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Assessing the Coastal Resilience of Manasquan Inlet to Sea Bright, New Jersey: Regional Sediment Budget 1992–2003

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ABSTRACT

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Assessing the resilience of regional coastal systems requires analysis of the short- and long-term erosion and accretion characteristics of beach material, including natural and anthropogenic sources and sinks. A regional sediment budget provides that accounting and is pivotal to successful management practices that enhance the resilience of coastal systems. The U.S. Army Corps of Engineers, New York District, updated the regional sediment budget for Manasquan Inlet to Sea Bright, New Jersey, for 1992–2003, which reflects the effects of various beach replenishment projects. The study area is approximately 33.8 km long and encompasses two inlets, mainland beaches from Manasquan Inlet to Long Branch, and a barrier-spit landform from Long Branch to Sea Bright. The previous sediment budgets represented a relatively eroded and limited source beach condition. This updated sediment budget is the first to analyze the with-project condition incorporating periodic beach nourishments/renourishments. The shore protection project consisted of an initial fill of approximately 17 Mm³ (million cubic meters) between 1994 and 2002 and additional fill/renourishment of 11 Mm³ between 2008 and 2016. Data for the sediment budget were based on volumetric change of the beach as developed from digitized, historical, aerial shoreline images as well as volumes and location of sediment replenishment (nourishment) activities in this region of the shoreline. Results from this budget indicate a net longshore transport of sediment northward from Manasquan Inlet toward Sea Bright, increasing from 106,000 m³/y just north of Manasquan Inlet to 343,000 m³/y north of Monmouth Beach. This updated sediment budget establishes a good understanding of the beach processes over time, which will enhance the ability to provide better coastal management and resilience for the northern New Jersey shoreline.

ADDITIONAL INDEX WORDS: Aerial shoreline, shoreline change, longshore transport, volumetric change.

INTRODUCTION

The U.S. Army Corps of Engineers (USACE), New York District, as part of the New Jersey Alternative Long-Term Nourishment Study developed an updated regional sediment budget from Manasquan Inlet to Sea Bright, New Jersey, incorporating beach fill projects from 1992–2003. A sediment budget determines the annual balance of sand within a self-contained coastal system (*i.e.* control volume) and provides valuable information concerning the resilience of the shoreline. This study area is approximately 33.8 km long and encompasses two inlets (Shark River and Manasquan), mainland beaches from the Borough of Manasquan to the Borough of Sea Bright in Monmouth County, and a barrier-spit landform from Long Branch to Sandy Hook (Figure 1). The scope of the current analysis was limited to the sediment budget north of Manasquan Inlet, which was prepared by the New York District. Two historic sediment budgets (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989) represent the study area for the without-project conditions (*i.e.* before nourishment/renourishment). Caldwell (1966) used shoreline survey data

from 1838–1953 for the sediment budget analysis. The transport rates were based on aerial changes between shoreline surveys. This current investigation is the first, to our knowledge, to represent the with-project condition, incorporating periodic beach nourishments/renourishments. The work described herein is the result of efforts to prepare such a with-project sediment budget. A with-project sediment budget can be a useful tool in investigating observed coastal changes and estimating future changes and management alternatives and is crucial to aid the understanding of how the regional coastal system performs in a sediment-rich condition. This current study is especially important because the previous budgets cover only sediment-starved conditions (*i.e.* before nourishment).

The New York District conducted a beach erosion control study titled *Atlantic Coast of New Jersey, Sandy Hook to Barnegat Inlet* (USACE 1954) focusing on shore history, geomorphology, and littoral materials and forces. The purpose of that study was to develop a comprehensive plan to restore protective beaches, provide recreational beaches, and formulate a program for providing continued stability and resilience to the shore for the Atlantic Coast of New Jersey, extending from the N extremity of Sandy Hook Peninsula S to Barnegat Inlet. The ocean frontage of the study area was approximately 82.1 km of the total 200 km of New Jersey shoreline. The study area included the shoreline within Monmouth County and the

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northern portion of Ocean County and can be divided into three distinct physiographic regions based on land formations, *e.g.*, barrier-spit and mainland beaches. The northern region, comprising Sandy Hook, consists of a peninsula and a narrow barrier beach (barrier-spit landforms), extending 17.7 km south to Monmouth Beach. The middle region or headlands, in the mainland coastal plain (mainland beaches), extends 30.6 km from Monmouth Beach to Bay Head. The southern region consists of 33.8 km of narrow barrier beach, extending from Bay Head to Barnegat Inlet. The sediment budget for this current study covers the shoreline of sections I and II (based on beach fill contracts), 19.3 km and 14.5 km, respectively, as illustrated in Figure 2.

The region between Manasquan and Barnegat inlets (Figure 1) represents the location of the nodal zone (bifurcation) in the longshore transport, in which sediment transport is generally N from this region northward, and southward from this region S (Gravens, Scheffner, and Hubertz 1989; USACE 1954). Although the littoral drift near Manasquan Inlet is predominantly to the N, transport reversals are known to occur at that location of the New Jersey shoreline, so some S movement of littoral drift can be expected (USACE 1954). The Sandy Hook Peninsula has been gradually accreting N as the headlands to the S erode through waves and currents and littoral forces continue to transport sand to the N. Features of the peninsula include low sand dunes interspersed with low sandy beach ridges, which were left inland as the beach accreted seaward. The peninsula and barrier beach that form the northern section of the study area separate the Shrewsbury River from the Atlantic Ocean. The barrier has a width varying from 30.5 to 457 m with an elevation of 1.79 to 3.32 m NGVD29 (National Geodetic Vertical Datum of 1929). The headlands or middle section of the study area has sustained significant erosion since the 1800s (USACE, 1954), which continues to the present. In this area, the bluff once extended further seaward and has since been eroded by wind and waves. The headlands, extending southward from Monmouth Beach to Bay Head, contain the southern portion of Monmouth Beach with an elevation from 3.32 to 7.89 m NGVD29, with higher elevations located along the northern portion. Shark River Inlet and Manasquan Inlet are located in this region of shoreline, with Shark River Inlet 24.1 km south of Sandy Hook and Manasquan Inlet approximately 9.66 km further south. The long narrow land form of the southern region of shoreline, which extends from the headlands to Barnegat Inlet, has been called both an offshore bar and a spit. The land form has a width varying from 152 m to 1.61 km, and an elevation of 1.18 to 3.93 m NGVD29 with relatively high dunes facing the ocean. The conclusion of the USACE (1954) study was that erosion has seriously reduced the width of beaches, and there was justification for the adoption of a Federal project for beach restoration efforts.

Because of the 1954 study, the Shore of New Jersey, from Sandy Hook to Barnegat Inlet, the Beach Erosion Control Federal project was authorized by the River and Harbor Act of 3 July 1958. Beach nourishment was determined to be the most suitable and economically feasible option for reducing the risk of future storm damage to beaches while building resilience. Beaches reduce the risks of storm surge-related wave attack

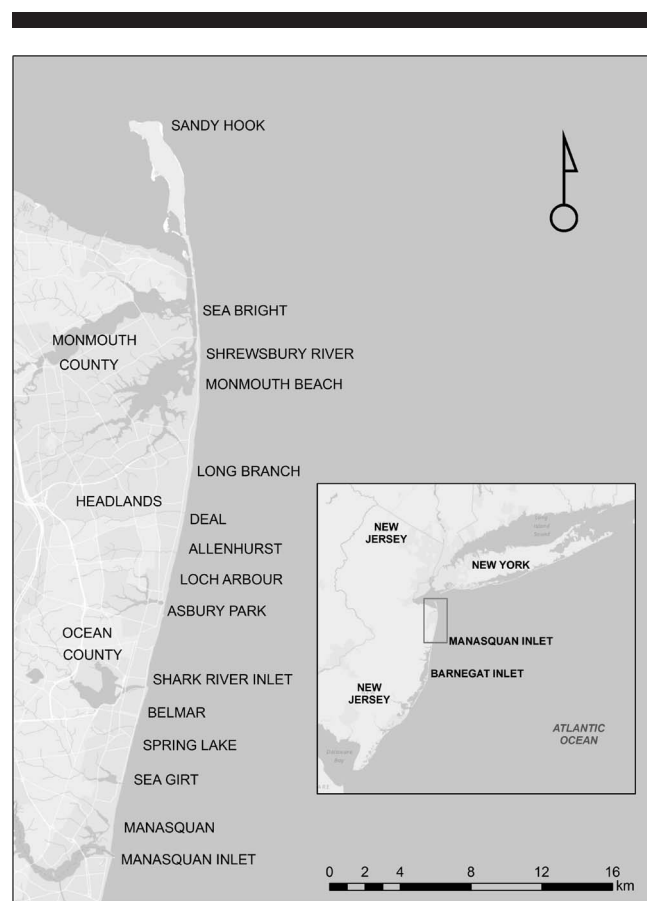


Figure 1. New Jersey shoreline representing the project study area of Manasquan Inlet to Sea Bright. The Sandy Hook Peninsula receives sediment from longshore transport as it moves from S to N over multidecadal time scales. Sandy Hook is a sand spit landform that continues to accrete because of the long-shore transport and is impinging on the federal navigation channel.

