenario, conduits of shoreface-attached ridges or RSDs would concentrate the onshore fluxes over smaller lengths of coast. The typical alongshore length scale of RSDs is of the order 1-2 km (Schwab *et al*., 2000; Thieler *et al*., 1999). If five such features provided pathways from deep water along central and western Fire Island, the average unit flux (locally) would have to be in the range 20-40 m^3/m/yr to provide ~10^5 m^3/yr total volumes. Obviously, the unit flux must increase within each conduit if there are fewer pathways. In short, to be credible as a significant sand source for Fire Island at decade-to-century time scales, and consistent with the assertions of Schwab *et al*. (2000) or Hapke *et al*. (2010), offshore material must be entering the Fire Island littoral system within limited reaches, thereby producing a readily observable or measurable short-term growth of the beach at those localities.

The temporal frame of reference for additions from offshore is likely to be episodic rather than continuous. The concept of fair-weather and storm-weather wave base is well established by theory and observation (Komar, 1998). A longshore bar persists in water depths of 3-5 m off the south shore of Long Island with minor movement during fair weather (Shipp, 1980). If the bar is stable most of the time, sediments residing much further offshore in deeper water are likely to be immobile for even longer periods. Breaks in the longshore bar are generally considered to be offshore-directed flow pathways for water that sets up under wave action in the surf zone (Inman and Bagnold, 1963). If net flow in these channels is seaward, it would oppose forces tending to advect sediment landward. Therefore the pathway for onshore sediment transport must be via the bars themselves rather than through channel breaks. This further supports the assumption that the onshore flux would have to be concentrated along limited pathways and be episodic.

Gaudiano and Kana (2001) documented episodic "shoal-bypassing" events for nine South Carolina inlets. They demonstrated that bypassing occurred in the form of discrete bars at high frequencies and low volumes for inlets with small ebb-tidal deltas and lower frequencies but high volumes for large tidal inlets. Volumes of the order 10^5 m^3/yr entering from offshore at Fire Island are analogous to those associated with large, infrequent shoal-bypass events in South Carolina. If there were an average of one event per five years that brought sand (*i.e*. ~10^6 m^3) from offshore off Fire Island, the net unit flux for the event would be of the order 25-50 m^3/m (over 20 km of shoreline) or 100-200 m^3/m if concentrated along several short segments of coast totaling 5-10 km. Additions to the surf zone in these ranges of unit volumes become readily apparent at the receiving localities.

Figure 6 illustrates a perturbation of the central Fire Island shoreline after a winter northeast storm. In plan view, the cross-shore variation in berm width is ~50 m, and the unit volume associated with the low-tide bar is ~50 m^3/m. An overflight of the island that day indicated only a limited section of central Fire Island had rhythmic shoreline features of this magnitude. Furthermore, the morphology of the berm and dune escarpments in the same area suggests the sediment in the low-tide bar did not originate offshore, but rather from the berm itself (*i.e.*, through erosion of the berm and transport into the low-tide bar during the storm).

In summary, if significant volumes in the order 10^5 m^3/yr (average) are being supplied to central Fire Island from offshore (water depths >10 m), they are likely to be concentrated over limited reaches (such as locations of shoreface-attached ridges or RSDs). They are likely to provide episodic rather than yearly additions of sediment in relation to the frequency of storms. And the unit flux of sediment in the receiving areas is likely to be visible and obvious in the event.

FACTOR 2 – STUDIES OF SCOUR AND SEDIMENT TRANSPORT OVER OFFSHORE FEATURES

To date, there have been no estimates of the net volume flux of material moving through RSDs at decadal scales. Further, there is uncertainty regarding the net direction of transport (offshore or onshore).

Cacchione *et al*. (1984) suggested RSDs are produced by downwelling; therefore, the net transport direction would be offshore. Thieler *et al*. (1999), working off Folly Beach, South Carolina (SC) and Wrightsville Beach, North Carolina (NC), also reported net transport offshore, inferred from sediment textures. Both Carolina beaches have been nourished and the fill is "macroscopically distinct from native sediment and can be used to identify sediment transport pathways and infer mechanisms for across-shelf transport" (Thieler *et al*., 1999, *pg*. 2118). The linear RSDs studied at Folly Beach were in water depths extending from the beach to ~10 m (out to ~4 km offshore). Water depths off Wrightsville Beach are greater with the 14m contour situated 1 km offshore. In both cases, Thieler *et al*. (1999) concluded there was a net offshore flux of nourishment sediment to or via these features.

