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Historical and Recent Shoreline Changes, Impacts of Moriches Inlet, and Relevance to Island Breaching at Fire Island National Seashore, NY

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Executive Summary.

A geomorphologic study of the natural and anthropogenic responses to an unusually high frequency of large magnitude storms in the early 1990s finds that natural processes return the Fire Island system to a more normal state at different timescales: shorelines within weeks to months; dunes within years; and inlet-affected areas take decades. There are significant shoreline trends persisting over decades but also localized areas of erosion, which migrate westward over months to a few years. Certain areas are identified as more predictable in response direction whereas others are dominated by variation, possibly due to offshore controls on incident wave energy and sediment supply. The latter dominate shoreline activity in the west of Fire Island, which is occupied by 17 communities of weekend to year-around residences with high monetary value being some 60 km away from the center of New York City. The context of a densely developed landscape that is highly dynamic and at risk to several threats, also means that certain policy issues go beyond the science of shoreline change. Known areas of erosion can be actively engineered to resist such threats but more innovative adjustments to ocean and bayside erosion would provide cost-effective, storm-hazard protection, based upon natural reconstruction processes, conjoined with many environmental benefits.

Net sediment transport along the south shore of Long Island is to the west and thus the littoral supply to eastern Fire Island is constrained by the management of Moriches Inlet for navigational purposes. Past erosion due to the Moriches-induced sediment deficit was limited to Smith Point Count Park. We show that substantial natural bypassing developed by the early 1990s resulting major accretion at Great Gun beach. This has implications to inlet management plans because it appears that Moriches, 40 years after

stabilization, and the downdrift barrier system apparently have reached a state where the natural rate of sediment transport is relatively unimpeded by the tidal processes of the inlet. Spatial distance effects of the managed inlet are shown to be restricted to within a few km (although any new inlet would migrate westward and impact more resource unless controlled quickly). Both long term and short-term shoreline changes are geographically separated by offshore depth controls upon incident wave energy and sediment supply factors. These conclusions are fundamental to planning for changes in the developed, western portion of the island whose shoreline position is largely controlled by an offshore sediment source and processes, especially during storms.

Shoreline change variability is statistically analyzed at 50-m intervals and spatial variability dominates temporal trends along the 50-km barrier island. The coastal system restores itself rapidly in natural areas but more slowly in densely developed coastal systems because the structures and traffic physically interfere with the restoration processes. Observed human responses confound the logical interpretation of trends in system activity but beach and dune fill projects appear to have short-lived effects, relative to longer-term trends and variability. In terms of policy, contravening federal and state and local desires are in conflict and there has not been a continued commitment to previously established goals and objectives for logical and efficient management of coastal resources, whether natural or cultural.

Along Fire Island shoreline changes are problematic in cause and effect over long time periods due to human interference but inlet processes, a net westward littoral drift, and offshore controls (both oblique ridges in depths >8m and nearshore bar morphology in shallower depths) are directly related to some observed patterns. Temporal sequences of *storms and their magnitudes also drive shoreline changes but their magnitude and persistence of change are shown to vary on event, seasonal, and inter-annual scales of measurement. No simple trend or pattern of shoreline change at Fire Island is found that specifies a location or probabilistic risk level of island breaching. However, there appears to be a greater threat of dune erosion in the Fair Harbor, Point O'Woods, and Fire Island Pines areas based on past patterns of dune response, difficulty of maintaining a beach in front of the artificial dunes, and their correspondence with oblique ridge locations. Qualitatively, some island sites are identified as being more at risk of breaching than others; chiefly these are the narrow center of the island near Barrett Beach and the low elevations at the western end of the communities from Fair Harbor to the Kismet area. Other locations are either sufficiently wide or high to be cut through, or possess insufficient tidal prisms to support a new inlet location. Although bayside erosion is documented west of Watch Hill, and implicated as a long-term threat to island thinning, a detailed discussion is beyond the scope of this assessment of resource threats.*

Understanding the patterns of past change does not equate to being able to predict future changes because neither storm histories nor human activities are deterministic. Their stochastic attributes confuse hazard forecasting, despite the large data set analyzed in this report. Oceanside shorelines and dune dynamics, bayside changes, and human interactions are profound but not predictable from empirical observations, no matter how rigorously measured and analyzed.

Chapter 1. Introduction and background.