and flooding on barrier islands and the mainland (NRC 2014). The project objective was to provide beach restoration and storm damage reduction to the communities and infrastructure along the shoreline. The primary problem in the study area was continuing erosion of the bluff frontage along the headlands near Long Branch and Deal. Continuing economic and recreational development had created a demand for a more stable shoreline. Coastal structures, such as groins, were placed perpendicular to the shoreline with the intent of modifying waves and currents that influence sediment transport. When waves break at an angle to the shoreline, sand is moved longshore (along the shore), and material becomes trapped by the groin in the lee of the structure to help maintain a section of beach (ASPBA 2011). The shoreline from Manasquan Inlet to Sandy Hook has >160 groins with the intent of controlling longshore sediment transport. As indicated by accretion on the south side (up drift fillet) of the Manasquan and the Shark River Inlet jetties, and major groins, the predominant littoral drift is to the north in the Manasquan to Sea Bright area (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989). A caveat is offered by Caldwell

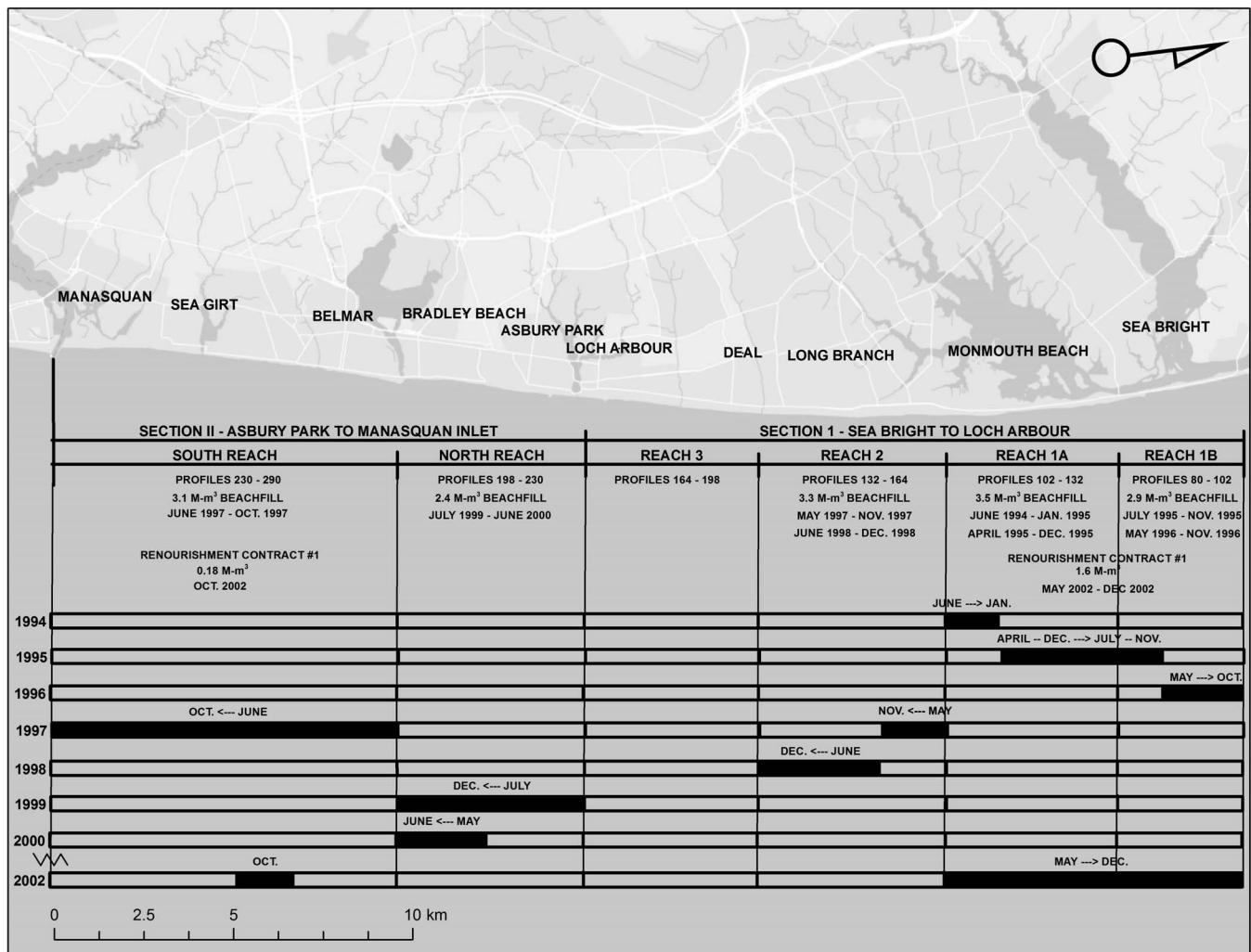


Figure 2. Atlantic coast of New Jersey Beach Erosion Control Project, Sea Bright to Manasquan Inlet site, map, and beach fill placement timeline. The project consisted of an initial fill of approximately 17 Mm³ between 1994 and 2002. Section 1, Sea Bright to Loch Arbour, Reach 3, is the only section within the project area that did not receive beach fill between 1994 and 2002.

(1966) that attempts to limit longshore transport by construction of groins up to the early 20th century were found to be ineffective for the period between 1903 and 1953. The elongation of the Sandy Hook Peninsula, as noted above, also indicates a northward net drift. The change of direction of predominant drift at the nodal zone with an increasing rate northward was due to the effect of Long Island in shielding the area from waves from the N and NE (USACE 1954). The accretion at Sandy Hook is ultimately balanced by an equal volume of sand eroded from the shore or near-shore areas along the study frontage north of the nodal zone. Beach material along the project reach occurs because of historic fluvial transport, glacial transport, or deterioration and fragmentation (weathering) of the adjacent uplands (Caldwell 1966). A large percentage of that sand may have been from the headlands between Bay Head and Monmouth Beach (USACE 1954). Studies of the historical erosion of the shoreline

indicated that the rate of littoral drift increased as the point of observation moved north from the nodal zone toward Sandy Hook (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989; USACE 1954).

A reanalysis of the federally authorized project was conducted by USACE in 1984, with an emphasis on the Sea Bright to Ocean Township section. The Water Resources Development Act of 1986 modified the initial 1958 authorization, such that the first increment consisted of a berm of approximately 15.2 m at Sea Bright and Monmouth Beach, extending to and including a feeder beach near Long Branch. That act was modified by the Water Resources Development Act of 1988 to extend the berm to approximately 30.5 m. A Project Viability Report was prepared in 1989 for Section II: Asbury Park to Manasquan Inlet (Figure 2), to reaffirm the authorized plan and to justify the revised improvement plan. In the 1990s, a General Design Memorandum (GDM) for Section I: Sea Bright

Table 1. *Sandy Hook to Barnegat Inlet, New Jersey Beach Erosion Control Project, 1994–2002.*

Reach (Contract)	CT Award	CT Completion	Fill Quantity (Mm ³)
Section I: Sea Bright to Loch Arbour (19.3 km) beach fill (30.48 m berm at +2.62 m NGVD29), selective groin notching, periodic nourishment.			
Reach 1B (contract 1B)	June 1995	November 1996	2.9
Reach 1A (contract 1A)	January 1994	December 1995	3.5
Reach 1A (contract 1A) first renourishment	May 2002	December 2002	1.0
Reach 2 (contract 1B) first renourishment	May 2002	December 2002	0.61
Reach 2 (contract 2)	May 1997	December 1998	3.3
Section II: Asbury Park to Manasquan Inlet (14.5 km) beach fill (30.48 m berm at +2.62 m NGVD29), selective groin notching, periodic nourishment.			
North Reach (contract 2)	June 1999	June 2000	2.4
South Reach (contract 1)	June 1997	October 1997	3.1
South Reach (contract 1) first renourishment	May 2002	October 2002	0.18

CT = contract, NGVD29 = North American Vertical Datum of 1929

Note: Data reflect federal project quantities in millions of cubic meters (Mm³).