Schwab *et al*. (2000), working off Fire Island, mapped low-relief, scoured-ridge features in water depths between 8 m and 20 m, having coarse sediment textures similar to the RSDs of Thieler *et al*. (1999). Hapke *et al.* (2010) infer linkage through bathymetry of some ridges and troughs from these depths to the back of the nearshore bar system in water depths of ~5-6 m along a segment of western Fire Island. As previously discussed, Schwab *et al*. (2000) concluded that these features are a likely source of sediment or the conduits for sediment to the beach along central and western Fire Island. Water depths of these features are deeper than those observed off Folly Beach. Yet the inferred net direction of transport is landward at Fire Island rather than seaward as at Folly Beach, according to the same research team that conducted both studies. No quantification of advection rates onshore or offshore was offered in either the Thieler *et al.* (1999) or Schwab *et al*. (2000) studies.

Gutierrez *et al*. (2005) analyzed data from an array of instruments placed over the linear rippled scour beds off Wrightsville Beach in 10-m and 14-m water depths in March and April 1996. The arrays of current meters, pressure sensors and transmissometers (the latter at 1.8 m above the bed) were used to identify sediment-transport events. Six distinct transport events were detected during the measurement period with measured, significant wave heights at those times averaging 1.7–2.9 m. Using the Dolan and Davis (1992) storm classification system for extratropical storms, Gutierrez *et al.* (2005) ranked three of the events as significant and the other three as weak to moderate. The storm intensities observed were considered characteristic of 97 percent of the storms on which the Dolan and Davis (1992) classification is based. Gutierrez *et al.* (2005) found that sediment transport was partitioned between bedload and suspended load fractions. Bedload fluxes were oriented principally in the cross-shore direction approximately aligned with the long axes of the linear rippled scour beds. Suspended sediment fluxes tended to be oriented parallel to shore. Bedload transport (coarse material) was principally in the direction of waves (generally onshore), whereas suspended load transport correlated most strongly with wind direction, which tended to be parallel to shore. Thus, Gutierrez *et al*. (2005) identified a mechanism for maintaining the coarse-grained ripple features while fine-grained material is swept away from the area. They found no evidence of cross-shore sediment transport caused by steady downwelling currents (an argument for offshore-directed transport).

Gutierrez *et al*. (2005) applied a benthic boundary layer and sediment transport model by Styles and Glenn (2000), which is based on the approach of Grant and Madsen (1979) and Glenn and Grant (1987). The net transport for six events at Wrightsville Beach was directed offshore using symmetrical waves and onshore using asymmetrical waves. The models predicted net volume transport (for six events) in the range ~0.25-0.6 m^3/m width for asymmetrical wave motion (onshore-directed) and ~0.5-2.2 m^3/m for symmetrical waves (offshore-directed). Notwithstanding the obvious disparity in net direction depending on the assumptions of wave forms, the net volume flux per event is low. Assuming net bedload transport is onshore, this would yield the equivalent of a shoreward flux (six events) of ~250-600 m^3/km or 2,500-6,000 m^3 per 10 km. One of the authors of the study cautions that the net flux estimates are likely to be overestimates, particularly closer to shore because the model does not account for return flows under wave setup (G. Voulgaris, pers. comm., September 2009). Regardless, it would appear that if there is net transport of coarse sediment in the shoreward direction during episodic events, it will have length scales similar to the alongshore width of the RSDs (typically <1 km) and net volume transport scales of the order 10^2 m^3 per event per kilometer of coastline. It would take hundreds of transport events at these magnitudes each year to yield fluxes of the order 10^5 m^3/yr from comparable depths off central Fire Island.

