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Northeast Region
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Anthropogenic influences on the dune/beach morphology of a moderately developed barrier island: Fire Island, New York

Technical Report NPS/NER/NRTR--2008/131

ON THE COVER
Eastward view of Fire Island with undeveloped land in the foreground, developed communities in the background.
Photograph by: Cheryl J. Hapke

Anthropogenic influences on the dune/beach morphology of a moderately developed barrier island: Fire Island, New York

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EXECUTIVE SUMMARY

This study assesses the influence of anthropogenic alterations to the dune/beach morphology of Fire Island, a moderately developed barrier island located along the south shore of Long Island, New York. Alterations include beach replenishment, beach scraping, and the presence of developed communities. Beach replenishment is an engineering method that adds material to beaches and dunes from an upland or offshore source. Beach scraping involves the transfer of sand from the berm to the foredune zone creating an anthropogenic foredune intended to protect property from overwash processes and erosion. Analyzed datasets include volume (dune and subaerial beach) and shoreline change calculated from lidar and RTK GPS grids to quantify spatial and temporal changes to the beach, and investigate whether development and/or human alterations affect volume and shoreline position at Fire Island. Beach profile characteristics were used to study the effects of beach scraping on dune/beach morphology in scraped versus non-scraped areas, and to determine if beach scraping has morphological effects on undeveloped areas downcoast.

Two study sites were selected for analysis that contain both developed and undeveloped areas. The study sites are located within Fire Island National Seashore (FIIS) which contains seventeen communities that are managed by the National Park Service (NPS). Understanding the effects of anthropogenic alterations to the dune/beach system within the National Seashore is needed for effective preservation of the beaches and other natural resources for future generations.

Results indicate that anthropogenic alterations in developed areas are detectable via changes in volume, shoreline position, and several beach profile characteristics. The western site increased in volume between 2002 and 2005 as a result of beach replenishment in the developed area which subsequently moved downcoast into the undeveloped area. On a decadal timescale (1998-2007), volume increased within 77% of the western site, but in contrast, 75% of the eastern site decreased in volume. Shoreline position retreated at the eastern site over the same time period and prograded at the western site which are results consistent with the volume change analysis. In the long-term (28 years, 1979-2007), both sites are characterized by an accretional trend. An erosional trend is present in one section of the eastern site from 1979 to 2007, and is located in the developed area.

The results of the beach profile analysis reveal morphological differences in scraped areas compared to non-scraped areas of the beach. Dunes constructed via beach scraping contain a greater volume of material than the natural foredunes of Fire Island. Within the western site, scraped material moved downcoast as shown by higher beach and dune volumes and wider beaches in undeveloped areas that have never been scraped. At the eastern site, the scraped profile location is the most erosional and dune elevations are lower than non-scraped locations. These results indicate that the most potential for overwash and flooding is at the scraped location. Beach scraping appears to accelerate downcoast transport in accreting locations and is ineffective protection in eroding areas.

This study quantified alterations to the dunes and subaerial beach of a moderately developed barrier island by comparing specific morphological characteristics in developed versus undeveloped areas. In addition, a new dataset directly isolated the effects of beach scraping which is a method of property protection on sandy coasts that has not been well studied. Methods established in this work are applicable at other barrier islands to determine the influence anthropogenic modifications have on the dune/beach system.

INTRODUCTION

Coasts are dynamic environments located at the interface of land, ocean, and atmosphere. Numerous processes occur in the coastal zone, including sediment transport and deposition by wind, tides, and waves. Land loss due to erosion is a major concern for human inhabitants of the coast. The amount of erosion occurring in any particular area is controlled by storm-induced wave action, storm surge, changes in sediment supply, and rising sea level. Maintaining infrastructure within the coastal zone is challenged by these natural processes. However, many people continue to visit or reside in coastal areas. The coupling of natural processes and human presence on coasts potentially defines a new field of study. Nordstrom and Lotstein (1989) emphasize the importance of accepting human beings as agents of change, and to manage our coasts accordingly. Acknowledging the modifications made by development and human alterations is integral to any study of morphology on a developed coast. There are different levels of development, and these must be considered separately, in order to accurately describe both natural and anthropogenic changes.

This work investigates the influence that development and anthropogenic alterations have to the morphology of barrier islands using a multi-scale approach at Fire Island National Seashore, New York (Figure 1). Specific characteristics of developed versus undeveloped areas are quantitatively compared, which has not been explicitly analyzed at Fire Island prior to this study. A new dataset directly isolates the impacts of beach scraping which has only been qualitatively assessed at Fire Island, and not well studied nationwide.

Fire Island is 50 km long, varies in width from 0.15 to 1 km, and is oriented southwest-northeast (Figure 1). The island is bounded to the west by Fire Island Inlet and to the east by Moriches Inlet. Fire Island has an established beach on the ocean side and dunes with a maximum height of 13 meters (Psuty et al., 2005). The evolution of Fire Island is affected by local controls such as tidal range, local wave climate, availability and rate of sediment supply, and the influence of sea level rise (Psuty et al., 2005). The barrier island is wave-dominated, has a mean tidal range of 1.25-1.3 m (microtidal), and the direction of net sediment transport is westward (Taney, 1961; Leatherman, 1985; Williams and Meisburger, 1987). Sources of sediment to Fire Island beaches include offshore glacial deltaic and moraine deposits, inner shelf Pleistocene material, and residual coastal plain sediments (Williams and Meisburger, 1987; Schwab et al., 2000; Psuty et al., 2005).

Construction of an anthropogenic foredune, beach replenishment, level of development, the addition of property, hotels, and shoreline protection structures all directly and indirectly affect the dune/beach system, and must be considered when studying the morphology of any given coastline. Direct effects include sand fence construction, planting, or trampling. Indirect effects include dredging, groin and seawall construction, and any other activity that affects the wave climate, tidal currents, and/or sand supply (Pye, 1990). A study by Nordstrom and McCluskey (1985) at Fire Island show that sand fencing alters aeolian transport patterns, and even moderate development can have strong effects. Properties including homes and hotels can serve as obstacles affecting aeolian transport and deposition of dunes (Carter et al., 1990). Nordstrom et al.

(1986) also investigated aeolian processes in developed areas of Westhampton Beach, New York, which is part of the barrier system along the south shore of Long Island. Results from that study indicate that aeolian processes are minor and cannot restore a dune until beach replenishment establishes conditions suitable for dune building (i.e. increases the supply of sediment).

New studies are needed for the assessment of moderately developed coasts, acknowledging human presence, and evaluating changes to the dune/beach system with specific consideration of morphological differences in developed with respect to undeveloped areas. While each barrier island system evolves according to unique local controls, understanding the effects of moderate development at Fire Island may provide evidence that could aid in management decisions or prompt studies at other moderately developed barrier islands along the east coast of the United States.

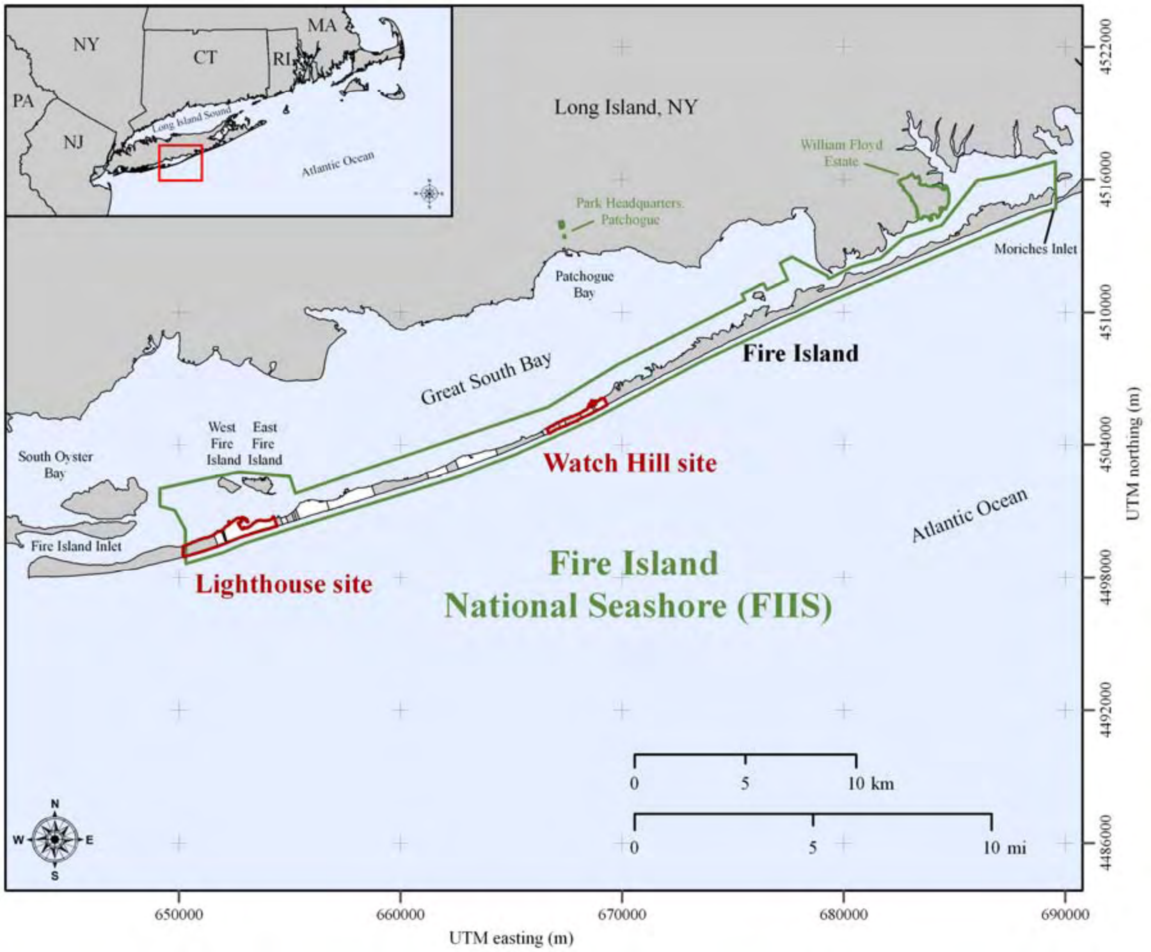


Figure 1. Map showing location of Fire Island, communities (white), boundary of Fire Island National Seashore (FIIS) (green), and study areas (red). The communities of Kismet, Seabay Beach, Saltaire, Fair Harbor, Dunewood, and Lonelyville are located within the Lighthouse site study area. Davis Park, Ocean Ridge, and Blue Point Beach are located within the Watch Hill site.

The desire to protect private properties from the natural processes of erosion and overwash spur engineering projects at some locations on Fire Island. This is done by the construction of hard and soft shoreline protection structures, including groins, beach replenishment, and beach scraping on the ocean side; bulkheads on the bay side. Structures emplaced on Fire Island have altered the beach, dunes, and sediment transport processes (Allen et al., 2002; Nordstrom and Jackson, 2005) which mask natural morphology, and reposition the dune crestline on the island (Psuty, 1990).