to Loch Arbour, Ocean Township (Figure 2), beach restoration and groins with beach restoration were the only two storm damage–protection alternatives selected for further consideration. The initial estimates for fill volume for the berm (30.5 m wide, 3.05 m above mean low water, elevation +2.56 m NGVD29, plus a 0.61 m berm cap to +3.17 m), showed 13.0–13.8 Mm³ of material would be needed. That 19.3-km-long design section was divided into several constructible reaches (Figure 2). Original construction was proposed to take 4.5 years, and renourishment was estimated for a 6-year period. The proposed project life period was 50 years. In the 1994 General Design Memorandum for Section II: Asbury Park to Manasquan, a fill-only plan, was determined to be the optimal plan for that particular section. Initial construction for the proposed 14.5-km-long berm, (30.5 m wide, 3.05 m above mean low water, elevation +2.56 m NGVD29, plus a 0.61 m berm cap to +3.17 m), was estimated to require 5.0 Mm³. Because of the length and size of the project, the area has been separated into construction reaches during the feasibility phase of the period of this sediment budget analysis. Beach fill has been placed in five of the six initial construction reaches (Figure 2), with no placement in Reach 3 during the time of this investigation. The planned renourishment cycle was 6 years; however, funding has limited renourishment efforts. The renourishment cycle was initially extended because of the longevity of the fill material potentially the result of more stable material (*i.e.* larger grain size). The first renourishment was conducted in the areas of Sea Bright, Monmouth Beach, and Long Branch (Table 1).

Historically the littoral material along the Atlantic Coast of New Jersey was from several sources and included material eroded from inland areas and transported to the coast by streams and rivers, material obtained through direct erosion of sedimentary material exposed to wave and current actions, and material supplied from the continental shelf. Caldwell (1966) reported fluvial sand was no longer being added to beach material between Manasquan Inlet and Sandy Hook. Caldwell (1966) further reported that surveys dating back 100 years (*i.e.* 1860–1960) showed no evidence of sand being supplied from offshore sources and concluded that material being moved through longshore transport to Sandy Hook must have come from beaches further south. The Atlantic Coast of New Jersey, Sandy Hook to Barnegat Inlet study (1954), computed the growth of Sandy Hook based on the littoral drift reaching it from ocean beaches to the south. The growth rate was a marker

to compute the volume of littoral drift (longshore transport). The study found that between 1885 and 1933 (45 y) the average annual accretion rate was 377,000 m³/y, and in 1933–51 (18 y), the annual rate was 333,000 m³/y. These estimates indicate that the average rate of drift reaching Sandy Hook has been relatively constant for that 66-year period of record. This area of New Jersey shoreline (Manasquan to Sea Bright) has had a general history of recession during the period of record, with Sandy Hook being an area of accretion. Before construction of the approved federal project, the study area shoreline was in a sediment-starved condition, and some of the large stone seawall segments (*e.g.*, Sea Bright) were in danger of failing.

For the period of this current sediment budget analysis (1992–2003), Section I contracts 1A, 1B, and 2 have been completed, and Section II is complete (Table 1). Section I, which extends for 19.3 km from Sea Bright to Ocean Township, is separated into four construction contracts. Monmouth Beach and Sea Bright have had up to 879 m³ of sand per meter of beachfront placed on the beach, extending the 0.0 NGVD29 shoreline up to 152 m seaward of the seawall. During 1997, Manasquan, Sea Girt, Spring Lake, and Belmar received sand. Section I, contract 2, for Long Branch, was completed in 1998. Section II, contract 1, Manasquan to Shark River was completed in October 1997. Section II, which reaches 14.5 km from Asbury Park south to the Manasquan Inlet, was divided into two contracts. Section II, contract 2, Asbury Park to Shark River was completed by October 1999. Construction continued during the spring of 2000 when the groins, storm water outfall pipes, *etc.* were modified or extended. The section of shoreline from Loch Arbour to Elberon, Reach 3 (Figure 2), was the last segment of the beach erosion control project to be nourished and was completed in December 2016.

Attempts to control erosion by groins and seawalls have been largely unsuccessful, and replenishment of the shoreline is a desirable solution (Caldwell 1966). Beach fill projects have been successful in providing reduction in damage (*i.e.* coastal resilience) from storm surge and wave attack providing beach erosion control (NRC 2014) and increased ecological habitat for threatened and endangered species. The Atlantic Coast of New Jersey, Sandy Hook to Barnegat Inlet Project, has provided increased recreational opportunities, especially in the sand-starved northern sections, where the beach has become more accessible to the public. Significant littoral transport to the north of the project area has alleviated the severe erosion that had occurred historically in sections of Sandy Hook. The

longevity of the fill material and the less-than-expected price per cubic meter of fill has provided considerable savings over estimated beach fill costs at the time of this current study. Despite the efforts put forth by the New York District, conditions along this portion of the north Jersey shoreline remain less than robust for sediment supply, hence, the need for periodic replenishment (nourishment). The Atlantic Coast of New Jersey, Sandy Hook to Barnegat Inlet Project, Sea Bright to Manasquan Section, was designed and analyzed for storm damage reduction (resilience) in the 1980s. Alternatives such as offshore breakwaters, additional groins, and beach fill were designed separately and in combination, and a beach fill-only plan, with addition of groin notching was recommended as the optimized plan evaluating benefits, costs, and environmental considerations. Groin notching (or low-profile groins) can help maintain the beach profile while allowing sand to move to the downdrift beach by longshore transport (ASBPA 2011). Donohue, Bocamazo, and Dvorak (2004) demonstrated that groin notching can achieve a positive benefit for maintaining beach width within the 33.8-km beach fill project area. The project provides beach restoration and storm damage reduction to the highly populated communities and infrastructure located along this area of the New Jersey shoreline, which was previously protected only by a seawall or eroded areas of beach. Protection is now provided by construction of a 30.5-m-wide beach berm at an elevation of 2.63 m NGVD29. Prior experience indicates that sand retention structures (*e.g.*, groins) can be incorporated with beach nourishment to develop economically beneficial projects for erosion control and effective regional sediment management (ASBPA 2011).

METHODS

Shoreline-change comparisons are a method used to calculate large-scale volumetric change in sediment along a shoreline on a regional scale (*e.g.*, hundreds of meters to tens of kilometers). This method involves comparing the progression of shoreline morphology over time and determining the gains and losses within a control volume. Aerial photographs of the shoreline from Manasquan Inlet to Sandy Hook for 1992–2003 were used to develop this current sediment budget. Ten time points with available aerial photographs comprise this analysis and are presented as follows: (1) 1992–96, (2) 1996–98, (3) 1998–99, (4) 1999–2000 Spring, (5) 2000 Spring–2000 Fall, (6) 2000 Fall–2001 Spring, (7) 2001 Spring–2001 Fall, (8) 2001 Fall–2002 Spring, (9) 2002 Spring–2003 Spring, and (10) 2003 Spring–2003 Fall.

Each set of the 10 pairs of dates accesses the shoreline change between the indicated time points. The historical, aerial shoreline was digitized and imported into the computer-aided design (CAD) software Microstation®/In-Roads® select series 2. In conjunction with a representative beach profile, that software was used as a tool to generate three-dimensional (3D) renderings of the shoreline, enabling a volumetric change analysis. To generate a 3D surface, the *x*, *y*, and *z* data for a given shoreline was modeled within Microstation/In-Roads. The modeled shoreline (a design [.dgn] file) was set at elevation 0.0 m NGVD29 and offset with a line 30.5 m to the W and 244 m to the E. The line to the W (berm height) was set at an elevation of +3.05 m NGVD29, and the line to the E (depth of closure) was

set at an elevation of –6.10 m NGVD29. That was accomplished by using the “Set Elevation” command from the In-Roads Surface–Design Surface tab. All three lines must be kept at a single level. Those three lines are used to create the surface model by using the command to create Surface from the File–Import menu. Surfaces are then triangulated to determine quantities (losses/gains) within the control volume. Surfaces were triangulation twice to ensure that Microstation/In-Roads exhibited reproducibility for performing the calculation for each shoreline time point.