FACTOR 3 – SEDIMENT SIZE DISTRIBUTION ACROSS THE FORESHORE

There tends to be a distinct variation in sediment size distribution across the foreshore along most U.S. East Coast beaches. Moving from the swash zone offshore, sediment becomes finer in the offshore direction as a result of natural mixing under energetic wave conditions. Coarsest sediments such as granules and pebbles (if present) become concentrated in the lower swash zone. The upper swash zone and berm will tend to have medium size distributions, and the dune and outer bar will have fine size classifications. Seaward of the bar, particularly at the toe of the foreshore/intersection with the inner shelf, very fine sediments will concentrate (Ippen and Eagleson, 1955; Niedoroda *et al*., 1978; Swift *et al*., 1971). This sorting of sediment sizes is in direct relation to wave energy variations at the bed. Fine-grained material is easily suspended in the surf zone and advected to less energetic areas where it is deposited. The slopes across the foreshore are, in turn, related to the predominant sediment diameter (Bascom, 1964; Komar, 1998). Beach face slopes across the swash zone where sediments are coarse tend to be much steeper than slopes from wading depth to the outer bar, a zone where fine sand is often the dominant sediment (Bowen, 1980).

Fire Island beaches conform to this simple sediment-distribution model. Liu and Zarillo (1987) obtained sediment samples from 11 cross-shore positions along 52 shoreface profiles between Montauk Point and Fire Island Inlet. Samples extended from mean high water to a distance of ~2.25 km offshore. Along Westhampton Beach and Fire Island (barrier island sections), the bar samples were in depths averaging ~4.5 m at a distance of ~0.25 km offshore. Deepest samples were around the 18-m depth contour situated ~2.25 km from mean high water (MHW). Liu and Zarillo (1987) plotted the cross-shore distribution (percent) of each of 17 grain-size classes (Figure 7). Consistent with the general cross-shore model of sediment sizes, they found medium-to-coarse sand (0.25-1.0 mm) in the inner surf zone (within 100 m of MHW). The predominant sediment over the bar and seaward of the bar to ~0.5 km offshore was 0.1-0.2 mm. Further, Liu and Zarillo (1987) observed increasing abundance of 0.074 to 0.015 mm grain size classes from east to west. There was a paucity of material coarser than 0.2-mm diameter in the zone from ~0.4 km to 0.8 km offshore. This zone is in depths around 5-10 m. Average slopes in this zone are ~1 on 75, whereas slopes seaward of this zone are ~1 on 200. Liu and Zarillo (1987) showed that grain size increases farther offshore. Predominant grain sizes between 1 km and 2.25 km offshore were in the 0.2-0.5 mm range. In short, they confirmed a grain-size minimum seaward of the bar in water depths of 5-10 m, where upward of 80 percent of the material was in the very fine to fine sand range. Such material is not a major fraction of the sediment on the subaerial beach along Fire Island.

The Liu and Zarillo (1987) data set is instructive because it confirms the presence of coarser sands in deep water (10-18 m depths) off Fire Island. This supports Schwab *et al.*'s (2000) identification of exposed coarse sediments on the inner shelf. But if there were significant onshore transport of those deposits, one would expect to find more medium-to-coarse sand in the lower shoreface (water depths of 5-10 m). To move from offshore to the beach, such material necessarily has to pass through the zone of "grain-size minima" situated seaward of the outer bar. An average flux even as small as 20 m³/m/yr (yields 200,000 m³ over a 10-km segment of beach) would undoubtedly leave a trail of material through this zone. The Schwab *et al.* (2000) offshore features were mapped in water depths beyond 8 m. If significant volumes of medium sand were moving from water depths >10 m into the surf zone, it is unlikely there would be a persistent size minima between the offshore source and the beach. The authors know of no physical process that could move large volumes of 0.3-0.5-mm sediment nearly 0.5 km from 10-m to 5-m water depths without resulting in mixing with finer material, or burial of the silty sands in that depth zone.