On September 11, 1964, Fire Island was designated a National Seashore (NPS, 2007) ensuring conservation of relatively unspoiled and undeveloped beaches, dunes and other features of the barrier island for future generations. Anthropogenic alterations may be affecting the undeveloped beaches in the National Seashore, and is part of the hypothesis and motivation for this study. If undeveloped areas are confirmed to be affected by engineering activity in developed areas, the foundation upon which this national park was built could be in jeopardy. Fire Island National Seashore (FIIS) is managed by the NPS, and seventeen communities that were established prior to the formation of the park remain interspersed within FIIS land. Several studies have been conducted at Fire Island that investigated the morphology of Fire Island (e.g., Nordstrom and McCluskey, 1985; Psuty, 1990; Psuty, et al., 2005; Hapke et al., 2007), but none of these have explicitly analyzed differences in developed versus undeveloped areas, or the direct impacts of beach scraping.

Beach Replenishment

Beach replenishment is defined by Valverde et al. (1999) and Psuty et al. (2005) as the introduction of new sand, placed on the beach by mechanical means (Figure 2), that has the immediate effect of increasing the dry (subaerial) beach width. The process is sometimes referred to as beach nourishment, and is the most widely used method in response to erosion in the United States. Approximately 268 million m^3 of sand have been added to barrier islands from New York to Florida between the 1920s and 1990s on over 573 occasions at 154 locations (Valverde et al., 1999).

Beach replenishment projects initiated by communities on Fire Island are locally or privately funded (Psuty et al., 2005), with the exception of emergency replenishment at the community of Davis Park after the Patriots Day extratropical cyclone in 2007. Davis Park received funding from the Federal Emergency Management Agency (FEMA) adding 18,926 m^3 to the beach and dunes (Land Use Ecological Services, Inc., 2008). In 1994, several communities opted to replenish their beaches with approximately 700,000 m^3 of sand (Gravens et al., 1999; Valverde et al., 1999; Land Use Ecological Services, Inc., 2008), likely in response to storm-induced erosion that resulted from the impacts of three major storms in the early 1990s. The most sand to be added to the island was in 2003-2004, in the amount of 978,105 m^3 at the communities of Saltaire, Fair Harbor, Dunewood, Lonelyville, and Fire Island Pines (Land Use Ecological Services, Inc., 2008). A detailed analysis of beach replenishment on Fire Island is beyond the scope of this study, however, the available replenishment information does contribute to interpretation of the results.

Figure 2. Photos showing beach replenishment activity at Fire Island, 2003-04 (Photos: http://www.fiyrra.com/fiyrra/FIRenourishment03.html).

Beach Scraping

A series of storms impacted Fire Island in the early 1990s, and caused extensive erosion and damage to existing properties. These particular erosional events prompted communities at Fire Island to explore a new method of mitigating future erosion that would protect their homes other than beach replenishment. A pilot project was launched in 1993 employing beach scraping as a preventative, non-structural solution to storm-induced erosion. Beach scraping (also referred to as bulldozing, or foredune creation) is the anthropogenic movement of sand from the foreshore or berm of the subaerial beach to the back beach, augmenting an existing dune or creating an anthropogenic dune which is still in active exchange with the beach (Figure 3). The new or enhanced dune fixed in place by sand fencing is intended to store sand and provide a barrier to storm surge flooding and overwash processes, mimicking the natural protection that coastal dunes provide. Beach scraping differs from beach replenishment in that new volumes of sand are not introduced to the system replacing eroded material. Instead, sand is moved from one location on the beach to another (Bruun, 1983, McNinch and Wells, 1992). At Fire Island, the size of protective foredunes is restricted landward by properties and seaward by wave action. The height of the dunes is limited by the volume of material that is allowed to be scraped.

Currently, there is no published research that explores the influence that beach scraping may have on the morphology of Fire Island. Bruun (1983) states in a non-site-specific review that beach scraping is effective on a short-term basis when employed correctly, meaning skimming only the uppermost foot of sand from the berm. Studies conducted in North Carolina (e.g., Wells and McNinch, 1991; McNinch and Wells, 1992) found beach scraping to be an effective method of erosion control over longer periods of time (years) and during storms of a lesser magnitude than hurricanes. Conaway and Wells (2005) found that beach scraping modifies natural aeolian beach/dune interactions by increasing foredune surface area with loose, unconsolidated sediment. Beach scraping methods are different at Fire Island than those used in North Carolina where McNinch and Wells (1992) and Conaway and Wells (2005) focused their studies. For example, the scraping design at Fire Island does not allow bulldozers to borrow sand from below the berm crest, whereas in North Carolina sand may be taken from any point seaward of vegetation (McNinch and Wells, 1992).

Scraping has taken place irregularly at a number of different communities. Scraping permits are issued by the NPS, the New York Department of Environmental Conservation (NYDEC), and the Towns of Islip and Brookhaven (depending on the community). In New York, the beach is privately owned to mean high water (MHW), and state owned to mean lower low water (MLLW) (Graham et al., 2003). In order for a community at Fire Island to qualify for beach scraping, the permit states that the beach must be at least 100 feet (30.5 m) wide and have an elevation above or equal to 7 feet (2.1 m) above NGVD29 (National Geodetic Vertical Datum of 1929). Excavation extends horizontally from the dry sand beach just above the wave run-up line at an elevation of 6 feet (1.8 m) above NGVD29, landward 60 feet (18.3 m), with an average depth of 1 foot (0.3 m) (Land Use Ecological Services, 1995). The scraping permits stipulate that the built or augmented dune cannot be higher than 20 feet (6.1 m) above NGVD29, 25 feet (7.6 m) wide at its crest, and have a slope greater than 1:5.

Figure 3. Photos showing stages of the beach scraping process taken on July 31, 2007 at Kismet, Fire Island. Sand is pushed into shore-perpendicular ridges (top), then dumped in front of the existing dune to create an anthropogenic foredune (bottom). Top photo: Erika Lentz. Bottom photo: Meredith Kratzmann.

In addition, permits stipulate that beach grass is to be planted on the newly built dune to promote stability through root systems. Dunes created by bulldozers are considered by some to be short-term, sacrificial features (Nordstrom and Arens, 1998). Planting may not be necessary since the plants do not always have time to become established enough to stabilize the dune over a storm season, which is also true for replenished material as shown in Figure 4.

Figure 4. Photo showing dead vegetation (inset) on eroding replenishment material at Fire Island. Photo: Rachel Hehre, April 2008.

This study contributes to our understanding of how beach scraping affects processes at Fire Island. Two communities were selected that have scraped beaches and adjacent non-scraped beaches, namely Kismet and Davis Park. This study also investigates developed and undeveloped parts of the island to assess larger-scale changes to the beach as a result of development and beach replenishment. The western and eastern study areas are the Lighthouse site, and Watch Hill site respectively, and will be referred to as such hereafter (Figure 1). These two sites were established prior to this work and are part of a larger study currently in progress (e.g., Hapke et al., 2007). The Lighthouse site includes Kismet, Saltaire, Fair Harbor, Dunewood, and Lonelyville. The Watch Hill site includes Davis Park, Ocean Ridge, and Blue Point Beach (Figure 1). Allen et al. (2002) states that at Fire Island, anthropogenic actions are profound, but not predictable from empirical observations regardless of the rigor of the analysis. Although this study does not predict the effects of anthropogenic actions, the methods established here quantify alterations to the dune/beach system as a result of development and engineering methods, and reveals the potential to measure anthropogenically induced changes on other barrier islands.

It has been well documented that development on barrier islands will alter the morphology of the dune/beach system, and influence sediment transport (McCormick et al., 1984; Nordstrom and McCluskey, 1985; Psuty, 1990; Nordstrom and Jackson, 1995; Allen et al., 2002; Psuty and Ofiara, 2002; Nordstrom, 2005). Most of these studies, however, focus on highly developed barrier islands where hotels, tall apartment buildings, and shoreline protection structures are ubiquitous (New Jersey and parts of Maryland, for example). Few studies have investigated the nature of anthropogenic alterations on a more moderately developed barrier island such as Fire Island, New York. Fire Island is ideal for this type of analysis as there are seventeen residential communities interspersed with undeveloped land for comparison. The level of development may be important in determining how intense the differences are in developed areas compared to undeveloped areas, and may reveal longer-term (decadal) impacts development has on volume (beach and dune) and shoreline change.

Shoreline and volume change help to identify areas that are persistently erosional, and also indicate time periods where either longshore or cross-shore transport dominates. Profiles extending to the shoreface are important for evaluation of cross-shore transport volumes. This study concentrates primarily on longshore transport since profile coverage is limited to the subaerial beach. To a user or manager of a beach, the subaerial beach is a better representation of observed changes than profiles extending offshore (Farris and List, 2007). Analyses of volume change, shoreline change, and beach profile characteristics all indicate that development, and human alterations that occur within developed areas, influence dune/beach morphology at Fire Island.

APPROACH

A multi-spatial scale approach was designed to investigate anthropogenic modifications to the dune-beach system at Fire Island through time. A site-scale (> 1 km coast) assessment examines the differences in volume change and shoreline change in developed versus undeveloped areas. A focused, community-scale (< 1 km coast) analysis assesses changes directly related to beach scraping by comparing beach profiles from scraped locations to non-scraped locations. These methods were developed to quantify changes to the dune/beach system and to identify possible effects of human alterations to beach and dune morphology.

An analysis of volume change and shoreline change was conducted to examine differences in morphological evolution of the beach in developed versus undeveloped areas. Developed areas are defined in this study as sections of coast within Fire Island National Seashore containing communities with numerous homes, roads, and other infrastructure. Undeveloped areas are comprised of federal (NPS) land without homes, or very small communities with a few homes only (example: Blue Point Beach at the Watch Hill site).

Volume Change

Volume indicates how much sand is stored on the beach, and when analyzed on varying spatial and temporal scales can indicate where sand is being transported alongshore. Volume is defined in this study as the area of sand under a cross-shore subaerial beach profile per meter of shoreline above mean low water (MLW). Locations (transects) were established at a spacing of 300 meters for the cross-shore profile analysis at both the Lighthouse site and the Watch Hill site. Volumes were extracted from topographic lidar (light detection and ranging) and RTK GPS (real-time kinematic global positioning system) grids (1 meter cell size) to assess how much sand is stored on the beach through time at developed versus undeveloped areas.

Lidar data used in this study were collected by the USGS in 1998 and 2002, and the USACE in 2005. The 1998 and 2005 datasets are available for public download at http://maps.csc.noaa.gov/TCM/. The RTK GPS data were collected in the field in March and September of 2006 and 2007 (Table 1). A shapefile was created in ESRI ArcGIS 9.2 containing transects extending seaward from a changing azimuth baseline to ensure profiles were extracted at the same location in each dataset using 3D Analyst. A total of 115 profiles were extracted from the both datasets. Possible sources of error associated with the lidar data include the accuracy of the data collection process (Table 1), error associated with the topographic interpolation process (TIN to grid, minimal error), and user error associated with profile extraction. A TIN, or triangulated irregular network, uses the z elevations of data points to create a digital elevation model. XY data points are connected forming the smallest triangles possible, with elevations determined by z values. A network of these triangles is created as well as an elevation surface. A grid is also a digital elevation model that uses cells of uniform size that contain many data points. TINs are converted to grids using linear interpolation regarding TIN triangles as planes. RTK GPS is accurate to within millimeters to centimeters, but user error involved in the data collection process, as well as the interpolation method (kriging) contributes additional error. Kriging is an interpolation method based on lag distance which allows a user to determine an elevation surface based on the proximity of points to one another, and also the pattern of the overall distribution. RTK GPS data are more accurate than lidar, but the lower spatial density of the datasets required more surface interpolation. Also, RTK GPS data take longer to collect whereas lidar is collected rapidly in large swaths.