Depth of closure was used to determine the offshore limit (E), whereas the berm height was the landward (W) limit of the 3D surface when creating the individual control volumes. Depth of closure can be defined as the minimum depth at which the standard deviation in depth changes (decreases) to a near-constant value (Rosati 2005). The application of this definition for the shoreline in this study area led to a depth of closure of –6.10 m NGVD29 at 244 m to the east. For the shoreline-based volumetric change estimation, the current technology only allows straight translation assumptions in shoreline change comparisons, which assumes the beach face moves in a parallel manner. All shorelines were carefully examined to ensure that the depth of closure (–6.10 m NGVD29 and 244 m to the E) and berm height and location (+3.05 m NGVD29 and 30.5 m to the W) for all control volumes were correctly constructed. The study area was divided into seven control volumes, correlating with the beach fill construction contracts from Manasquan Inlet to Sandy Hook, *e.g.*, Control Volume 6 is Section I–Reach 1B, Sea Bright (Table 2). It was necessary to make an assumption and consider the offshore loss to be zero. That was done in part because the depth of closure extended only to –6.10 m, and project funding limited this investigation to assume no offshore loss. Because uncertainty is inherent in developing a sediment budget and can be significant, it is a reasonable engineering assumption to consider offshore losses as zero.

Control volumes define the boundaries for each sediment budget calculation and denote the existence of a completely self-contained sediment budget within its boundaries. The volumes of the 3D surfaces were compared over progressive years (time points), and the differential quantities were calculated as described above using Microstation/In-Roads. Sediment budgets typically report transport rates in a volume-per-year context, allowing for comparisons among data periods (*e.g.*, 1992–96). The beach fills were broken into reaches by proration, based on the length and then on the annualized period duration. Each of the 10 time points has seven control volumes, and the final sediment budget incorporated (averaged) the time points within the control volume. Sediment pathways connecting (to/from) control volumes reflect either a sediment source or sink to the individual control volumes. Sediment sources may include beach fill, longshore transport, shoreline erosion, and inlet shoal growth, whereas sediment sinks include longshore transport, shoreline accretion, dredging, and sea-level rise. The Sediment Budget Analysis System or its equivalent can be used as a visualization and balancing/calculation tool for the final sediment budget, which enables a representation of sediment moving into and out of the control volumes, accounting for beach fill placements and creating a

Table 2. Sediment budget results for Manasquan Inlet to Sandy Hook.

Cell	Description	Location	Longshore Transport South (m^3/y)	Longshore Transport North (m^3/y)	Longshore Transport Q_2 (m^3/y)
7	Sandy Hook	Sandy Hook	-82,000	561,000	479,000
6	Section I-Reach 1B	Seabright	-57,000	400,000	343,000
5	Section I-Reach 1A	Monmouth Beach	-216,000	582,000	365,000
4	Section I-Reach 2	Long Branch	-154,000	414,000	259,000
3	Section I-Reach 3	Deal	-174,000	334,000	161,000
2	Section II-North Reach	Shark River Inlet to Asbury Park	-192,000	369,000	177,000
1	Section II-South Reach	Manasquan Inlet to Shark River Inlet	-271,000	425,000	154,000

Q_2 = the difference of the longshore transport from the N vs. the S.

Note: Sign convention is positive, which indicates northbound transport; negative indicates southbound.

visualization of the balanced sediment budget. A balanced sediment budget means that the sediment sources, sinks, and net change within each individual control volume equal zero.

RESULTS

This sediment budget was developed from the digitized, historical, aerial shoreline data for the period of 1992–2003. The sediment transport control volumes (cells) were delineated based on reaches in the federal coastal storm-risk management project and represent the with-project conditions for the beach fill contracts in Table 1. The study area was approximately 33.8 km long and encompassed two inlets, mainland beaches from Manasquan Inlet to Long Branch, and a barrier-spit landform from Long Branch to Sea Bright. Seven cells (control volumes) were delineated for this study from Sandy Hook to Manasquan Inlet, as indicated in Table 2. The description corresponds to the data in Table 1, and location designates the specific township. The input values on the south end of each cell were calculated from the sand placed during beach nourishment projects. Volumetric change rates were calculated using the shoreline change method detailed above. Shoreline comparisons were calculated for 10 time points for which there were aerial images as follows: (1) 1992–96, (2) 1996–98, (3) 1998–99, (4) 1999–2000 Spring, (5) 2000 Spring–2000 Fall, (6) 2000 Fall–2001 Spring, (7) 2001 Spring–2001 Fall, (8) 2001 Fall–2002 Spring, (9) 2002 Spring–2003 Spring, and (10) 2003 Spring–2003 Fall.

Figure 3 illustrates the net sediment transport (in cubic meters per year) for the shoreline change comparisons performed for 1992–2003. Values for longshore transport to the south (using a negative sign to designate a southerly direction) range from a low of $-57,000 \text{ m}^3/\text{y}$ in cell 6 (Seabright) to a high of $-271,000 \text{ m}^3/\text{y}$ in cell 1 (Manasquan Inlet to Shark River Inlet). Values for longshore transport to the north ranged from $334,000 \text{ m}^3/\text{y}$ in cell 3 (Deal) to $582,000 \text{ m}^3/\text{y}$ in cell 5 (Monmouth Beach). Importantly, the net transport ranged from a low of $154,000 \text{ m}^3/\text{y}$ in cell 1 (Manasquan Inlet to Shark River Inlet) increasing northward to $479,000 \text{ m}^3/\text{y}$ in cell 7 (Sandy Hook). Transport rates increase gradually from the $106,000 \text{ m}^3/\text{y}$ entering cell 1 from the S to $479,000 \text{ m}^3/\text{y}$ for N transport leaving cell 7. The transport rates increase from ca. 15% of the potential northbound transport below cell 1 to 55% leaving cell 7. Values for transport to the N and S are provided to help illustrate the sediment dynamics.

No offshore (*i.e.* cross-shore) losses were determined as part of this current study, in part, because no bathymetry data were

available. Offshore losses were assumed to be zero across the oceanward boundary. Determining offshore losses was outside the existing scope of this study, and the assumption was deemed warranted. Volumetric accretion was assumed to be retained in the cell, and thus taken out of the amount available to transport into the next adjacent cell. Erosion was assumed to increase the amount of sediment available to be transported to the next cell. This sediment budget also reflects $15,300 \text{ m}^3/\text{y}$ for the average infilling rate into Manasquan Inlet and $2294 \text{ m}^3/\text{y}$ average removal from Shark River Inlet into the longshore transport (Figure 3) based on channel dredging data. Table 3 provides values for volumetric change (ΔV) of sediment based on the relationship: $\Delta V = P + Q_1 - Q_2$, where Q_2 is obtained by taking the difference of the longshore transport from the N vs. the S, balanced with fill placement (P), and the net transport from the prior cell (Q_1) in a northerly direction. The volumetric change increased from S to N from $154,000 \text{ m}^3/\text{y}$ to $479,000 \text{ m}^3/\text{y}$, corresponding to cell 1 (Section II–South Reach) and cell 7 (Sandy Hook), respectively (Figure 3).

DISCUSSION

The sediment budget from this study can be the basis for a regional sediment management (RSM) approach for maintaining the resilience of the shoreline from Manasquan Inlet to Sandy Hook. The modeling of the sediment budget from this current study, coupled with prior sediment budgets (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989), will enable an understanding of the dynamics of the shoreline over a multi-decadal scale. Furthermore, issues of sediment management within the Sandy Hook Peninsula (managed by the U.S. National Park Service, as the Sandy Hook Unit of the Gateway National Recreation Area) and the Sandy Hook federal navigation channel may be evaluated from a regional sediment budget perspective.

Modeling Sediment Budgets

Historical, aerial photographs are a valuable source of data for studies of shoreline change comparison and morphological evolution, particularly at the regional scale (Morang 2003). This regional sediment budget (the current study), using aerial photographs covering the Atlantic coast of northern New Jersey, can be a potential tool to help solve local sediment-related issues, investigate observed changes, and estimate future change. A sediment budget is useful when designing the most cost-effective solutions for resilience, which take into account a regional strategy. A sediment budget represents an accounting of all sediment movement both natural and