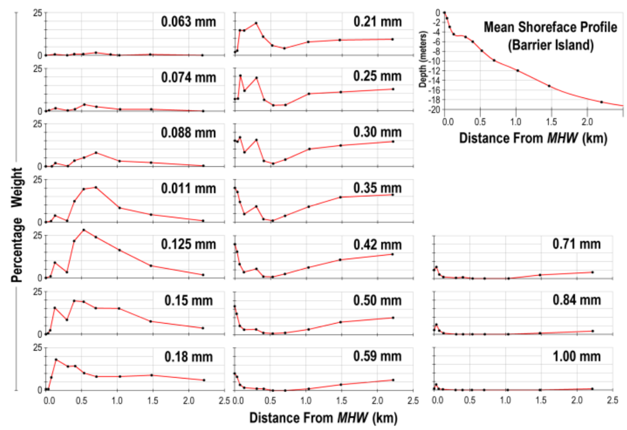

Figure 7. Mean cross-shore distribution (%) of 17 mean grain sizes from a population of 40 sediment sample transects along the barrier island section of Long Island (based on Liu and Zarillo, 1987, Figures 2 & 3). Note the paucity of material coarser than 0.2 mm diameter in the zone from 0.4 km to 0.8 km offshore (water depths ~5-10 m).

FACTOR 4 – DEPTH OF CLOSURE (DOC) ANALYSIS

The concept of depth of closure (DOC) is one of the most important factors in coastal zone management. Kraus *et al.* (1999) offer the following general definition. *"The depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore."*

For purposes of the present paper, the authors assume that both requirements of the definition must be satisfied. That is, there must be no significant or measurable change in bottom elevation (a condition that can occur under a large flux of sand across the depth of closure as well as the no-transport condition), <u>and</u> there must be no significant sediment transport landward or seaward across the boundary. DOC, when applied at appropriate time scales (particularly decades used for planning in most jurisdictions), facilitates estimates of net erosion volume or nourishment requirements in a given reach. It establishes a maximum depth for disposal of material beyond which little is expected to be advected onshore or offshore (Douglass, 1995, 1997). It can be computed or approximated using a number of techniques.

Using rigorously collected profiles, DOC can be observed as the depth beyond which there is little change in bottom elevation and slope. This does not preclude some exchange of sediment across the DOC contour. Rather, it implies such exchanges result in no net change in elevation at that depth over the time period of interest. Changes in bottom elevation result from gradients in sediment transport in the cross-shore and longshore direction. An accepted method for establishing the approximate DOC is to calculate the mean and associated standard deviation for the envelope of a suite of profiles. The water depth at which the standard deviation approaches a minimum (typically <0.25 m) and remains relatively constant with distance offshore provides an accepted approximation. An example analysis for a suite of Fire Island profiles from December 1979 to March 2003 is shown in Figure 8, and indicates that the standard deviation in profile depths decreases to <0.15 m at (~)−6.9 m NGVD, or shallower. It is rare that the standard deviation for comparative profiles spanning decades will be near zero because of inherent

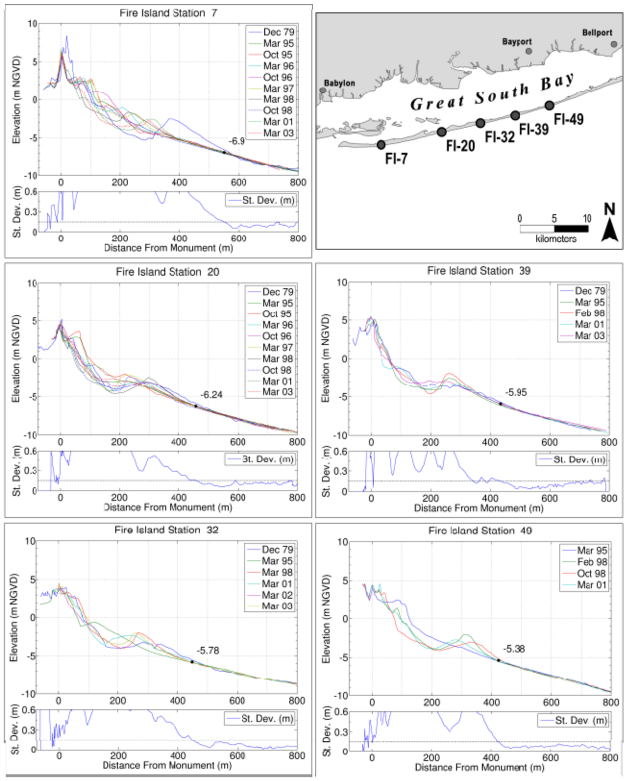

Figure 8. Representative comparative profiles (1979 to 2003) off central (station #s 20-49) and western Fire Island (#7) showing estimated depth of closure (DOC). DOC is based on standard deviation <0.15 m around the mean profile among the suite of profiles at each station. NGVD datum is approximate mean sea level. (Source data: Courtesy U.S. Army Corps of Engineers, A.V. Strock Associates, and N.Y. State Department of State)