In the early 1990's four storms, with recurrence intervals of several decades as measured by peak storm surge at the Sandy Hook, NJ tide gauge, caused much beach and dune retreat plus breaching of some barrier islands, in the northeastern United States. Each of the National Park units (Gateway National Recreation Area (GATE), Fire Island National Seashore (FIIS), and Cape Cod National Seashore (CACO)) were impacted differently but the additive combination of storms upon prior impacts led to incremental losses beyond that measured by individual stage-recurrence levels. The December 1992 storm contributed especially high wave energy over a long period of storm disturbance, as the surge exceeded 0.3 m for ten high tides as measured at Sandy Hook, with a peak height of 1.4 m. This study measures the natural and cultural responses of the system over the past five years to the shoreline changes driven by this unusual storm pattern (see Fig. 1 to visualize the shoreline conditions in 1993).

Figure 1. Aerial view of shore conditions westward of Saltaire, Fire Island in early1993.

Fire Island is the principal area of study, a barrier island offshore of Long Island, NY (see Fig. 2). Its oblique East-West geographic orientation on the Atlantic Coast of the U.S. is unusual and results in different beach and dune responses to northeasterly-tracking coastal storms than the normally east-facing beaches along the east coast. This south-facing shoreline responds to storms occurring well to the south, given the counter-clockwise rotational winds of cyclonic disturbances driving waves northward, some of which can include offshore hurricanes bypassing the locale without making landfall. More regionally centered storms also have erosional and flooding impacts on both oceanside and bayside beaches due to local wind-generated waves and ocean set-up. Net sediment transport is from the east to the west on the ocean side. Until jettied in 1940 at the western extremity (Democrat Point), Fire Island was extending westward at 64 m/yr., although subsequent dredging of Fire Island Inlet is needed to maintain navigational safety. Estimates of the longshore transport rate converge at approximately 200,000 m^3/yr entering past Moriches Inlet but between 370,000 and 540,000 m^3/yr. into Fire Island Inlet (for sediment budget discussion see RPI, 1984; DuBois, 1995; Kana, 1995; and Rosati *et al.*, 1999). This increase in longshore transport rate cannot be balanced by shoreline losses so Kana (1995) attributed the excess to onshore transport from a presumed Fire Island Inlet ebb-tidal delta, which has been lost. Schwab *et al.* (2000) provides much clarification to this argument by showing that, west of Watch Hill, onshore transport on the order of 200,000 m^3/yr. from the remnants of a Cretaceous age source. As a result of these natural and human actions, the island is becoming thinner on the western side and migrating landward on the eastern limb, according to the geological interpretation of Leatherman and Allen (1985).