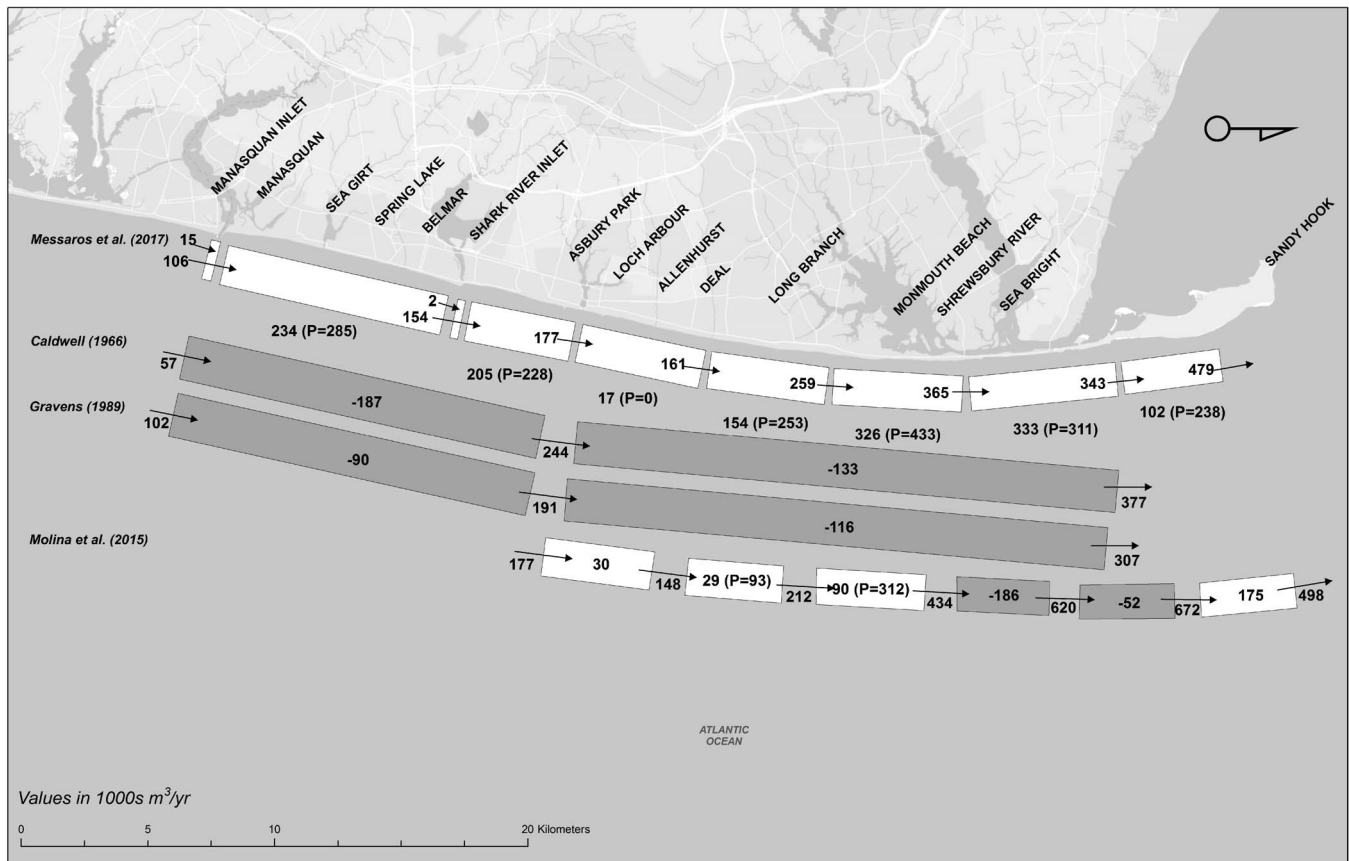


Figure 3. Sediment budget results for Manasquan Inlet to Sandy Hook. In addition to the results of the current study, sediment budget results also reflect Caldwell (1966), Gravens, Scheffner, and Hubertz (1989), and Molina, Smith, and Podoski (2015). All values are in units of 1000s of m³/y.

mechanical (e.g., beach nourishment) within a defined shoreline reach (i.e. control volume) for a specified time and duration. A sediment budget can facilitate a regional-scale inventory of data and analysis of coastal processes. Willey *et al.* (2013) used a sediment budget analysis to identify RSM opportunities along the upper coast of Texas. An RSM approach can foster communication among project partners and assist with sources and quantities of material for future projects (Willey *et al.* 2013). A sediment budget analysis was used as a tool for sediment-management issues relating the needs of eroding beaches in Saco, Biddeford, and Scarborough, Maine (Morang 2016). This analysis enabled determination of the volume of sediments gained or lost from the shoreline, which will aid in future RSM strategies. This current study represents the first sediment budget that has analyzed the with-project conditions, incorporating periodic beach nourishments/renourishments that have occurred between 1992 and 2003. This sediment budget is useful for developing an understanding of how the shoreline performs under project (beach nourishment) conditions. It is especially important because previous sediment budgets (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989) reflect sediment-poor (preproject) conditions.

Profile comparisons and shoreline change comparisons are two methods that currently exist to estimate large-scale volumetric change along a shoreline. Profile data are two-dimensional in offshore shape and can capture bar development or any other cross-shore shape change; however, profile data are typically sparse (e.g., one profile per kilometer of shoreline). Therefore, the longshore changes (i.e. groin trapping, areas of high erosion, undulations, etc.) are not adequately captured. Furthermore, the sparse data can misrepresent changes by encouraging the assumption that the volume change measured in the one profile represents the volume change throughout the entire area. For instance, suppose one profile had a large bar formation that happened to be localized. That accretion could be assumed to occur over 1 km, potentially giving the erroneous impression that the entire shoreline had experienced similar accretion, whereas the opposite might be true. Conversely, suppose that one profile was located in the middle of an area of high erosion. The volumetric changes would reflect 1 km of severe erosion, whereas the other 9/10th of the kilometer may have experienced significant accretion. For shoreline-based volumetric change estimation, current technology allows only straight translation assumptions in shoreline change comparisons,

Table 3. Sediment budget results for Manasquan Inlet to Sandy Hook.

Cell	Description	Location	Fill Placement P (m^3/y)	Longshore Transport Q_2 (m^3/y)	Net Transport Prior Cell Q_1 (m^3/y)	Volumetric Change ΔV (m^3/y)
7	Sandy Hook	Sandy Hook	238,000	479,000	343,000	102,000
6	Section I-Reach 1B	Seabright	311,000	343,000	365,000	333,000
5	Section I-Reach 1A	Monmouth Beach	433,000	365,000	259,000	326,000
4	Section I-Reach 2	Long Branch	253,000	259,000	161,000	154,000
3	Section I-Reach 3	Deal	0	161,000	177,000	16,800
2	Section II-North Reach	Shark River Inlet to Asbury Park	228,000	177,000	154,000	205,000
1	Section II-South Reach	Manasquan Inlet to Shark River Inlet	285,000	154,000	106,000	234,000 [†]

P = fill placement, Q_1 = the net transport from the prior cell in a northerly direction, Q_2 = the difference of the longshore transport from the N vs. the S, ΔV = volumetric change

[†]Includes 2294 m^3/y average removal rate from Shark River Inlet into the longshore transport.

which assume the beach face moves in a parallel manner, and offshore bar development and scarp formation cannot be included. Shoreline geometry is digitized into an x - y - z data format, plotted, and the analyst (the modeler) visually measures the offset between the shoreline at set intervals. The interval is only limited by the data collection density, and when the shoreline data were digitized, they resulted in data points every 3.05 m.

The method selected for this project-conditions sediment budget between Manasquan Inlet and Seabright was based on shoreline change. Furthermore, a new approach was incorporated by entering the shoreline data into graphical modeling software (CAD), which generated 3D “surfaces” of each shoreline and by having the software calculate the volume change between the two “surfaces.” That allowed a much smaller interval of shoreline to be evaluated. The interval was only limited by the data collection density, so if the shoreline data were digitized resulting in data points every 3.05 m, all the data are used to develop the volume change (as opposed to the visual method), where the density is limited to about every 30.5 m. The assumption of parallel translation was still required, but it was expected that some differences would occur between volume change based on data sampled every 30.5 m and volume change based on data sampled every 3.05 m. Both of those sets of data should agree in trend and order of magnitude, unlike comparing profile-based volume change, where the result may be several orders of magnitude different and trend changes might be different as well. Should the shoreline-based graphics software method prove effective and accurate (when compared with other methods), it may be possible that such software can be innovated to incorporate the best of shoreline-change comparisons and profile-change methods, thus making truly unique 3D surfaces accurate in the alongshore and cross-shore direction and, thereby, drastically advancing sediment-budget methodology and accuracy.