differences among depth recorders and positioning systems. These electronic devices depend on calibration for water temperature, water levels (prior to the availability of Real Time Kinematic-Geographic Position System, RTK-GPS), and transponder characteristics, not to mention operator skills. Signals over soft bottoms are particularly variable from recorder to recorder, depending on how the transponder is set for the acoustic return off low-density material.

The authors obtained comparative profiles for Fire Island (courtesy of New York State and USACE) spanning the period 1979-2005 and plotted the mean and associated standard deviation for each suite of profiles at 34 transects. Closure was assumed when the standard deviation was <0.15 m over a ~500-m (or longer) section of the outer profile. Results for Fire Island are given in Table 2. DOC estimates, using the comparative profile method, ranged from 5.3 m to 8.4 m NGVD. The average for 15 transects encompassing central Fire Island (NY State lines FI-11 through FI-49) was 5.72 m NGVD. This value is shallower than the DOC assumed in the RPI (1985a), Kana (1995), and Rosati *et al.* (1999) sediment budgets. Applying the sediment budget calculations with a shallower DOC reduces the calculated transport rate at Democrat Point. For example, Rosati *et al.* (1999) calculated volume change of 203,000 m^3/yr for Fire Island using a DOC=7 m NGVD. Instead, if a DOC=5.7 m NGVD is applied, the calculated volume change is 178,000 m^3/yr.

A second method for estimating DOC is based on the work of Hallermeier (1978), who defined DOC (dn_1) as a function of the nearshore storm wave height (H_e) exceeded only 12 hours per year (hrs/yr):

$$dn_1 = 2.28\, H_e - 68.5\, (H_e^2)/gT_e^2 \qquad (2)$$

where g is the acceleration due to gravity and T_e is the wave period associated with H_e . This semi-empirical equation correlates expected wave parameters with changes in bathymetry, independent of a flux of sand across the DOC, which could possibly be present.

Birkemeier (1985) refined Equation (2) for Duck, NC, where there were long-term, good-quality wave and profile data available for several storm events:

$$dn_2 = 1.75\, H_e - 57.9\, (H_e^2)/gT_e^2 \qquad (3)$$

He also found a simple estimate of DOC (dn_3):

$$dn_3 = 1.57\, H_e \qquad (4)$$

At Duck, mean wave energy is generally considered to be as high as any locality along the U.S. East Coast (USACE, 1984). Birkemeier (1985) estimated DOC under 3.3-3.8 m waves at 5.2-6.0 m depths using Equations (3) and (4), and at 6.8-7.8 m depths using Equation (2).

The authors contacted Bill Birkemeier who has managed the profile data set encompassing nearly 30 years of monthly measurements at the U.S. Army Research Pier at Duck. Comparative profiles in the vicinity of the pier spanning ~30 years show only minor variations seaward of the 9-m contour (B. Birkemeier, pers. comm., June 2006). This period encompassed numerous northeast storms where significant wave heights greatly exceeded 3.8 m.

The authors calculated the 12-hour wave height for 1998-2008 data at NOAA offshore buoy 44025 in a depth of 36 m off Fire Island. Normally, an inshore wave height in ~10 m depth is used in Equations (2), (3) or (4), therefore the analysis using a deeper water wave is conservative (*i.e.*, will result in a deeper DOC). The resulting 12-hour wave (H_e = 4.81 m, T_e = 10.0 seconds) yields DOCs ranging from 7.05 m (Equation 3) to 7.55 m (Equation 4) and 9.35 m (Equation 2). These values bracket the range of DOCs assumed by RPI (1985a), Kana (1995), and Rosati *et al*. (1999) in the regional sediment budgets for Fire Island.