Once the profile volumes were extracted from the lidar and RTK GPS grids, volume change was calculated from 1998 to 2007 (end point). Additionally, volume changes over sub-decadal intervals (1998-2002, 2002-2005, 2005-2007) were calculated to assess shorter-term variability. A statistical analysis was conducted on the volume data at the Lighthouse and Watch Hill sites to detect significant differences between developed and undeveloped areas.

Table 1. Details and accuracy of data used in this study organized by analysis.

Analysis	**Year**	**Month**	**Data Type**	**Accuracy** Horizontal (Vertical)	**Source**
Total Volume Change	1998	December	Lidar	0.80 m (0.15 m)	USGS*
	2002	November	Lidar	1.0 m (0.20 m)	USGS
	2005	November	Lidar	< 1.0 m (0.15 m)	USACE*
	2006	September	RTK GPS	0.01 m (0.02 m)^	Field work
	2007	September	RTK GPS	0.01 m (0.02 m)^	Field work
Shoreline Change	1979		HWL Aerial Photographs	~5.0 m**	USGS
	1988		HWL Aerial Photographs	~5.0 m**	USGS
	1998		MHW Lidar	0.8 m	USGS
	2007	March	HWL RTK GPS	< 1.0 m	NPS

* http://maps.csc.noaa.gov/TCM/

^ http://trl.trimble.com/docushare/dsweb/Get/Document-140079/022543-079F_TrimbleR8GNSS_DS_0507_lr.pdf

** estimated based on aerial photographic source

Shoreline change

Shoreline change at Fire Island is used to quantitatively assess how much the shoreline is changing within the two study areas, identify where the most extreme erosion is, and whether the patterns of shoreline change are different in developed versus undeveloped areas. These differences are important for the prediction of future shoreline position and management of the National Seashore.

Defining and mapping an accurate shoreline is challenging in a coastal environment because conditions are constantly changing with time (Anders and Byrnes, 1991; Parker, 2003). Shoreline position at any given time is a function of wave and current processes, sea level change, sediment supply, coastal geology and geomorphology, and human intervention (Anders and Byrnes, 1991). It is a goal of this study to assess the detectability and level of human intervention at Fire Island using shoreline change in conjunction with other data.

The shoreline is essentially a zone of vertical water level variability, therefore proxies are used in order to make accurate measurements of change. A datum-based shoreline proxy is commonly used to define the intersection of the beachface with a datum (mathematical reference ellipsoid) such as MHW. Visually interpreted proxies, such as high water line (HWL) or wrack line can also be used (Pajak and Leatherman, 2002; Graham et al., 2003; Boak and Turner, 2005; Farris and List, 2007). In this study, the shoreline position is defined as the intersection of the MHW datum or HWL with the foreshore of the subaerial beach. Lidar, RTK GPS, and aerial photographs were used to identify shoreline position, and were digitized prior to this analysis.

There are several methods of calculating shoreline change, such as end point (shoreline movement per unit time) or linear regression (slope of regression trendline). Linear regression will produce superior predictions when non-storm shorelines are used (Honeycutt et al., 2001). In this study, shoreline change was determined for four time periods using four shorelines (non-storm) acquired from the USGS and the NPS (1979, 1988, 1998, and 2007) (Table 1). These intervals were established to determine shoreline change (end point) prior to the implementation of beach scraping and major (> 25,000 m^3) replenishment (1979-1988), during and after beach scraping and replenishment (1988-1998, 1998-2007), and also longer term change using linear regression (28 years, 1979-2007). A comparative statistical analysis was conducted to determine if development influences shoreline change at the study sites. Shoreline change rates were generated at 20 meter spacing based on previous studies (e.g., Hapke et al., 2006), using DSAS (Digital Shoreline Analysis System) following methods described in Thieler et al. (2005).

Estimates of shoreline change are only as accurate as the data from which they are derived, and the techniques by which the shoreline position and change are calculated (Thieler and Danforth, 1994; Moore, 2000). Some examples of error associated with aerial photographs include distortion, shrink/stretch, and tilt (Moore, 2000). In this study, the accuracy of shoreline position (high water line, HWL) from aerial photographs was determined to be approximately +/- 5.0 m (Table 1). The lidar-derived shorelines have a sub-meter accuracy and have been shown to be ideal for large-scale (kilometers)

(Stockdon et al., 2002), and long-term (decadal) shoreline change studies (e.g., Allen et al., 2002; Hapke et al., 2007).

Maximum error (E_m) for the end point shoreline change analyses in this study is presented by summation in quadrature (Taylor, 1997; Hapke et al., 2006) where shoreline position error (E_{sp}) is calculated by:

$$E_{m\ 1979\text{-}1988} = \sqrt{((E_{sp\ 1979})^2 + (E_{sp\ 1988})^2)} \qquad (1)$$
$$E_{m\ 1979\text{-}1988} = \sqrt{((5.0\text{ m})^2 + (5.0\text{ m})^2)} = +/\text{-}\ 7.1\text{ m}$$

$$E_{m\ 1988\text{-}1998} = \sqrt{(\ (E_{sp\ 1988})^2 + (E_{sp\ 1998})^2)} \qquad (2)$$
$$E_{m\ 1988\text{-}1998} = \sqrt{(\ (5.0\text{ m})^2 + (0.8\text{ m})^2)} = +/\text{-}\ 5.1\text{ m}$$

$$E_{m\ 1998\text{-}2007} = \sqrt{(\ (E_{sp\ 1998})^2 + (E_{sp\ 2007})^2)} \qquad (3)$$
$$E_{m\ 1998\text{-}2007} = \sqrt{(\ (0.8\text{ m})^2 + (1.0\text{ m})^2)} = +/\text{-}\ 1.3\text{ m}$$

Maximum error (E_m) for the longer term analysis (28 years, 1979-2007) is calculated by:

$$E_{m\ 1979\text{-}2007} = \sqrt{((E_{m\ 1979\text{-}1988})^2 + (E_{m\ 1988\text{-}1998})^2 + (E_{m\ 1998\text{-}2007})^2)} \qquad (4)$$
$$E_{m\ 1979\text{-}2007} = \sqrt{((7.1\text{ m})^2 + (5.1\text{ m})^2 + (1.3\text{ m})^2)} = +/\text{-}\ 8.8\text{ m}$$

Beach Profile Analysis (Scraped versus Non-Scraped Beaches)

Volume change and shoreline change are larger-scale parameters for assessing coastal change, but for a more focused analysis, beach profiles were used to examine the potential impacts of beach scraping to the dune/beach system. Changes to specific characteristics of beach profiles in scraped versus non-scraped beaches in two communities at Fire Island were assessed. Kismet, and Davis Park were chosen for this study due to the high temporal resolution and availability of the data (Figure 1). Kismet and Davis Park beachfront communities are flanked on the east and west by undeveloped land that has never been scraped.

Approximately 150 hard copy profiles were acquired from Land Use Ecological Services, Inc. (Land Use), a consulting firm that oversees the beach scraping process and conducts monthly monitoring profiles following scraping. The temporal coverage at Kismet spans ten years (1996-2006), whereas there are three years of complete profile data available for Davis Park (1997-2000). Beach scraping does not necessarily occur every year, therefore gaps are inherent in the data, and are noted where applicable. The dataset of hard copy profiles has a good temporal resolution, but required extensive processing (scanning, orientation, digitizing) since digital tabular data were unavailable. Also, the monitoring profiles are a relatively coarse morphological representation of the beach profile when compared to other profile formats, such as those derived from lidar or RTK GPS data.

Specific profile dates were selected to represent the morphology of the beach in different seasons. Profiles dated in August represent the time of scraping in the summer, when storm activity is less frequent and the beach is typically accretional. December or January profiles, depending on availability, represent winter, when a bar (storm) profile is typical, and profiles from March or April were selected to represent a spring (recovering) beach.

Each representative beach profile was scanned and rotated to achieve an accurate horizontal position prior to digitization using ImageDIG (SciCepts Engineering). ImageDIG is a software program designed to extract XZ data (cross-shore position and elevation) from a graphic. The Z data (elevation) were converted from feet above NGVD29 to meters above NAVD88. Once digitized and converted, the beach profile data were imported into Regional Morphology Analysis Package (RMAP). RMAP was developed by the U.S. Army Corps of Engineers to calculate beach profile changes, among other functions.

The beach profile characteristics selected for analysis include beach width (dune toe to mean sea level as noted on the profiles), subaerial beach volume (to mean low water), beach slope, dune volume, dune crest elevation, dune toe elevation, and berm crest elevation (Figure 5). Profiles were collected at multiple locations during monitoring, from which three profiles were chosen to represent the scraped area of the beach, and control areas to the east and west. These locations are referred to as the scraped area (SC), the western control (CW) and the eastern control (CE) hereafter (Figure 6). A statistical analysis was used to compare profile groups for Kismet and Davis Park. The null hypothesis is that beach profile characteristics at the scraped location are the same as each control profile (H_0: CW = SC = CE). Errors associated with the beach profile analysis are difficult to quantify but certainly include: data collection error (morphological interpretation, total station survey error), processing error (due to manual scanning and digitizing), user interpretation error, and possible errors in calculation. Although the exact error is uncertain, these beach profile data were only compared within the dataset relative to each other, and likely have minimal effects on the results and interpretation.

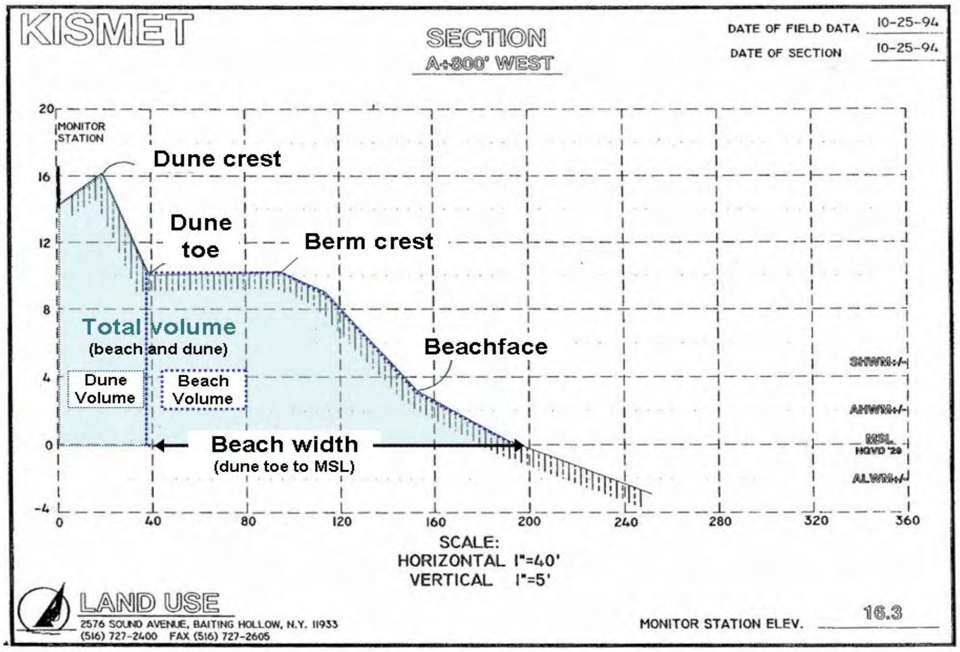


Figure 5. Beach profile characteristics superimposed on an example of hard copy profiles obtained from Land Use Ecological Services, Inc.