Current and Historical Sediment Budgets

The results from this current study (1992–2003) estimated that 106,000 m^3/y of material (Q_1 , Table 3) was the net transport from the prior control volume, south of Manasquan Inlet, moving into cell 1 (Figure 3). The value of 106,000 m^3/y that is moving north above Manasquan Inlet is in comparison to the estimate from Caldwell (1966) of 57,000 m^3/y and from Gravens, Scheffner, and Hubertz (1989) of 102,000 m^3/y

(Figure 4). The 106,000 m^3/y is 86% higher than the Caldwell (1966) estimate of 57,000 m^3/y and 3.9% higher than the Gravens, Scheffner, and Hubertz (1989) estimate of 102,000 m^3/y . Accounting for those differences could be confounded by the presence of the nodal zone, which has been defined as the region between Manasquan and Barnegat Inlets (Figure 1), in

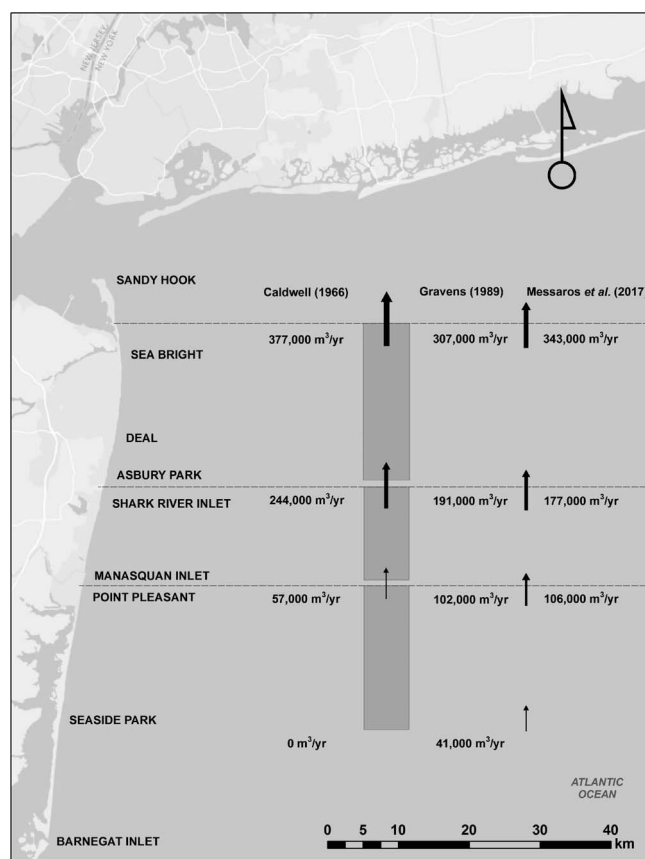


Figure 4. Comparison of sediment budget results from Caldwell (1966), Gravens, Scheffner, and Hubertz (1989), and the current study. These results represent the longshore transport north of Manasquan Inlet and illustrate a somewhat consistent pattern over multidecadal time scales. These results are valuable for long-term shoreline management and planning for coastal resilience.

Table 4. *Sandy Hook to Barnegat Inlet, Atlantic Coast of New Jersey Beach Erosion Control Project, 2008–2016.*

Reach (Contract)	CT Award	CT Completion	Fill Quantity (Mm ³)
Section I: Sea Bright to Loch Arbour (19.3 km) beach fill (30.48 m berm at +2.62 m NGVD29), selective groin notching, periodic nourishment.			
Reach 2 (contract 2) first renourishment	November 2008	January 2009	0.56
Reach 2 (Hurricane Sandy FCCE contract 2B)	September 2013	June 2014	2.5
Reach 1A (contract 3) second renourishment	November 2011	January 2012	0.63
Reach 1A (contract 4) third renourishment	November 2012	January 2013	0.92
Reach 1A, 1B (Hurricane Sandy FCCE contract 2A)	July 2013	November 2013	1.6
Reach 3 (contract 1) Loch Arbour – Deal	April 2015	October 2015	1.0
Reach 3 (contract 2) Deal – Elberon	April 2016	December 2016	2.3
Section II: Asbury Park to Manasquan Inlet (14.5 km) beach fill (30.48 m berm at +2.62 m NGVD29), selective groin notching, periodic nourishment.			
North Reach (Hurricane Sandy FCCE contract 3A)	August 2013	April 2014	0.99
South Reach (Hurricane Sandy FCCE contract 3B)	October 2013	April 2014	0.67

CT = contract, FCCE = Flood Control and Coastal Emergencies, NGVD29 = North American Vertical Datum of 1929

which sediment transport is generally N from this region northward, and southward from this region S (USACE 1954). Although the littoral drift near Manasquan Inlet is predominantly to the north, transport reversals are known to occur at this region (USACE 1954). If the assumption is made that the nodal zone is not confounding, the observed 86% difference between the 57,000 m³/y and the 106,000 m³/y may be attributable to another sediment-transport phenomenon, but without additional survey data and analysis, that would be difficult to resolve. However, there is good agreement between the 106,000 m³/y and the 102,000 m³/y (Gravens, Scheffner, and Hubertz 1989), the two most recent sediment-budget studies.

Moving north and comparing the longshore transport (Q_2) values from historic levels to those of the current study, the control volume, as defined by Caldwell (1966) and by Gravens, Scheffner, and Hubertz (1989), from Manasquan Inlet to Asbury Park, is equivalent to combining cells 1 and 2 (Figure 3) in the current study. Furthermore, cells 3–6 (Figure 3) represent the next control volume to the north, as defined by Caldwell (1966) and by Gravens, Scheffner, and Hubertz (1989). The USACE (1989) predicted that the amount of sand entering the south project limit at Asbury Park (Ocean Township), from cells 2 to 3 would reduce over time from the historical rate of 244,000 m³/y (Caldwell 1966). The USACE (1989) statement appears valid when considering the value reported by Gravens, Scheffner, and Hubertz (1989) of 191,000 m³/y and 177,000 m³/y (current study). Those values represent a decrease of 22% for Gravens, Scheffner, and Hubertz (1989) and a decrease of 27% (current study). Recalling that the current study (1992–2003) reflects beach fill projects that have occurred from 1997 to 2002 within the S and N reaches of Section II (Asbury Park to Manasquan Inlet), totaling $5.7 \times \text{Mm}^3$ (Figure 2), it may be counter-intuitive to expect that pattern of decrease to still apply. Because federal beach fill projects have added $5.7 \times \text{Mm}^3$ to Section II, transport to the north (*i.e.* into cell 3) could be anticipated to be greater than the historic pattern of 244,000 m³/y (Caldwell 1966). However, it may be that coastal structures, such as groins, have succeeded in beach fill stabilization or that the spatial patterns of longshore transport have remained consistent from 1992 to 2003.

In the current study, longshore transport, Q_2 , was estimated to be 343,000 m³/y (Table 3) from Sea Bright to Sandy Hook, represented by cell 6 (Figure 3). That result is in comparison to

the Caldwell (1966) result of 377,000 m³/y, the Gravens, Scheffner, and Hubertz (1989) result of 307,000 m³/y, and Molina, Smith, and Podoski (2015) result of 620,000 m³/y (Figure 3). Using the historical rate of 377,000 m³/y (Caldwell 1966) as the basis for comparison, the Gravens, Scheffner, and Hubertz (1989) results represent a decrease of 19%, the current study is a 9% decrease, and Molina, Smith, and Podoski (2015) is an increase of 64%. Subsequent to construction of beach restoration within the project area, sediment transport rates may increase because of the availability of sand and be similar to historic or potential rates, which occurred between 1882 and 1932 (USACE, 1989). From 1994 to 2002, a total of 17 Mm³ of material was placed as part of the Sandy Hook–Barnegat Inlet, New Jersey Beach Erosion Control Project (Table 1). From 2007 to 2013, an additional 11 Mm³ had been added as the beach fill project continued (Table 4). Molina, Smith, and Podoski (2015) analyzed shoreline changes from 2007 to 2013, which reflect the 17 Mm³ plus >11 Mm³ of material (Table 4), totaling 28 Mm³, and perhaps is evident in the sediment transport value of 620,000 m³/y moving from cell 6 (Section 1, Reach 1B, Sea Bright) to cell 7 (Sandy Hook). Molina, Smith, and Podoski (2015) investigated the shoreline from Asbury Park to Sandy Hook and not the entire length of shoreline reported in this current study (*i.e.* Manasquan Inlet to Sea Bright). The general observed pattern of littoral drift increasing as the point of observation is moved north from the nodal zone (Manasquan Inlet) toward Sandy Hook has been reported historically, *i.e.* 1850–1950 (USACE 1954) and continues to hold (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989; Molina, Smith, and Podoski 2015; Figure 3). Because the growth rate of Sandy Hook resulted almost entirely from longshore transport from the south, the rate of growth of the peninsula can be used to compute the volume of littoral drift (USACE 1954). Estimates for the sediment transport made from available hydrographic surveys of Sandy Hook by the U.S. Coast and Geodetic Survey in 1882–96 and 1932–36 determined that between 1885 and 1933, the average annual accretion rate was 377,000 m³/y, and in 1933–51, the annual rate was 333,000 m³/y. This indicates that the average rate of transport reaching Sandy Hook has been relatively constant during this 66-year period.