A third method for estimating DOC is to adopt values determined at similar sites. DOC has been estimated to be ~6 m along Bogue Banks, NC (Bodge *et al*., 2006), a 40-km barrier island with similar sheltering from northeast waves as Fire Island, similar tide range, and wave energy from both westerly and southeasterly directions. There are no sites along the U.S. East Coast where DOC has been reported to exceed 10-m

Table 2. *Estimated depth of closure (DOC) for profiles along central and western Fire Island for available dates (1979 to 2003). DOC is based on standard deviation around the mean profile <0.15 m. (Data: Courtesy USACE – New York District and N.Y. State Department of State)*

Profile	DOC (m)	DOC (ft)	Location	Profile	DOC (m)	DOC (ft)	Location
1	-5.07	-16.62		43	-5.70	-18.71	Central FI
3	-5.83	-19.11	Robert Moses Park	46	-5.96	-19.55	Central FI
5	-8.25	-27.07	Robert Moses Park	49	-5.38	-17.65	Central FI
7	-6.90	-22.63	Robert Moses Park	50	-7.06	-23.16	
9	-7.16	-23.47		55	-6.84	-22.45	
11	-7.09	-23.26		58	-9.03	-29.63	
12	-6.26	-20.55		60	-7.21	-23.66	
17	-5.56	-18.23		62	-7.26	-23.83	Eastern FI
20	-6.24	-20.47		66	-7.19	-23.58	Eastern FI
24	-6.58	-21.60	Central FI	68	-6.85	-22.46	Eastern FI
30	-5.61	-18.41	Central FI	70	-7.29	-23.91	Eastern FI
32	-5.78	-18.96	Central FI	72	-8.43	-27.65	Eastern FI
33	-5.61	-18.41	Central FI	76	-6.68	-21.92	Eastern FI
35	-5.43	-17.83	Central FI	77	-6.34	-20.79	
36	-5.25	-17.21	Central FI	79	-7.96	-26.12	
38	-6.48	-21.26	Central FI	81	-8.39	-27.54	
39	-5.95	-19.52	Central FI	82	-9.44	-30.96	

Data courtesy USACE-New York District. Average of profiles 11-49 (n=15) is -5.93 meters based on ±1 std dev around the mean elevation (<0.15 m for each profile data set). Dates 1979 (limited) to ~2005.

depths. For significant volumes of sediment to be advected shoreward from water depths of 10-20 m (as postulated by Schwab *et al*., 2000 and Lentz *et al*., 2008), the DOC off Fire Island would have to be much deeper than any previously documented estimates for other U.S. East Coast sites.

In summary, depth of closure (DOC) was evaluated for Fire Island three ways: 1) via comparative profiles; 2) via empirical formulae; and 3) via comparison with results from similar sites. DOC at decadal time scales was found to be in the range ~5 m to 9 m, with the majority of estimates by any method shallower than 7 m (relative to ~mean sea level). Prior sediment budgets (*e.g.,* Kana, 1995; Rosati *et al*., 1999) assumed DOC in this range. While some may still argue that a large flux of beach quality sediment could be moving across this depth zone from deep water (but yielding no change in bottom elevation over 100s of meters), the sediment size distribution gradient (Factor 3) off Fire Island violates that hypothesis. Cross-shore gradients in grain size distribution result from cross-shore gradients in transport. And cross-shore gradients in transport are fundamentally what produce changes in bottom elevation. East coast profiles from Fire Island and elsewhere show negligible change in bottom elevation over broad zones at decadal scales in water depths between 5 and 10 m.

FACTOR 5 – CONTRIBUTION OF INLET SHOALS

Some previous sediment budgets for Fire Island have demonstrated the largest gradients in volumetric change within the control volumes occur along the western ~25 percent of the shoreline. RPI (1985a) and Kana (1995) showed 275,000 m³/yr average losses 3-11 km east of Democrat Point for the period 1955 to 1979. Leatherman (1985) reported higher shoreline recession in this area compared with central Fire Island. Rosati *et al*. (1999) did not subdivide the western third of Fire Island, but show losses from the control volume compared with significant gains in the (next updrift) central Fire Island control volume for the period 1979 to 1995. Rosati *et al*. (1999) also show the majority of beach nourishment during the period (*i.e.* ~80,000 m³/yr) was placed between 3 km and 17 km from Democrat Point. The net effect of erosion and beach nourishment in the sediment budget is to increase net longshore transport significantly along the western end of the island.