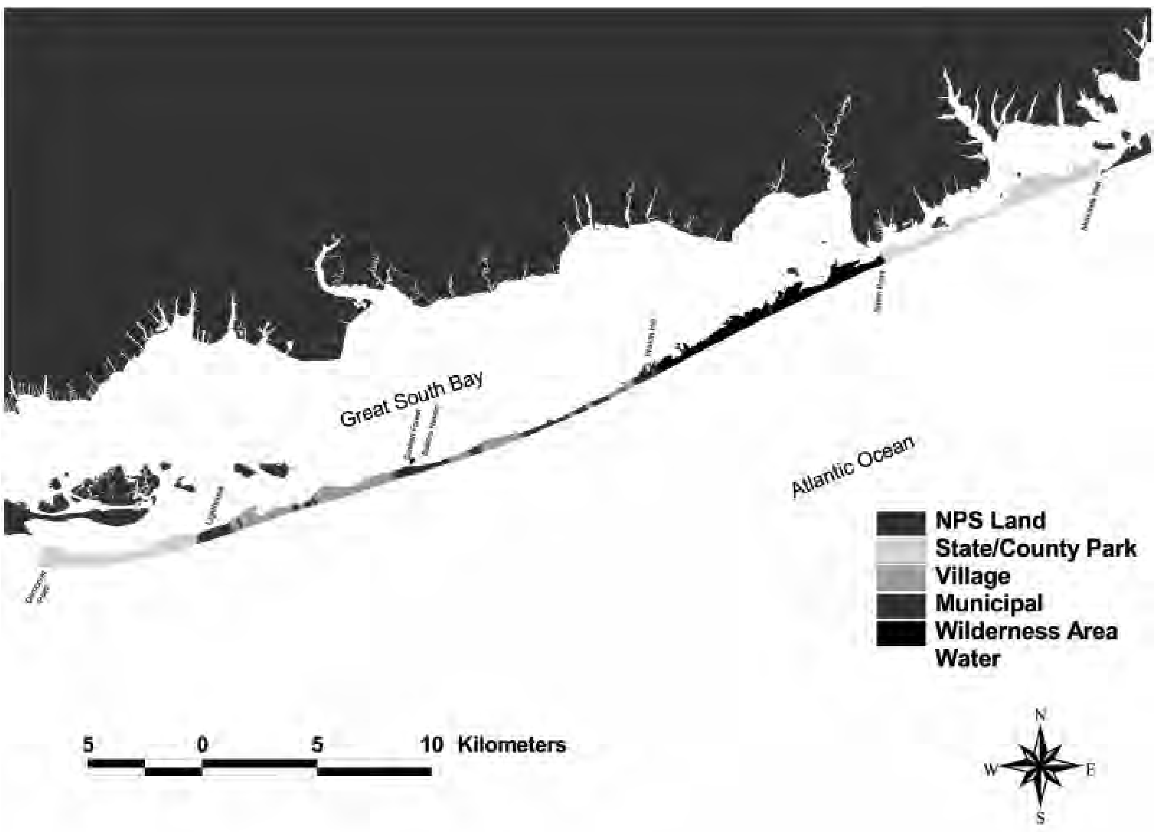


Figure 2. Map of the location of Fire Island barrier system in the middle of the south shore of Long Island, NY, its complex land use, and some key sites.

Study Problem.

This pattern of barrier island thinning must eventually reach a threshold where dune breaching is common, cross-island overwash occurs more often, and island migration begins. When dune breaching and cross-island overwash cut a channel that is deep enough to ensure tidal transport across the high-to-low regime, an inlet is cut that may be ephemeral if closed by wave-driven sediment transport, or relatively permanent if tidal hydraulic forces exceed wave-driven forces of sedimentation.

The initial proposal identified four research questions to be addressed at Fire Island N.S. (and also at Sandy Hook/GATE and Cape Cod N.S., which are not part of this report):

1) *Where* are the specific sites at risk to overwash and island breaching/inlet formation?
2) *What* is the level of risk of inlet formation at each identified site (*e.g.* relative: high/moderate/low or probabilistic: 0.2, 0.05 for example) in terms of storm breach becoming a permanent, recurring, or only temporary feature?
3) *How far* away from a new inlet will geomorphic responses be substantial and what will be the magnitude of the response?
4) *What* is the magnitude of human interference upon the present sediment budget of the island?

Another problem that has developed at Fire Island, subsequent to the initial proposal results from the quest by local property owners to seek relief from perceived erosion and flooding threats to future storms. This has led to a lengthy dialogue between many agencies about the about the wisdom, design, and justification for a planned "interim" beach nourishment project at Fire Island by the U.S. Army Corps of Engineers (USACOE), New York District (NYD). The project has been criticized by many federal and state agencies, plus non-governmental opposition has been generated. The *interim* length of activity is viewed to add protection to the island and mainland in the void between the previous storm damage and that would be addressed by completion of the re-instituted USA COE Reformulation Study for Storm Damage Reduction from Fire Island Inlet to Montauk Point, NY. The data in this study will help in assessing these extra-agency pursuits to assess the physical dynamics of the problem and possible alternatives to decrease the potential threats. Beyond the measured physical changes, there are bureaucratic problems of resolve to enforce dune district regulations while obtaining political support to continue this initiative. For various reasons, this has been difficult to do despite the fact that physically and politically, the Dune District Management Act is superior in definition to the NYS coastal erosion regulations because of a more recognizable topographic boundary and the unheeded need to update at regular intervals of five years instead of the ten required by NYS law.

Chapter 2. Study Design and methodology.

Our goal in this project is to improve present knowledge of barrier system changes by trying to identify if and where sites are more threatened than others. The objective is to identify critical time and scales of shoreline change that are irreversible, and to measure those that are naturally "healed". We attempt to field data, statistical, and numerical modeling to separate natural from anthropogenic processes where possible—noting fence lines on profiles, alongshore surveys of fence extents, and trying to track beach fill, beach scraping, and dune destruction and reconstruction in a quantified manner. The objective is to build towards a better understanding of the processes so that improved prediction of future conditions/responses will result in better coastal zone management practices at private to federal levels of jurisdiction.

To obtain the most precise data and generate the most accurate information, we used the current state of electronic technology to survey geomorphic changes during the 1990s and employed the current spatial analysis software used by the National Park Service, ArcInfo 3.1, to both manage and provide analytical insights. Topographic field mapping utilized a laser-based total station theodolite with internal data storage (ITS) capable of 2mm vertical resolution at one km ranging distances. Horizontal control and shoreline mapping was facilitated by a Global Positioning System receiver (Trimble GeoExplorer) which, in conjunction with differential correction of individual measurements, can resolve locations to within 2-5 m by manufacturer's qualifications.