Figure 6. Profile locations established by Land Use. Kismet is shown here as an example, note that the relative locations of CW, SC, and CE (yellow lines) are the same for other communities. Orthophoto from 2004.

VOLUME CHANGE: DEVELOPED VERSUS UNDEVELOPED AREAS

The volume of the subaerial beach and dunes at Fire Island varies through time as a result of numerous processes that transport and deposit sediment alongshore, and onshore/offshore. These processes are primarily controlled by storms, and the offshore geologic framework (nearshore bar morphology, offshore sand ridges) which is discussed in detail by Leatherman (1985) and Schwab et al. (2000). In developed areas, a gain or loss of beach volume is of interest with respect to property inundation protection and erosion potential. High volumes and dune elevations are preferred because of the perceived protection provided against storm surge and overwash processes. In this study, volume (beach and dune to MLW) is used to analyze increases or decreases in both the beach and the dunes.

Volume change: Lighthouse site

Volume at the Lighthouse site generally increased in both developed and undeveloped areas between 1998 and 2007. The end point volume calculations for the shorter-term time intervals show variability within the dataset (Figure 7A). Between 1998 to 2002, volume decreased in 92% of the Lighthouse site by a total of 181,896 m^3 (Figure 7A, Table 2). In 1999, large waves associated with a tropical storm (downgraded from Hurricane Floyd) impacted Fire Island and may account for some of the volume decrease observed during the interval 1998-2002 (Table 2, Figure 7A). When wave energy is high during a storm, sand is transported to an offshore bar and therefore a lower subaerial beach volume would be expected. However, some variability in volume is expected depending on wave energy and sediment supply.

In 2003-04, 549,062 m^3 of material was added to the beaches in front of the Lighthouse site communities as part of a replenishment project (Land Use Ecological Services, Inc., 2008). The increase in volume is reflected in the data, most prominently at transect LH9 in the 2002-2005 time interval (Figure 7A). As a result, between 2002 and 2005, 54% of the Lighthouse site shifted to an accretional regime. Along 50% of developed beaches, volume increased, which is an expected result since replenishment took place at this location (Table 2). Almost half of the undeveloped area (40%) lost volume between 2002 and 2005 (Figure 7A, Table 2). Transect LH5, closest to the developed area, showed the greatest volume increase in the undeveloped area, which indicates that material added during replenishment in 2003 was transported downcoast within the three year period (Figure 7).

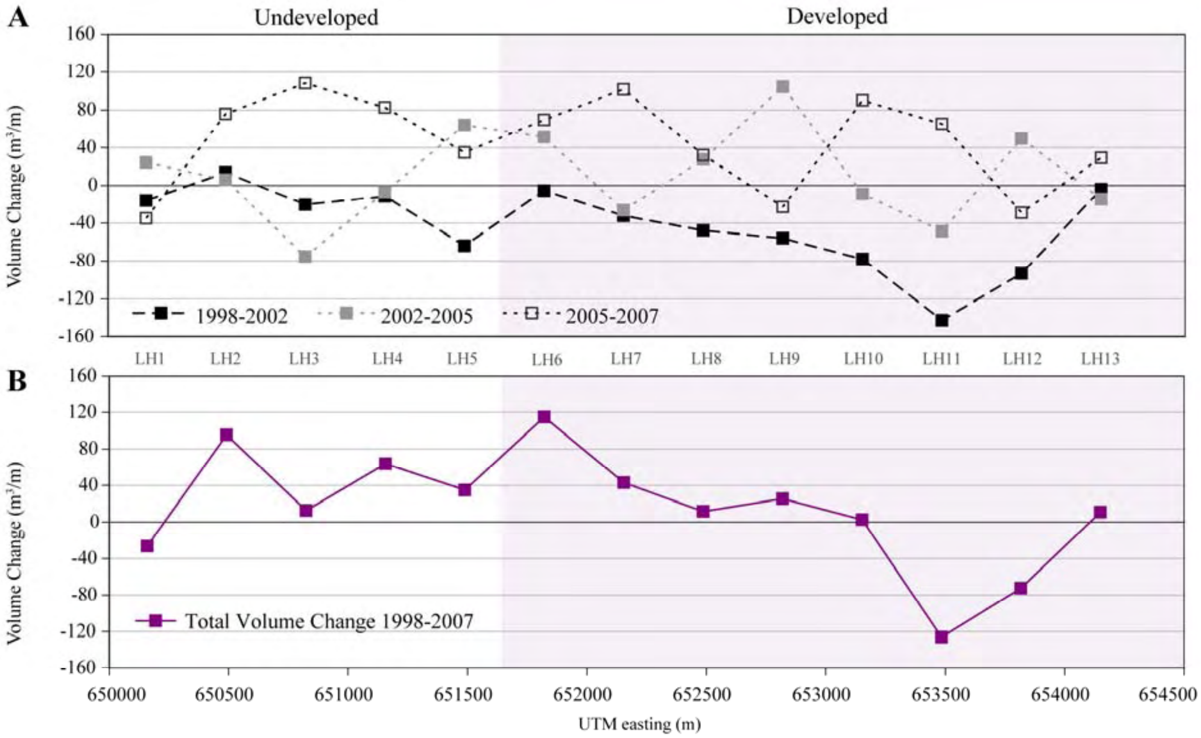


Figure 7. Volume change at the Lighthouse site between 1998 and 2007. Short-term variability (A) is shown along with total volume change (B) over the nine-year study period. Transect names are located in the center of the plot (LH*x*). Transects are spaced 300 m apart.

Table 2. Summary of volume changes in developed and undeveloped areas of Fire Island for four time intervals. The Lighthouse site is 4,240 m long and contains 13 transects. The Watch Hill site is 2,635 m long and contains 8 transects. Data between 1998 and 2007 (shaded) represent an end point calculation and is not an average of the other three intervals. Spatial representations of the data are presented in Figures 7 and 8.

Study site	**Time interval**	**Site-wide decrease or increase in volume (% of site)**		**Mean profile volume change (m^3)***	**Volume change (% of area)****			
					Undeveloped		**Developed**	
		Decrease	Increase		Decrease	Increase	Decrease	Increase
Lighthouse	1998-2002	92%	8%	- 181,896	80%	20%	100%	0%
	2002-2005	46%	54%	47,488	40%	60%	50%	50%
	2005-2007	23%	77%	196,312	20%	80%	25%	75%
	1998-2007	23%	77%	61,904	20%	80%	25%	75%
Watch Hill	1998-2002	88%	12%	- 95,124	75%	25%	100%	0%
	2002-2005	88%	12%	- 133,331	75%	25%	100%	0%
	2005-2007	0%	100%	141,500	0%	100%	0%	100%
	1998-2007	75%	25%	- 87,219	50%	50%	100%	0%

* Mean profile volume change (m^3) = site length (m)*mean profile volume change in (m^3/m)

** % = [number of transects that decreased or increased in volume / total number of transects in undeveloped or developed areas]*100

The analysis of the most recent time interval (2005-2007) shows that volume increased in most (77%) of the Lighthouse site, in both developed and undeveloped areas. Volume increased in 80% of the undeveloped area, which is greater than the previous time interval (2002-2005) (Table 2). It is likely that material added by replenishment activity was transported further downcoast by aeolian and wave processes, noting that some material was likely transported offshore. The volume increase in the undeveloped area marks a shift from an eroding to an accreting regime after 2005 (Figure 7A).

Decadal change (1998-2007) reveals that most (77%) of the Lighthouse site beaches increased in volume over the study period (Figure 7B, Table 2). The greatest volume decrease occurred in the developed area at LH11 (> 120 m^3/m) (Figure 7B). Visual examination of the volume change trends from 1998-2002 and 1998-2007 reveal that there is a similar pattern of change alongshore, but an overall volume increase is observed on the decadal timescale (Figure 7). When compared statistically, there is no significant difference ($p > 0.05$) between volumes at the developed versus undeveloped areas of the Lighthouse site between 1998 and 2007. Therefore, volumes in developed and undeveloped areas are considered statistically similar, but human alterations (e.g., beach replenishment) are likely masking natural differences by adding large amounts of material to the system. Replenished material provides a large source of material that would not otherwise be present, and is transported downcoast by both wave and aeolian processes thereby increasing the volume of beaches in undeveloped areas. A greater amount of sediment is eroded and transported during storm events due to increased wind and wave energy, and storm surge. Therefore, in the winter months when extratropical storms affect Fire Island, sediment is transported more rapidly alongshore and offshore.

In summary, the volume of material at the Lighthouse site increased during the study period. The data show that the developed area volume increased more than the undeveloped area due to the addition of sediment by beach replenishment in the interval 2002-2005. Some of this sediment is transported downcoast into undeveloped areas relatively quickly (years). Therefore, any protection provided by the anthropogenic addition of material to the beach and dunes is short-lived, a result supported by Allen et al., 2002. Allen et al. (2002) state that the coastal system is restored rapidly in natural (undeveloped) areas, but more slowly in densely developed areas due to the interference of structures with restoration processes.

Volume change: Watch Hill site

Beaches at the Watch Hill site generally decreased in volume over the study period (1998-2007). In the interval 1998-2002, volume along 88% of the site decreased by a total of 95,124 m3 (Table 2). During this four-year period, the only increase occurred in the undeveloped area at transect WH1 (a very small amount, < 5 m^3/m) (Figure 8A). From 2002 to 2005, 88% of the Watch Hill site decreased in volume (Table 2). There is no change in percentage compared to the previous time interval (1998-2002) in both developed and undeveloped areas (Table 2), indicating continued erosion at the Watch Hill site until 2005. The beach at transect WH4 is the only area that increased in volume during this time (Figure 8A). There is no record of replenishment at this location, indicating that natural variability is likely responsible for the observed volume increase at WH4 from 2002 to 2005.

Within the next time interval, 2005-2007, the entire Watch Hill site increased in volume (Table 2). Although 18,926 m^3 of sand was added to the beaches and dunes of Davis Park following a severe extratropical cyclone in April of 2007, the replenishment did not take place until late 2007 and into early 2008 (Land Use Ecological Services, Inc., 2008). Therefore replenishment does not account for the volume increase in the developed area. The volume increase from 2005-2007 could be explained by the timing of data collection in this interval (Table 1), or natural accretion from an upcoast source.

Volume decrease is greatest in the developed area compared to the undeveloped area between 1998 and 2007. The entire developed area decreased in volume during the decade, while 50% of the undeveloped area decreased (Figure 8, Table 2). The beach at transect WH4, adjacent to the developed area, anomalously increased in volume from 1998 to 2007 (Figure 8B). This is the same location that increased between 2002 and 2005 without a definitive explanation. Statistical analyses show that volumes in the developed area are significantly different than the undeveloped area of the Watch Hill site ($p < 0.001$). Therefore, the differences apparent in the datasets are more than are expected by chance, which may be due to the increase in volume at WH4. This adds strength to the evidence that development has an impact on the amount of sand stored in the subaerial beach on a decadal timescale at the Watch Hill site.