Spit growth obviously transports sand from western Fire Island a prime source of sediment for the littoral transport system updrift of migrating tidal inlets is trailing, ebb-tidal delta shoals (FitzGerald, 1984; Hayes, 1980). As the inlet migrates, shoals that previously extended seaward along the updrift side of the delta migrate onshore, lagging evolution of the new delta (*c.f.,* Figure 3 and Figure 9). Schwab *et al.* (2000) and Lentz *et al*. (2008), without providing any volume measurements, suggest that the ebb-tidal delta of Fire Island Inlet is too small to account for the apparent increase in net longshore transport from central to western Fire Island. However, Walton and Adams (1976) and Moffatt and Nichol (2002) have estimated the ebb shoal volumes for Fire Island Inlet at 38 and 31 million cubic meters (respectively).

Between 1825 and 1940, when the inlet migrated ~7.5 km to the west, there would have been net displacements in the order 300,000 m³/yr[1] of the delta volume to keep pace with the migration rate. The RPI (1985a) and Kana (1995) sediment

[1] Assumes an average annual spit growth of ~65 m (longshore direction), ~450 m (cross-barrier width), and ~10 m (vertical accretion from the base of the channel to the toe of the foredune).

Figure 9. Oblique aerial photo of Monomoy Island (MA) spit at low tide (circa 1970) showing trailing, ebb-tidal delta shoals welding to the updrift beach. This process is considered analogous to spit growth at western Fire Island between 1825 and 1940, prior to jetty construction. (Source photo: Courtesy of Miles O. Hayes, Research Planning, Inc.)

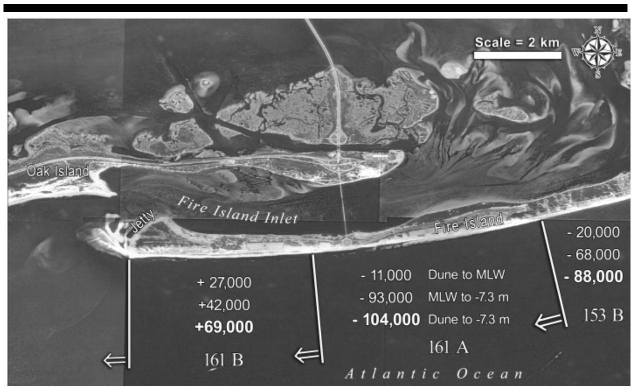

Figure 10. Average annual volumetric changes (m^3/yr) along western Fire Island based on comparative profiles for June 1955 and December 1979 for the subaerial beach to mean low water (MLW) and underwater to the −7.3 m mean sea level contour, as reported by Kana (1995). Note large, underwater sand losses in sediment-budget compartments 153B and 161A, which the authors believe reflect depletion of former inlet shoals. The 1825 inlet was situated near the boundary between compartments 153B and 161A. Gradients in erosion from compartment to compartment account for the inferred acceleration of LST in this area.

budgets for 1955 to 1979 documented major changes in the profile volume below mean high water. Focused erosion in the area of Robert Moses State Park and Saltaire (see Figure 1; *i.e.* ~3-12 km updrift of Democrat Point) in the past two decades suggests the earlier inlet shoals have been depleted, and the berm and dune are feeding the longshore transport system. Curvature of the shoreline in this section of western Fire Island (see shaded area in Figure 1, and Figure 4) exacerbates the erosion by increasing the angle of approach of waves as the shoreline turns as much as 17° over its western 10 km. The rotation of the shoreline to an east-west orientation increases the longshore component of wave energy flux, increases westerly longshore transport, and potentially draws off more sand from the surf zone. Erosion rates increase 3-5 fold in the area between Saltaire and Robert Moses State Park (Fig. 1; Kana, 1995).