Sandy Hook Peninsula

The Sandy Hook federal navigation channel, immediately off the tip of Sandy Hook (Figure 1), is maintained by the USACE.

Table 5. Sediment budget comparison between current study and Molina, Smith, and Podoski (2015).

Cell	Description	Location	Longshore Transport, Q_2 (m ³ /y)		Volumetric Change, ΔV (m ³ /y)	
			1992–2003	2007–2013	1992–2003	2007–2013
7	Sandy Hook	Sandy Hook	479,000	672,000	102,000	–52,000
6	Section I-Reach 1B	Seabright	343,000	620,000	333,000	–186,000
5	Section I-Reach 1A	Monmouth Beach	365,000	434,000	326,000	89,200
4	Section I-Reach 2	Long Branch	259,000	212,000	154,000	29,000
3	Section I-Reach 3	Deal	161,000	148,000	16,800	29,800

Q_2 = the difference of the longshore transport from the N vs. the S, ΔV = volumetric change

Note: Sign convention is positive, which indicates northbound transport; negative indicates southbound.

That area of shoreline is managed by the National Park Service (NPS) as the Sandy Hook Unit of the Gateway National Recreation Area. It is, therefore, in the interest of the federal government to effectively manage regional sediment issues. The results of this current study, together with Molina, Smith, and Podoski (2015), enable a good understanding of the sediment transport phenomena and will facilitate the evaluation of alternatives intended to alleviate the frequency of channel dredging. An RSM approach may potentially balance NPS considerations and those of USACE frequency of channel dredging. Beginning in 2009, it was reported that there has been a dramatic increase in the frequency of dredging to maintain the authorized depth of –11.18 m NGVD29 (–10.7 m mean lower low water). The increase in shoaling observed since 2009 is primarily due to the northern migration of the Sandy Hook spit, which has been progressing for decades (Caldwell 1966; Molina, Smith, and Podoski 2015; USACE 1954). Within the regional sediment budget, the navigation channel is acting as a sediment sink for the longshore transport to the north. Before 2009, maintenance dredging occurred four times from 1977 to 2008 (a 30-y period). Between 2009 and 2015 (a 6-y period), the channel was dredged four times, removing (1) 26,000 m³ in 2009, (2) 131,000 m³ between 2011 and 2012, (3) 200,000 m³ in 2013, and (4) 257,000 m³ in 2015. Because of the economics associated with the need for more-frequent dredging because sediment was impinging on the channel, Molina, Smith, and Podoski (2015) conducted an analysis of shoreline change as part of the RSM program for this region of the Atlantic coast. The goal was to better understand the sediment transport issues and impoundment within the navigation channel. The sediment budget examined the shoreline from Deal Lake to the tip of Sandy Hook for 2007–13. The analysis used ArcGIS and historical imagery from the New Jersey Geographic Information Network and the U.S. Geological Survey (USGS) Earth Explorer. Further analysis of shoreline change was evaluated using imagery from Google Earth. Both the ArcGIS and Google Earth analyses, together with dredging records from the Sandy Hook navigation channel and beach nourishment-placement quantities (Table 4), were used to create a regional sediment budget. The results of this RSM study are given in Table 5 and are compared with the data from the current study. Molina, Smith, and Podoski (2015) used six control volumes starting at Deal Lake and ending at Sandy Hook that correspond to cells 3–7 (Table 2), with one additional cell for the northern-most portion of Sandy Hook. Longshore transport (Q_2) results from Molina, Smith, and Podoski (2015) are presented in Table 5 and are compared with the current study (1992–2003). The results are also presented in Figure 3,

which graphically represents a comparison of the control volumes (cells 3–7) with the additional cell for Sandy Hook.

The longshore transport (Q_2) for cell 3 (Deal) is 161,000 m³/y for the current study, which is similar to 148,000 m³/y found by Molina, Smith, and Podoski (2015), which implies that the littoral processes remained the same for approximately 20 years (1992–2013). Beach fill did not occur along the stretch from Loch Arbour to Deal (Figure 2) until 2015, which may account for this observed similarity in longshore transport for 20 years. There was a decrease of 18% for cell 4 (Long Branch) when comparing 259,000 m³/y (current study; 1992–2003) to 212,000 m³/y (Molina, Smith, and Podoski 2015). The decrease for this section of shoreline (Deal to Long Branch) was absent a beach fill project and, therefore, has remained sediment-starved with very limited material available for transport to the north. Cell 5 (Monmouth Beach) has a longshore transport (Q_2) of 365,000 m³/y for the current study (1992–2003) *vs.* 434,000 m³/y for Molina, Smith, and Podoski (2015). The difference between those two values represents an increase of 19% and may be potentially accounted for based on the completed beach fill projects (Table 4). Comparing the difference in cell 6 (Sea Bright) between the current study (343,000 m³/y; 1992–2003) *vs.* Molina, Smith, and Podoski (2015) (620,000 m³/y) represents an increase for longshore transport (Q_2) of 81%. That difference is meaningful, and the increase can, most probably, be attributable largely to the beach fill projects that have been completed since 1994 (Tables 1 and 4) and the net longshore transport to the north from the Manasquan Inlet to Sandy Hook project reach. Cell 7 (Sandy Hook) representing the southern portion of the peninsula, shows an increase in longshore transport (Q_2) of 40% (479,000 m³/y [1992–2003] *vs.* 672,000 m³/y [2007–13]). As with the increase for cell 6, the net longshore transport to the north is likely the result of the completed beach fill projects. Molina, Smith, and Podoski (2015) reported that cells 6 and 7 were found to be erosive rather than accretive. NJBPN (2011) identified a specific location for Monmouth Beach and southern Long Branch (cells 4 and 5, respectively) to contain shorelines with high erosional rates. Molina, Smith, and Podoski (2015) had an additional control volume representing the northern-most portion of the peninsula (Figure 3) with a longshore transport (Q_2) of 498,000 m³/y moving beyond the spit. That quantity of material moving north is a direct impingement to the Sandy Hook navigation channel.

The USACE (1954) reported historical accretion along the north portion of Sandy Hook Peninsula of approximately 382,000 m³/y. The longshore transport rate at the north end of cell 7 was estimated to be 672,000 m³/y (Molina, Smith, and

Podoski 2015) as compared with the current study estimate of 479,000 m³/y. The longshore transport rate along the Sandy Hook coastline is currently estimated to be about 153,000–612,000 m³/y. Molina, Smith, and Podoski (2015) do not reflect the most recent beach fill projects consisting of contract 1 (Loch Arbour to Deal, April 2015 to October 2015 with 1.0 Mm³) and contract 2 (Deal to Elberon, April 2016 to December 2016 with 2.3 Mm³; Table 4). Given that these two contracts have been completed and represent the last section of shoreline north of Manasquan Inlet to receive a beach fill project, the values for longshore transport (Q_2) could potentially be higher in the future. The prior rate of Sandy Hook Channel impoundment may increase further and so might the required frequency of dredging to maintain the authorized depth of 10.7 m. That is a potentially important outcome for future RSM consideration in this region of the New Jersey shoreline. The investigation performed by Molina, Smith, and Podoski (2015) considered potential management alternatives that might alleviate the shoaling and the dramatic increase in the frequency of maintenance dredging for the navigation channel in the presence of the continually accreting Sandy Hook Peninsula. The reported increase in shoaling is likely the result of migration of the Sandy Hook spit as part of the natural shoreline progression and the beach fill from the Atlantic Coast of New Jersey, Sea Bright to Manasquan Inlet project, which began in 1994 (Tables 1 and 4). Although the Sandy Hook Peninsula has been accreting for hundreds of years, sediment-starved conditions before 1994 may have led to slower historic growth (Molina, Smith, and Podoski 2015). The federal beach fill project (Manasquan Inlet to Sea Bright) has now added millions of cubic yards of material to the littoral transport system, providing a near continuous supply of sand reaching Sandy Hook. It appears that the spit grew at a rate of about 306,000 m³/y after the federal project began (1994) and most recently (2007–13), at about 76,500–153,000 m³/y of sand is shoaling (impinging) the channel, which corresponds to the amounts dredged in recent years (Molina, Smith, and Podoski 2015). It is plausible that the rate may increase from 153,000 m³/y because of the completion of the Federal project in 2016 (Table 4).