The majority of the Watch Hill site was eroding from 1998 to 2007, although the most marked decreases in volume occurred in the developed section of coast. This evidence indicates that development has an influence on the amount of sand stored on the beach and in the dunes.

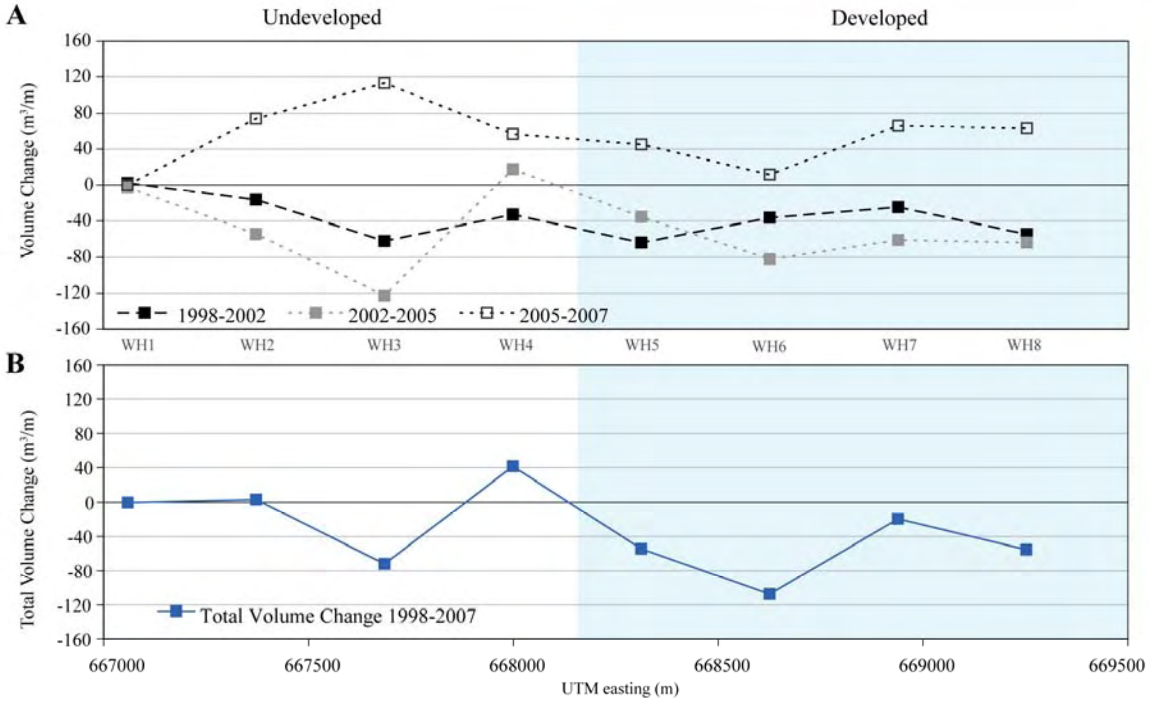


Figure 8. Volume change at the Watch Hill site between 1998 and 2007. Short-term variability (A) is shown along with total volume change (B) over the nine-year study period. Transect names are located in the center of the plot (WH*x*). Transects are spaced 300 m apart.

Summary: Volume Change

At both the Lighthouse and Watch Hill sites, volume generally decreased prior to 2002. Volume increased after 2002 at the Lighthouse site, and increased after 2005 at the Watch Hill site. Over a nine-year period (1998-2007), 77% of the Lighthouse site increased in volume in both developed and undeveloped areas, while volume decreased in 75% of the Watch Hill site. In the developed area of the Watch Hill site, the entire beach decreased in volume compared to only half in the undeveloped area. The analysis revealed that the beaches in front of Watch Hill site communities decreased in volume, while the Lighthouse site beaches increased in volume over the study period. When either site was erosional, the majority of erosion occurred in the developed area.

SHORELINE CHANGE

Quantification of volume change provides useful information on which areas of Fire Island are volumetrically decreasing over time, and are influenced by development, but shoreline change information is needed from a decision-making perspective. When volume change data are considered in conjunction with shoreline change, a more complete interpretation can be made with respect to the magnitude of sand on the beach and whether shoreline position is prograding or retreating. This information influences management decisions, for example, the evaluation of a setback line location.

Areas in developed and undeveloped portions of the study sites were analyzed to determine if the influence of development is limited to volumetric change, or if shoreline position is also affected by anthropogenic alterations. Since volume change and shoreline change have been shown to correlate well (Farris and List, 2007), it is likely that shoreline change will also show accretion at the Lighthouse site and erosion at the Watch Hill site. When means or medians were similar in both areas, it was concluded that development does not affect shoreline change significantly. However, if the shoreline is retreating or prograding to a greater extent in developed areas with respect to undeveloped areas, it will be interpreted that development likely influences shoreline change by changing the way natural littoral processes are acting on the beach.

Shoreline change: Lighthouse site

The majority (96%) of the Lighthouse site is characterized by a retreating shoreline from 1979 to 1988, indicating a trend of site-wide erosion (Figure 9, Table 3). This trend is consistent with historical data that show this section of Fire Island is persistently erosional over the past ~150 years (Hapke et al., 2007). Most of the shoreline erosion during this time interval occurs in the developed area (62%) (Table 3). The percentages are based on the number of erosional transects in developed and undeveloped areas divided by the total number of erosional transects (or, areas of shoreline retreat). The mean shoreline change from 1979 to 1988 in the developed area is -12.8 m versus -10.2 m in the undeveloped area (Table 3).

During the ten year period from 1988 to 1998, 91% of the Lighthouse site shifts to an accretional regime, most markedly in the eastern section of the site (653250 to 654000 UTM easting, zone 18N) (Figure 9). In this area, material was added to the system via beach replenishment in 1994 (~451,800 m^3) (Table 3), which explains the large spike in shoreline progradation observed. Mean shoreline change in the developed area is 13.4 m, versus 7.2 m in the undeveloped area (Table 3, Figure 9). The greater shoreline accretion in the developed area is a direct result of the replenishment. The beach in front of western Kismet, a community within the Lighthouse site, is the only area that continues to be erosional between 1988 and 1998 as well as a small length of coast in Saltaire (Figure 9). The amount of shoreline retreat is relatively small in these areas (< 10 m at maximum) and is likely due to natural variability. The dominant trend of shoreline change from 1988 to 1998 is accretional. However, within the small areas where the shoreline was eroding (9%, or 380 m), 79% of erosional transects are in the developed area (Figure 9, Table 3).

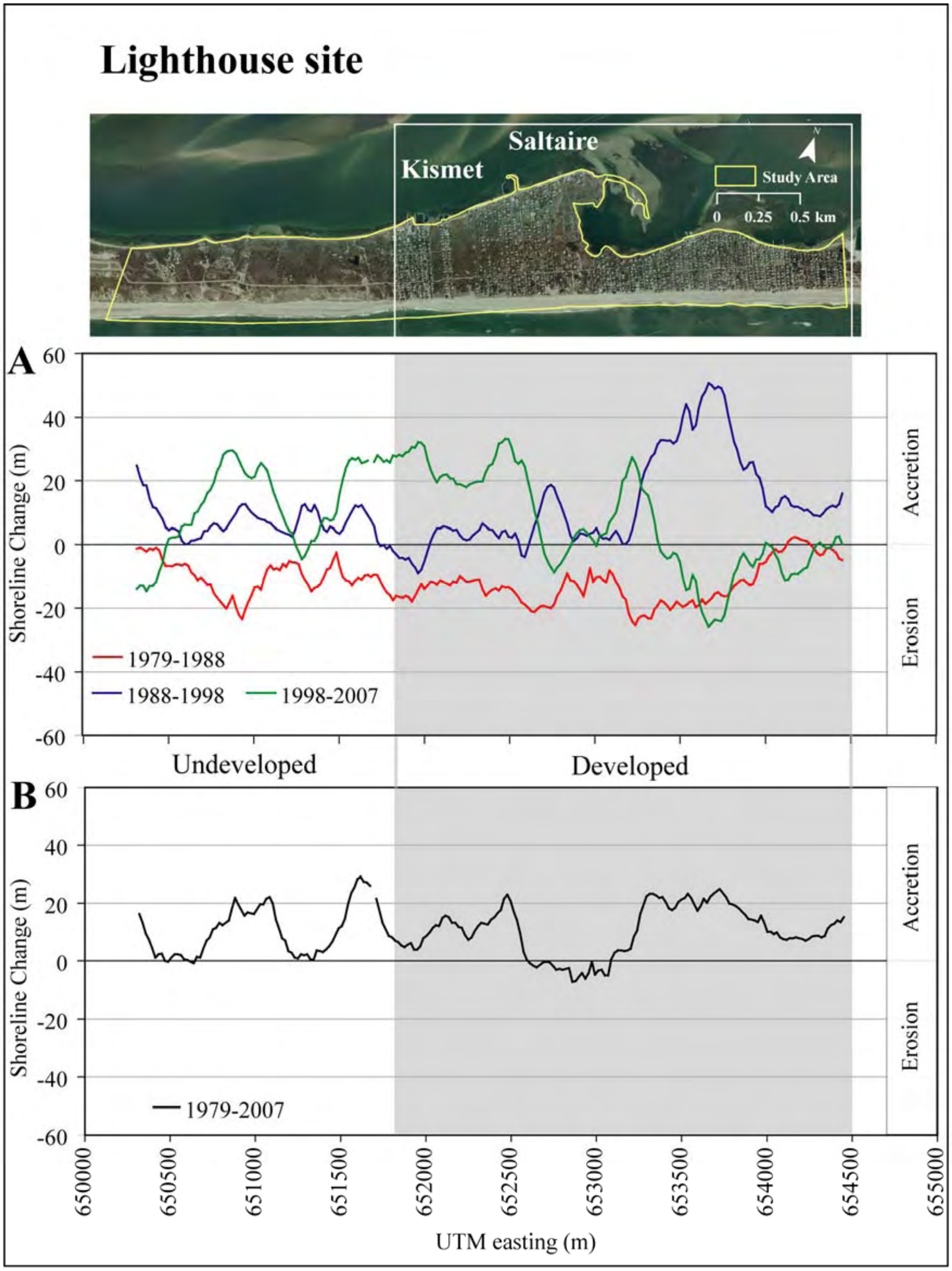
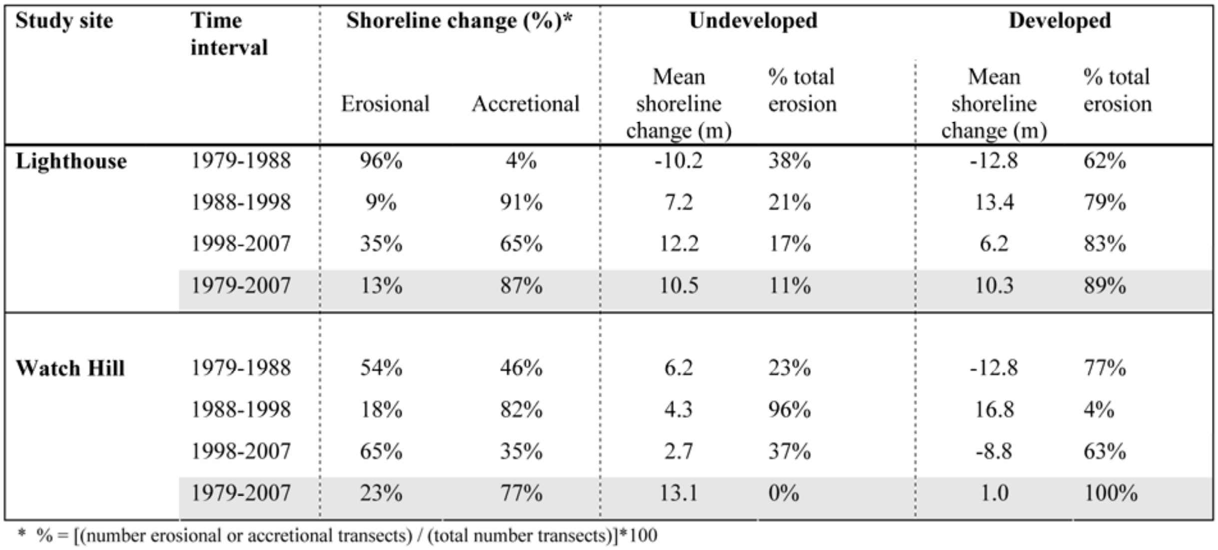