There is considerable evidence that longshore transport accelerates along western Fire Island, and the transport system has been fed by nourishment, inlet shoals, and cannibalization of the beach and inshore zone (water depths <~8 m) over the past century (Figure 10). The gradient in transport between Moriches Inlet and Fire Island Inlet is largely concentrated along the western ~18 km of shoreline (*c.f.,* Figure 5 and Table 1). Volumes associated with the trailing ebb-tidal delta shoals of Fire Island Inlet, periodic nourishment, or erosion of the beach and inshore area are considered more than sufficient to add in the order 200,000 m^3/yr. Further, depending on the period considered and quality of the available survey data, this average is bound to have multi-year variations in the order 10^5 m^3/yr, an amount corresponding to the discrepancies in prior sediment budgets.

SUMMARY AND CONCLUSIONS

This paper reviewed literature and data documenting sediment transport processes along Fire Island, New York. The primary focus of this study was whether there are measurements and calculations that support the existence of an onshore deep water (depths >10 m) source of sediment to Fire Island. An onshore source of sediment has been postulated because of the relative stability of Fire Island during the past 200 years, as compared to nearby islands, and, possibly, the requirement for a source to balance the sediment budget for the island and the downdrift inlet, Fire Island Inlet. Whether or not there is an onshore source of sediment has implications for future planning and management of the barrier island. Within a sediment budget context, the authors have concluded that up to 10^5 m^3/yr uncertainty exists in the budget, which could potentially be explained by an onshore source of sediment (as well as a change in the sediment budget over time). To investigate this potential source, five primary lines of evidence, or factors, were examined: (1) the spatial and temporal frames of reference necessary for decadal-to-century sources of sediment; (2) studies of scour and sediment transport over offshore features; (3) sediment size distribution across the foreshore; (4) depth of closure; and (5) contribution of inlet shoals. Findings pertinent to each of these factors are reviewed below.

In discussion of (1), it was concluded that an onshore flux of sediment of the order 10^5 m^3/yr would have limited onshore pathways and be episodic, and by necessity visible and obvious as a result of a storm event. No such evidence is known for Fire Island. Factor (2) evaluated previous studies of scour and transport concerning existing, visible, offshore features. The magnitudes of net transport of these features were discussed, and it was concluded that hundreds of transport events of the magnitude 10^2 m^3 per event would be required to sum to the required flux each year. This number of forcing events is not observed at Fire Island. Sediment size and distribution were evaluated in Factor (3), with data from Fire Island examined as it agrees with the general coastal model that sediment tends to be coarse in the swash zone and becomes finer offshore, related to the wave and current energy available to transport sediment. The presence of coarse sediment offshore of Fire Island has been used to support evidence of an onshore source. However, if the coarse sediment were moving onshore, there would be a pathway of coarse sediment to the beach. This is not observed in the available data.

Depth of closure (DOC), the depth beyond which there is insignificant advection of sediment either onshore or offshore, was evaluated in Factor (4). The application of DOC does not imply that sediment is stationary beyond this depth; but rather that significant *net* transport of sediment does not occur at the DOC and deeper. Three methods were applied in evaluating the DOC: profile data, available calculation methodologies, and knowledge from sites with similar forcing. From profile data, DOCs ranged from 5.3 m to 8.4 m. Calculations yielded a maximum DOC equal to 9.4 m. There are no reported sites along the U.S. East Coast with a depth of closure >10 m depth. From this analysis, the authors conclude that a net influx of sediment does not occur from depths greater than ~10 m.

The final Factor (5) evaluated whether inlet shoals provide a significant source to the beach. Fire Island Inlet has an ebb-tidal delta which contains in the order 35 million m^3. This volume yields enough sand in the form of trailing shoals to account for the spit growth observed between 1825 and 1940. Following jetty construction at Democrat Point in 1940, additions of nourishment, depletion of abandoned ebb shoals in water depths <8 m, and erosion of the updrift beach are considered more than sufficient to account for the observed acceleration in longshore transport along western Fire Island.

In conclusion, the authors find no evidence that there is an offshore source in water depths greater than ~10 m providing a significant (order of 10^5 m^3/yr) flux of sediment to Fire Island beaches. Reluctance to use offshore deposits beyond this depth for beach nourishment because these areas, particularly shoreface-attached ridges, may provide a natural transport pathway is not supported. Rather, the authors believe that anthropogenic mining of these shoals for nourishment of Fire Island is the only way to ensure that relict sand on the inner shelf reaches the barrier island within commonly accepted planning time frames.

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