Uncertainty in Modeling

Uncertainty can be associated with experimentally measured quantities and, in the case of this sediment budget, with shorelines that were digitized from aerial imagery. There are various sources of error and uncertainty in any physical measurements that are inherent in all modeling. Uncertainty may arise in sediment budgets for reasons such as data collection limitations and errors with the instrumentation used to make measurements. Given the project timeline and budget constraints, it was not feasible to conduct an investigation into uncertainty for this sediment budget, but the existence of uncertainty should at least be acknowledged. Caldwell (1966) recognized that none of the coastal phenomenon relating to beach erosion was completely understood. For coastal processes, uncertainty can exist based on natural variability within the system (Kraus and Rosati 1998). Furthermore, without having an adequate control and knowledge of all parameters associated with a sediment budget (*e.g.*, monthly or annual

wave climate, meteorological forcing, sediment grain size distribution of the beach fill, *etc.*), an analysis of uncertainty may not garner any further understanding of the littoral system. Measured quantities may also have bias (related to accuracy) and possess random variation (related to precision). How bias and random variation are propagated into the uncertainty of the derived sediment quantities within a control volume is of interest. An analysis of uncertainty for the sediment budget north of Manasquan Inlet could be an area of future investigation.

Meteorological Influences on Patterns of Sediment Transport

Reversals in the net annual transport can occur in some years, either because of the influence of a few major storms or because of longer-term weather features, such as the Bermuda High—the semipermanent area of high pressure over Bermuda in the summer and fall that drives many storm systems westward across the Atlantic. For that reason, long-term records are the key to predicting project performance occurring on decadal time scales, but analysis of shorter-term, potential transport (*i.e.* extremes) may be just as important. New Jersey experiences cyclical sediment transport patterns of high and low transport depending on the prevailing weather conditions. The most severe storms to which the study area is subject are hurricanes that originate in the belt of the equatorial calms in the Caribbean area. Hurricanes are those tropical cyclones that have a central barometric pressure of 737 mm Hg or less and sustained wind speeds in excess of 119 km/h in the northern hemisphere; the revolving winds blow in a counter-clockwise direction. Nor'easters also represent a potential for causing coastal erosion and damages with economic loss. Nor'easters have winds that blow E or NE with essentially an unlimited fetch over the Atlantic Ocean. Stormy periods in this region have included the late 1930s to early 60s. Table 6 provides storms of record during the late 1930s to early 60s *e.g.*, the Great New England Hurricane, September 1938, and the Great Atlantic Hurricane, September 1944. In contrast, the period between 1962 and the mid-80s was relatively calm. The mid-1980s to early 2010s exhibited active weather patterns, *e.g.*, Hurricane Gloria, September 1985, and Hurricane Sandy, October 2012. Following Hurricane Sandy, beach fill projects had sustained fewer damages as a result of reduced overland surge propagation and reduced wave impacts (USACE 2013).

Summary

A primary concern in the study area is the continuing erosion and sediment transport to the north with insufficient accretion of sand in the absence of beach fill projects. Beach fill projects have provided an economic benefit to this coastal community from Manasquan Inlet to Sandy Hook, which includes maintaining a resilient shoreline and mitigating storm damage. Commercial and residential development along the shoreline remains vulnerable to damage from potential storm surge and wave action. Those effects may be attenuated in the presence of protective beaches, which has been justification for the Atlantic Coast of New Jersey, Sandy Hook to Barnegat Inlet, Beach Erosion Control Project (1954). The continuing economic and recreational development drives the demand for a more stable shoreline. Historically, the northerly portions of

Table 6. Representative storms of record.

Date	Name	Sustained Wind Speed (km/h)	Barometric Pressure (mm Hg)
September 1938	Great New England Hurricane (Long Island Express)	260	710
September 1944	Great Atlantic Hurricane	233	700
November 1950	Great Appalachian Storm	180	734
August 1954	Hurricane Carol	185	716
September 1960	Hurricane Donna	230	697
September 1985	Hurricane Gloria	233	689
October 1991	Perfect Storm	121	729
December 1992	December 1992 Nor'easter	129	739
November 2009	Nor'Ida (November 2009 mid-Atlantic nor'easter)	105	744
October 2012	Hurricane Sandy	185	705

the headlands, extending through the city of Long Branch and the Borough of Deal, have sustained extensive shoreline recession over a long periods (decades). Potential sea-level rise and subsidence (sinking of the land relative to the sea level) could jeopardize both shoreline stability and resilience. Material eroded from inland areas and transported to the coast by streams and rivers and material from direct erosion of sedimentary material exposed to wave and current action may be potential sources but are all limited in quantity. The fact remains that the historic rate of material leaving the system, *via* longshore sediment transport to the north coupled with other minor losses (*e.g.*, offshore), exceeds the rate of replacement (Caldwell 1966; Gravens, Scheffner, and Hubertz 1989; Molina, Smith, and Podoski 2015; USACE 1989). After Hurricane Sandy in 2012, beach fill projects had reduced overland storm surge propagation and wave impacts to structures (USACE 2013). To maintain a resilient shoreline, beach nourishment/renourishment may be an important component to shoreline stability.

Caldwell (1966) and Gravens, Scheffner, and Hubertz (1989) provide a good understanding for preproject sediment dynamics from Manasquan Inlet to Sandy Hook. The results of this current study advance the understanding of coastal processes from Manasquan Inlet to Sandy Hook. Future efforts are warranted for sediment budgets that would incorporate the beach fill quantities of nearly 11 Mm³ placed from 2008 to 2016 (Table 4). Future sediment budgets will enhance the ability to understand longshore transport, which will aid in management and planning for coastal resilience along this region of shoreline. Efforts to improve the determination of a sediment budget may also be useful. For example, obtaining nearshore bathymetry data would enable estimating offshore sediment losses. Future work may be useful toward evaluating the individual control volumes to a depth of closure below -6.10 m NGVD29 (*e.g.*, -8.23 m to -9.14 m). Bathymetric surveys were not included as part of this current investigation. After beach fill, project-specific, sediment-budget forecasting would be valuable as part of a project performance evaluation. It also could be useful to development inlet-specific sediment budgets for Manasquan and Shark River Inlets to update the regional sediment budget. This could entail studying inlet activities and sediment pathways on adjacent project shorelines. In 2016, the last section of shoreline (*i.e.* Deal), from Manasquan Inlet to Sea Bright, received beach nourishment (Table 4). Monitoring the performance of the beach fill and modeling the correspond-

ing sediment budget within the project area will be useful for enhancing coastal resilience. Given the beach fill projects from 1994 to 2016, which covered Manasquan Inlet to Sea Bright, a postproject, regional sediment budget would be warranted, even though it has been fairly well established that the sediment transport rates from Manasquan Inlet are increasing N to S toward Sandy Hook. Understanding sediment quantities within individual control volumes in relation to coastal structures (*e.g.*, groins) can be useful.

CONCLUSIONS

The results from the current study compare favorably with Caldwell (1966) and Gravens, Scheffner, and Hubertz (1989) when evaluating control volumes. This would imply that the magnitude and direction of sediment transport north of Manasquan Inlet has remained essentially the same for approximately the past half century (a multidecadal time scale or longer). Longshore sediment transport rates are likely constant over five decades with potential variability in narrower temporal scales. The results from this study are valuable for long-term shoreline management and planning for coastal resilience. The federal beach fill project has added significant quantities of material to the longshore sediment transport system and has maintained adequate fill for shore protection and resilience between the nourishment cycles. This with-project sediment budget has shown that the beach fill project is performing as expected. The nourishments/renourishments have added fill material to the previously sediment-starved longshore transport system and have maintained adequate fill between nourishment cycles. Several cells remain accretionary for a while after each placement, and in fact, the nourishment operations have been able to decrease in frequency because of fill longevity. This is the first sediment budget analysis that has been performed that reflects with-project conditions and can be a useful tool in investigating observed coastal changes and estimating future changes and management alternatives for building/maintaining resilience.

Coordination with the NPS is recommended to facilitate the greatest longevity of the fill within the project area (Manasquan Inlet to Sandy Hook). Once the sediment leaves the Sandy Hook spit, it is lost to the system, currently unable to be retrieved effectively or efficiently. It would be beneficial for RSM to consider options for the best alternative to alleviate the frequency of dredging, along with possible beneficial reuse of material. One option may be to move migrated material to the

south (back pass) from northern Sandy Hook, which would extend the life of the Seabright Borrow Area (future beach fill projects) and keep the material in the system for a longer period. Monitoring activities are recommended to continue for profiles, shorelines, and grain size to better predict fill longevity and fill needs. Comparative offshore bathymetry, extending from the shoreline to the depth of closure, would benefit the project greatly, as sand bar formation and on-and-offshore transport beyond the depth of closure would be an invaluable tool in lifetime conservation of project sediment.

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