Figure 9. End point shoreline change at the Lighthouse site over four time periods in developed and undeveloped areas: 1979-1988, 1988-1998, 1998-2007, 1979-2007 (A), and total change 1979-2007 (28 years, linear regression) (B). Orthophotograph from 2004.

Table 3. Summary of shoreline change in developed and undeveloped areas of Fire Island. At the Lighthouse site, n=223 transects and at the Watch Hill site, n=136 transects at 20 m spacing. Data between 1979 and 2007 (shaded) represent shoreline change calculated using linear regression, whereas other time intervals were calculated using end point. Spatial representations of the data are presented in Figures 9 and 10.



Study site	Time interval	Shoreline change (%)*		Undeveloped		Developed	
		Erosional	Accretional	Mean shoreline change (m)	% total erosion	Mean shoreline change (m)	% total erosion
Lighthouse	1979-1988	96%	4%	-10.2	38%	-12.8	62%
	1988-1998	9%	91%	7.2	21%	13.4	79%
	1998-2007	35%	65%	12.2	17%	6.2	83%
	1979-2007	13%	87%	10.5	11%	10.3	89%
Watch Hill	1979-1988	54%	46%	6.2	23%	-12.8	77%
	1988-1998	18%	82%	4.3	96%	16.8	4%
	1998-2007	65%	35%	2.7	37%	-8.8	63%
	1979-2007	23%	77%	13.1	0%	1.0	100%

* % = [(number erosional or accretional transects) / (total number transects)]*100

From 1998 to 2007, the position of the shoreline prograded in 65% of the Lighthouse site (Figure 9, Table 3). Of the areas where the shoreline was eroding, 83% occurred in the developed area (Table 3). Figure 9 shows an area of accretion during this period (1998-2007) in the central part of the site (651500 to 652750 UTM) that is interpreted to reflect accretion due to replenishment activity during this period, as well as the movement of material downcoast from the replenished area in the east during the previous decade (1988-1998). The erosion observed in the eastern Lighthouse site indicates that the beach that was replenished in 1994 has lost material over time despite replenishment again in 2003-04. Based on this evidence, it appears that replenishment resulted in shoreline progradation, but the effect of this anthropogenic alteration at the Lighthouse site is short-lived (< decade).

In the long-term (28 years, 1979-2007), the shoreline change trend is accretional at 87% of the Lighthouse site. The majority of eroding transects are located in the developed area (Figure 9, Table 3). However, the Lighthouse site is dominantly accretional with several evenly spaced zones of higher progradation present in the record (Figure 9). These zones are accretional “cells” which have been previously identified and discussed by Allen et al. (2002), Psuty et al. (2005), and Hapke et al. (2007).
Since the historical shoreline change record shows the Lighthouse site to be erosional over the past ~150 years (Hapke et al., 2007), a shift to accretion in the late 1980s to 1990s is anomalous. It is likely that a combination of anthropogenic alterations (beach replenishment, beach scraping, sand fencing) influence shoreline change from 1979-2007. The accretional trend is dominated by the replenishment activity that took place in the 1990s and in 2003-04, totaling over 1,008,000 m^3 of material (Gravens et al., 1999; Land Use Ecological Services, Inc., 2008).

Shoreline change: Watch Hill site

The shoreline retreated along more than half of the Watch Hill site (54%) between 1979 and 1988 (Figure 10, Table 3). Most (77%) of the erosion occurred in the eastern part of the Watch Hill site, an area characterized by development (Figure 10, Table 3). The greatest amount of erosion occurred in eastern Davis Park where the shoreline retreated by approximately 30 m (Figure 10). Mean shoreline change in the developed area was -12.8 m, in contrast to the undeveloped area where the shoreline prograded an average of 6.2 m over the nine-year period.

During the decade from 1988 to 1998, the Watch Hill site was dominated by shoreline progradation, in contrast to the trend of the previous nine-year period (1979-1988) (Figure 10). Beaches at the community of Davis Park were replenished in 1993, but only 3,800 m^3 of sand were added to the system. This small amount cannot account for the shift to an accretional regime that is observed in the data (Table 3). Accretion during this period is unexpected since a series of severe storms impacted Fire Island in the early 1990s. It is possible that a natural process (such as post-storm beach recovery) resulted in increased sediment supply at the Watch Hill site from 1988 to 1998. During this period, only 18% of the site was eroding, and 96% of the erosion occurred in the undeveloped area in the western part of the site.

The shoreline change trend at the Watch Hill site was dominantly erosional from 1998-2007 with the exception of some parts of the undeveloped area (Figure 10). Sixty-five percent of the site was erosional, and 63% of the erosional transects were in the developed area where mean shoreline change was -8.8 m (Table 3). The long-term trend (1979-2007) shows that most (77%) of the Watch Hill site was accretional over the 28-year period (Figure 10). An erosional section of coast is located in the central part of the developed area. This erosional peak is spatially consistent with the narrowest part of the island and in a low-lying area of the Watch Hill site. The island was breached at this location forming the Bay Berry Dunes Inlet, possibly as early as 1770 (Leatherman and Joneja, 1980). Since the island was historically breached here, it is possible that an inlet could reopen at this location if a large enough storm impacts Fire Island.

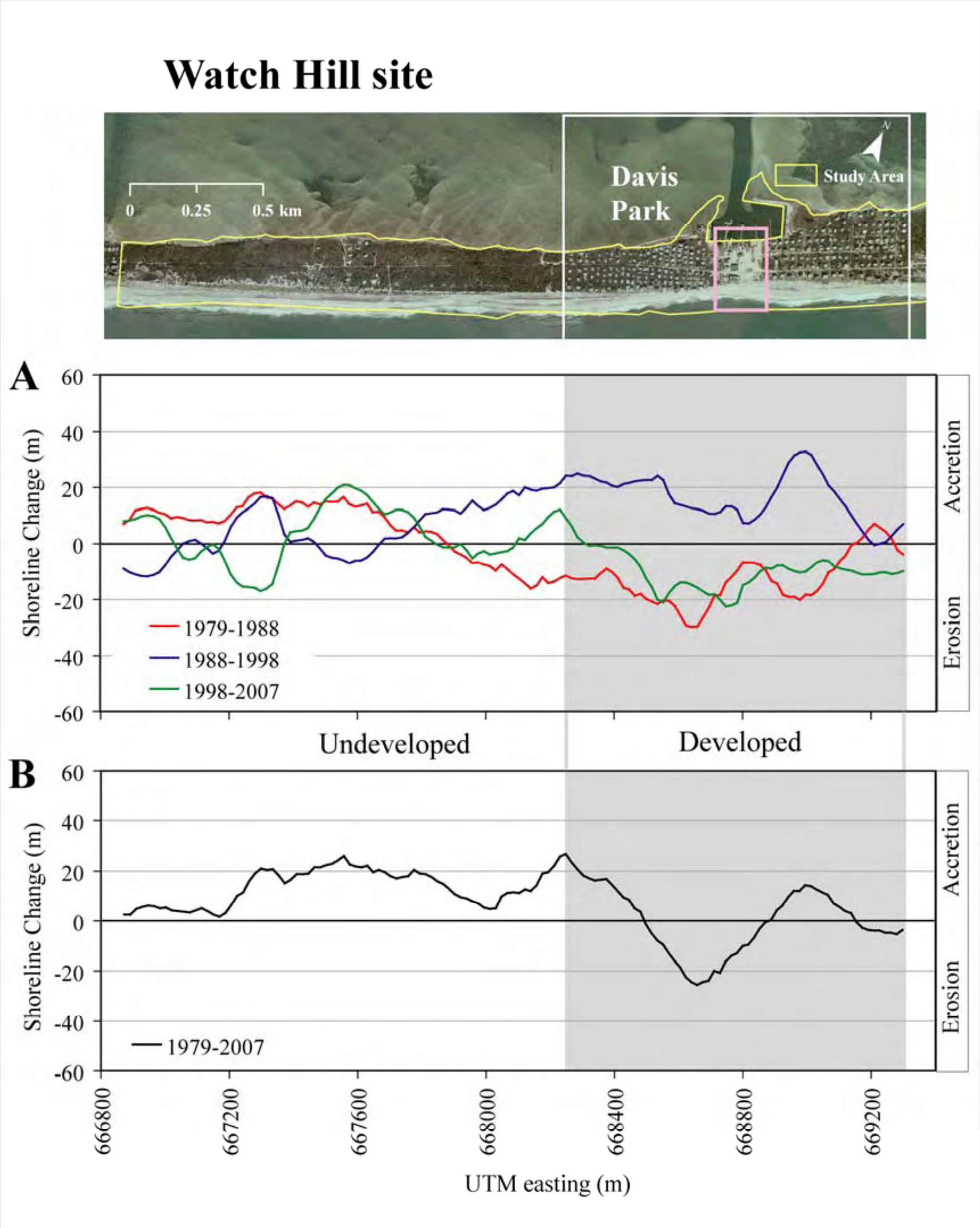


Figure 10. End point shoreline change at the Watch Hill site over four time periods in developed and undeveloped areas: 1979-1988, 1988-1998, 1998-2007, 1979-2007 (A), and total change 1979-2007 (28 years, linear regression) (B). Location of former inlet shown by pink box. Orthophotograph from 2004.

Summary: Shoreline change

The shoreline at the Lighthouse site is dominantly accretional over the entire study period (28 years, 1979-2007). In areas where there is erosion, the majority occurs in the developed area (Table 3). The data suggest that anthropogenic modifications to the island influence shoreline change at the Lighthouse site, especially the shift to an accretional regime in the 1990s from replenishment. Statistically, shoreline changes in developed areas of the Lighthouse site are significantly different ($p < 0.05$) than undeveloped areas in three of the four time periods analyzed (not different in the total time period between 1979 and 2007, $p > 0.10$). This suggests that over a long (28-year) period of time, differences between shoreline change in developed and undeveloped areas are comparable, and known anthropogenic activities are masked in the long-term trend.

At the Watch Hill site, long-term shoreline change is variable, but dominantly erosional in the developed area. On a decadal scale, the site is accretional with the exception of one area within the developed part of the site. This supports the hypothesis that development is influencing shoreline change at Fire Island. A statistical analysis shows that shoreline change in the developed area is significantly different than the undeveloped area ($p < 0.001$) in all time intervals providing strength to the interpretations made in this study.

BEACH PROFILES: SCRAPED VS. NON-SCRAPED BEACHES

Larger scale volume and shoreline change analyses effectively identify differences between developed and undeveloped areas of Fire Island, and the erosional and accretional patterns therein. However, morphological changes due to localized methods of property protection (i.e., beach scraping) are difficult to isolate with the larger scale datasets. A more focused analysis using profiles that are directly related to beach scraping activities (required as part of the permitting process), and that have a high temporal resolution are better suited to assess the influence of beach scraping on the dune/beach system of Fire Island. Statistical analyses using beach profile characteristics (Figure 5) in scraped and non-scraped locations revealed differences in morphology that are detectable on a short (sub-decadal) timescale. The two communities chosen for the study are Kismet and Davis Park.

Kismet (1996-2006)

The results of the analysis conducted on beach profiles at Kismet indicate that several characteristics are statistically different at the scraped profile location (SC) with respect to the controls (CW, CE). Beach volume, dune volume, and beach width were all statistically different over the ten year period of analysis (1996-2006) as indicated by rejection of the null hypothesis (H0: CW = SC = CE) ($p < 0.05$). The other beach profile characteristics were not different and therefore results are not shown. All three significant characteristics display seasonal variation, therefore mean values are used to interpret differences over the ten-year study period.

At Kismet, dune volume is 101% larger at the scraped location relative to the controls (Table 4, Figure 11). This is an expected result due to the addition of material to the foredune zone during the scraping process. Beach volume at the scraped location is 31% lower than the controls, also expected since the beach (berm) is the source of material for the anthropogenic foredune (Table 4). Beach width at the scraped profile location is 23% narrower compared to the controls (Table 4). Beach width is measured from the dune toe (Figure 5), therefore the narrower beach in the scraped area reflects a seaward shift in position of the dune toe through the creation of a larger and wider foredune during scraping. Subsequently, there is passive narrowing of the beach.

Figure 11 shows the temporal variation of the three statistically different characteristics at Kismet: dune volume (A), beach volume (B), and beach width (C). Beach volume and beach width are most variable downcoast of the scraped location (at CW), while dune volume varies most at SC (Figure 11). The highest volumes and beach width occur at CW over the study period (1996-2006) in all three characteristics (Figure 12A), likely related to upcoast beach scraping since the same changes are not observed at CE. Due to beach scraping, more material is available for westward transport by aeolian and wave processes because the loosely-compacted scraped dune at SC is twice as large as the natural dunes at CW and CE. Also, narrower beaches and a foredune more seaward of its natural position increase the potential for waves to reach the dune, resulting in erosion and transport of material (Psuty, 2005).

The higher variability and greater changes taking place at CW indicate that the scraping process and subsequent change to the morphology of the beach at SC is influencing downcoast beach morphology which, notably, is undeveloped land outside of the boundaries of Kismet. However, the results presented here do not imply that beach scraping is the sole factor of influence on beaches downcoast of Kismet. The data suggest that scraping alters the dune/beach morphology by increasing dune volume, thereby allowing more material to be eroded and transported downcoast. Material in the anthropogenic (scraped) dune dries out following emplacement in the foredune zone, and is unconsolidated. Dry, loose material is more easily erodible than material in the berm. Berm material is more compacted (more tightly packed), wetter, and is more dense, making it harder to erode than dry, loose dune sand.

Table 4. Results of beach profile analysis at Kismet and Davis Park. The scraped profile (SC) is shown to be higher (+) or lower (-) than the control profiles (CW and CE). For example, at Kismet, dune volume is an average of 101% higher at the scraped location than the controls in undeveloped land.

Community	**Profile Characteristic***	**Profile Location**			**SC higher (+) or lower (-)** % = [(SC-CW)/CW]*100		
		CW (mean)	SC (mean)	CE (mean)	Relative to CW	Relative to CE	Average % difference
Kismet (1996-2006)	**Dune Volume** (m^3/m)	56.0	106.6	49.6	+ 90%	+ 115%	+ 101%
	Beach Volume (m^3/m)	123.4	87.6	130.0	- 29%	- 33%	- 31%
	Beach Width (m)	66.9	50.6	65.7	- 24%	- 23%	- 23%
Davis Park (1997-2000)	**Total Volume** (m^3/m)	235.3	147.0	167.0	- 38%	- 12%	- 25%
	Beach Volume (m^3/m)	141.8	76.3	94.1	- 46%	- 19%	- 33%
	Dune Toe Elevation (m above NAVD88)	3.5	2.1	2.8	- 39%	- 24%	- 32%
	Dune Crest Elevation (m above NAVD88)	7.0	4.5	6.8	- 36%	- 34%	- 35%

* Statistically different characteristics only for each community

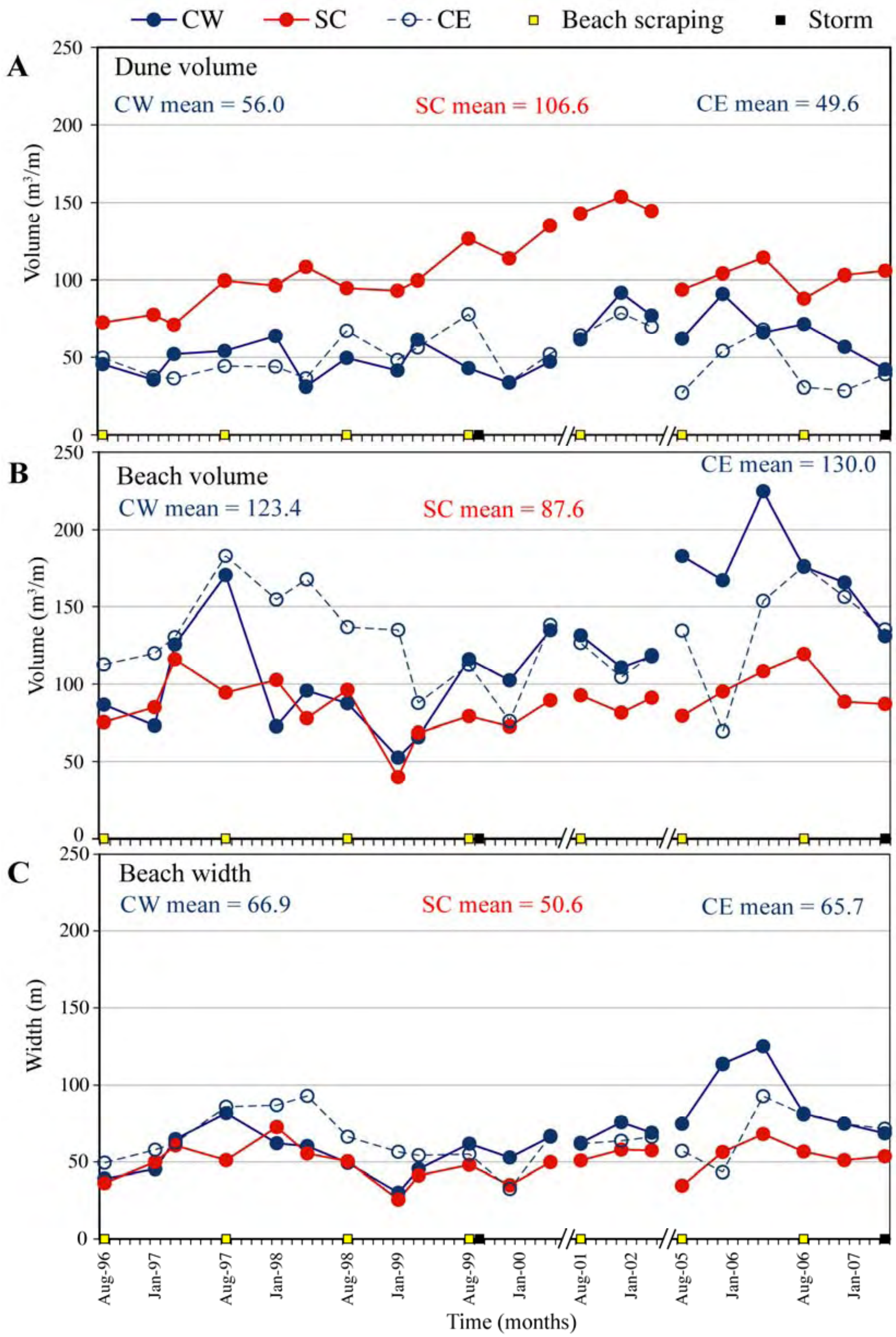


Figure 11. Variation of dune volume (A), beach volume (B), and beach width (C) through time at Kismet. CW= western control, SC= scraped area, CE= eastern control. Beach scraping events and storms are also noted.

Davis Park (1997-2000)

Total volume, beach volume, dune crest elevation, and dune toe elevation are significantly different at the scraped location with respect to the controls at Davis Park ($p < 0.05$) (Table 7). Total volume (beach and dune) at SC is an average of 25% lower than the controls, which are variable (38% lower relative to CW, and 12% relative to CE) (Table 4). There is a sharp decrease in total volume, beach volume, dune crest elevation, and dune toe elevation at Davis Park between December 1997 to April 1998 (Figure 13). Although there are no severe storms on record, maximum wave height during this period was 6.1 m, which is much greater than the average wave height reported for the area (1.1 m) (Table 1) (USACE, 2008). The large wave heights suggest that storms capable of erosion may have occurred but were not reported as severe between December 1997 and April 1998. For comparison, the reported wave height during the December 1992 extratropical cyclone was 7.8 m (USACE, 2008).

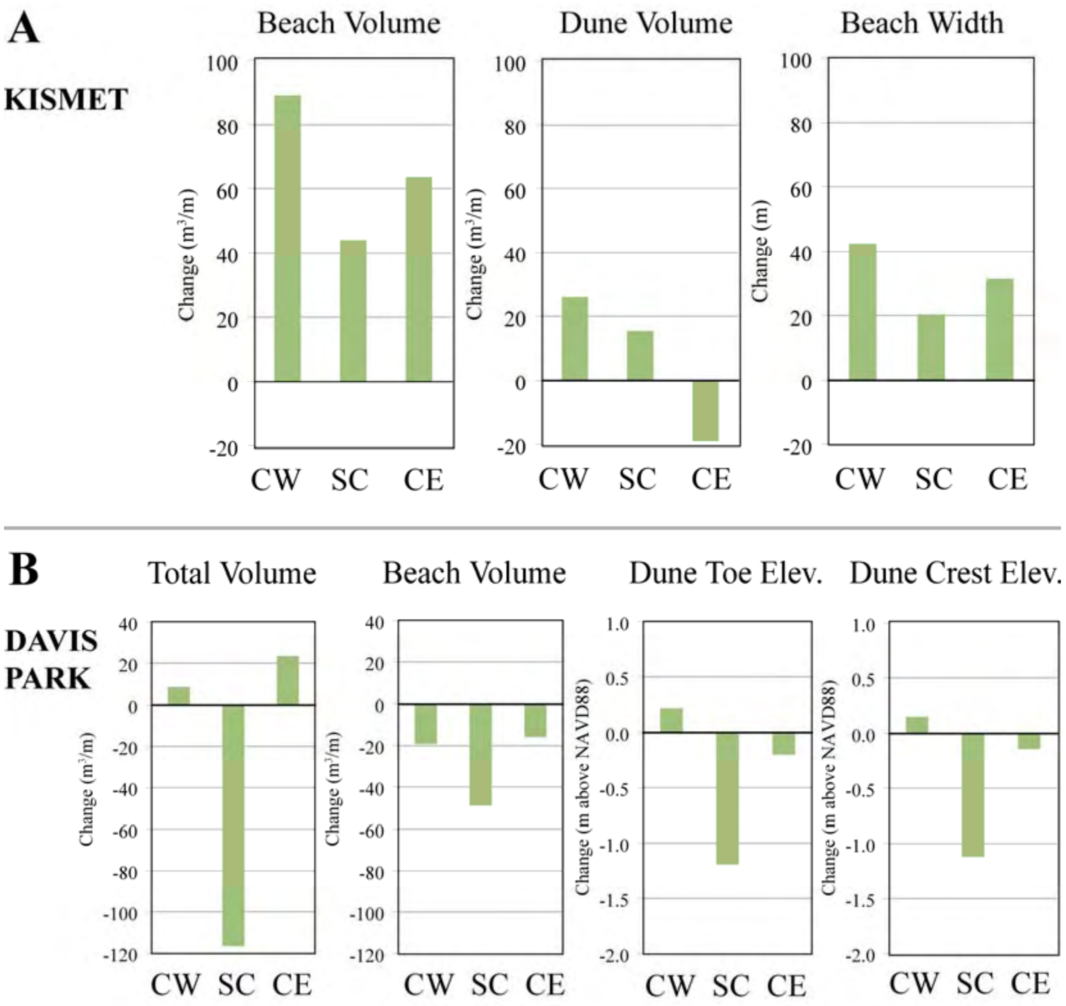


Figure 12. Plots show net change for each significant parameter at Kismet 1996-2006 (A), and Davis Park 1997-2000 (B). Note: scales are different on each plot depending on the parameter (volume or length).

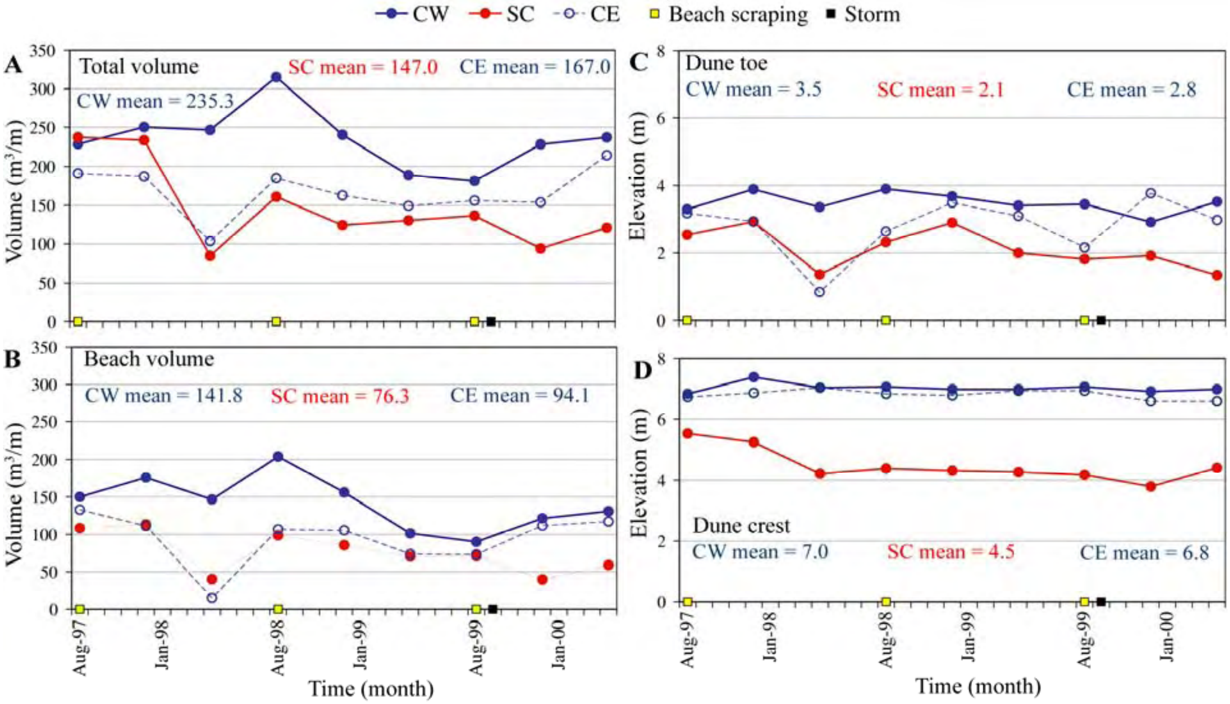


Figure 13. Variation of total volume (A), beach volume (B), dune toe elevation (C), and dune crest elevation (D) through time at Davis Park. CW= western control, SC= scraped area, CE= eastern control. Elevation in meters above NAVD88. Beach scraping events and storms are also shown.

Beach volumes at Davis Park are 33% lower at the scraped location relative to the controls (46% lower than CW, 19% lower than CE) (Table 4, Figure 13). Based on total volume and beach volume, CW averages twice as much sand as SC over three years, and the greatest loss of material occurs at SC (Figure 12B). The results suggest that the beach in front of Davis Park was eroded to a much greater extent than the downcoast beach and somewhat greater than the beach upcoast. It is unclear whether beach scraping is affecting the amount of erosion at Davis Park since the data span only three years. To determine whether the beach recovered after this period of erosion, beach volume data covering a longer period of time would be required. However, Davis Park has not scraped in recent years because beach widths and elevations have been too low to meet permit requirements.

Dune crest and dune toe elevations are 35% and 32% lower, respectively, at the scraped location relative to the controls (Table 4), which are consistent values over the study period (Figure 13C, D). The lower dune elevations at SC are somewhat unexpected, based on contrasting results from Kismet. However, homes at Davis Park are directly on top of the primary and secondary dunes, therefore the maximum elevation of the anthropogenic (scraped) dune is limited by the elevation of existing structures. A study by Nordstrom and McCluskey (1985) shows that the aeolian sediment budget is affected by methods of house construction and the use of sand fences, as well as the density of homes built on the dune crest. The authors found that houses elevated on pilings (in low density areas or, areas with fewer houses) have little effect on transport, allowing aeolian processes to take place naturally. Homes placed directly on the ground, however, reduce the amount of sand transported inland, even more so with sand fencing in place (Nordstrom and McCluskey, 1985).

Lower total volume, beach volume, and dune elevations (Figure 12B) indicate that the highest (short term) potential for property damage due to inundation and overwash processes is at the scraped location. Based on this evidence, the protective capability of an anthropogenic foredune at Davis Park is questionable. The observation that Davis Park is losing material on a sub-decadal scale is supported by recent shoreline change studies that cover larger time periods (e.g. Allen et al., 2002; Hapke et al., 2007). Also, the area east of Davis Park is the location of a former inlet (Leatherman and Joneja, 1980) that has the potential to reopen during a severe storm. Erosion is a serious and imminent threat to the properties and infrastructure of Davis Park. Since the area is persistently erosional despite larger scale engineering efforts (i.e., beach replenishment), it is not likely that the cheaper, less technically complex method of beach scraping is going to be effective in this particular part of Fire Island.

Beach profile characteristics at scraped locations in each community show morphological differences when compared to non-scraped beaches. Dunes constructed by beach scraping contain a greater volume of material than natural dunes, and much of this material moved downcoast as evidenced by increased beach and dune volumes and beach width at the western control profile at Kismet. In Davis Park, the scraped location is losing the most material and dune elevations are lowest, showing that the most potential for overwash is at the scraped location. It is notable that beach volume is the only profile characteristic that is statistically different in both communities, suggesting that subaerial beach volume is consistently affected by beach scraping island-wide, where the other profile characteristics are community-specific. Beach scraping appears to accelerate the amount of material transported downcoast, ultimately increasing the volume of adjacent, undeveloped beaches.

CONCLUSIONS

This study quantifies and describes the influence of anthropogenic alterations on the morphology of dune/beach system at Fire Island, a moderately developed barrier island located along the south shore of Long Island, New York. Volume change (dune and subaerial beach) and shoreline change were calculated from lidar and RTK GPS data to estimate changes in the amount of sand on the beach through space and time, and to assess whether development and/or human alterations affect the position of the shoreline. Beach profile characteristics were analyzed to quantify the effects of beach scraping to dune/beach morphology in scraped versus non-scraped locations of the beach, and to determine if beach scraping influences downcoast beaches. Combined results indicate that human alterations (e.g., beach scraping, beach replenishment) in developed areas measurably affect subaerial beach volume, shoreline change, and several beach profile characteristics by adding material and changing the amount of material transported downcoast. Generally, the majority of erosion at both sites is located in developed areas.

Beach volume and shoreline change analyses characterize changes on a larger scale, but a more detailed analysis of profile characteristics isolates the effects of beach scraping to the dune/beach system. The analysis in the western study site shows that beach scraping influences downcoast beaches. Anthropogenic foredunes are larger than natural foredunes at Fire Island, and as a result, the amount of material transported alongshore by aeolian and wave processes increases. Decreases in volume and lower dune elevations indicate that scraping is an ineffective method of property protection at the eastern study site. Homes are positioned directly on the dunes preventing the anthropogenic (scraped) dune from being built high enough to serve its purpose as currently designed. As beach scraping continues at Fire Island, it would be advantageous to analyze data concentrating on beach width, beach volume, and dune width, to test the longevity of the anthropogenic dunes. Over time, a wider dune could be more protective and last longer, but as observed in this study, some of the material will be transported downcoast. For accretional beaches (i.e. increasing in volume, shoreline is prograding), a much less expensive alternative could be tested. Nordstrom et al. (2000) discuss the use of symbolic fencing in the foredune zone to allow aeolian processes to restore the foredune naturally while an accretional trend is in place. However, for beaches that are persistently erosional, beach replenishment is likely the most effective option for increasing volume of the beach and dunes in the developed area, but does not have a lasting effect. Replenishment would need to occur every year or every few years to maintain volume and width of the beach.

This study investigated anthropogenic alterations and the associated impacts to the dune/beach system on a moderately developed barrier island. The utilization of multiple datasets supported by statistical analyses quantitatively assessed morphological differences between developed versus undeveloped areas recognizing human beings as intrinsic agents of change. Additional studies may eventually provide a degree of predictability to morphological changes in developed areas of varying density, from scattered homes to heavy development. Methods established in this study can be applied to determine how much influence anthropogenic modifications have on the dune/beach system at other barrier islands along the east coast of the United States.

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