We tested this by occupying several benchmarks for 30 sec. in various open coastal locations at Fire Island and resolved their location to within a few decimeters of the published locations; despite the URI based base-station distance of 220 km. For more distant locations such as Sandy Hook or outer Cape Cod, the 95% rejection level of benchmark locational error increased to 0.5 m for a 30 sec. sampling, which again is much less than the subjective or analytical difficulties with processing and interpreting the point data from a mobile (rover) receiver. For the very large data sets gathered, we assume that their accuracy is the same at the 95% rejection level but now we know of no way to test mobile deployment point accuracy over large (tens of km) survey ranges with our equipment. We did add the decimeter resolution software for improved accuracy but its >20 min occupancy time for each site constraints limited it to only benchmark locations and not to mobile survey deployment. Bathymetric surveys used a survey-grade acoustic fathometer for vertical (z) measurements coupled with real-time, differentially corrected GPS for horizontal (x,y) control and are thus assumed to fit only within the 2-5m range but they may be more accurate than that in the optimal conditions of open water.

For most GPS surveys, we used the base station at the Environmental Data Center (EDC) at the University of Rhode Island (URI) to calculate horizontal corrections. The site and support staff is centrally located within the geography of northeastern barrier parks and is contractually connected by a Cooperative Agreement with the NPS for GIS support to the Northeast Region. URI can perform differential correction of locational measurements of beach/dune sites with an accuracy of less than a meter in open coastal environs, usually for units from Cape Cod NS to Sandy Hook/GATE. Testing of various base station locations led us to believe that the error due to distance of URI from the various parks did not exceed 0.6 m than with a local base station within 10 km. Other agency studies were carefully monitored to provide data and additional monetary support for surveys and analyses, which would contribute to the following objectives.

The proposal focused on the following tasks and work assignments are identified for their accomplishment:
Objective 1: *identify* high risk erosion locales by identifying systematic trends and spatial patterns of variance of the highly dynamic shoreline at long time scales over the past 150 years as well as the more conservatively changing dune crestline change patterns to describe coastal spatial patterns at various space and time scales, including storm events. This was conducted with assistance from scientists at URI, Rutgers Univ., and Univ. of Maryland.
Objective 2: *characterize* degree of breach threat at high-risk sites by evaluating alterations to spatial parameters of estuarine tidal and storm surge elevations in Great South Bay plus relative sedimentary inputs, which may close the breach. Local topographic surveys of responses, both natural and anthropogenic in origin, of dune toe and shoreline morphology through time depending on local management programs of manipulation or letting nature continue. Numerical modeling of the estuarine threats was contracted to SUNY/Stony Brook Marine Science Center and their report (Conley, 2000) is referred to for results but see also recent COE/NYD reports;
Objective 3: *assess* effects upon Fire Island of sediment entrapment at Moriches Inlet via detailed surveys of bathymetric change of ebb-tidal delta and interpreting bypassing volumes and mechanisms at inter-annual time scales and after navigational dredging. The goal is to determine if delta is continuing to accrete or, if not, what are the geomorphologic mechanisms of bypassing—discrete shoal detachments or ebb-delta rim transport to downdrift sites—and where it is effective upon maintaining the present shoreline. The surveys were conducted with Woods Hole Oceanographic Institution (WHOI) with EDC/URI analytical assistance;
Objective 4: *model* barrier breach threats to natural resources via GIS analysis of inter-annual to sub-annual GPS surveys of shoreline changes occurring after the storms of the early 1990's and during the period of human responses such as beach scraping and dune building plus beach renourishment in order to separate human from natural processes. Objective testing of the matrix of change by accepted statistical techniques has been accomplished by summary statistics of the rows and columns (spatial locations and survey times, respectively), Principle Components Analysis of the prime matrix different solutions for maximizing space, time, and matrix-size strategies, and Geostatistical Analysis of spatial covariance analysis of the changes by time period. Although what has happened in the past is not necessarily going to happen in the short-term future, some aspects of predictability may be provided because some physical interactions may be persistent. All tasks were done to identify whether there is an appropriate time scale as to what is random vs. what is deterministic in shoreline change patterns. Both URI and Rutgers staff helped in this effort.

Methodology.

We gathered 34 surveys for analysis of the estimated Mean High Water line changes at Fire Island to define spatial/temporal trends and associated variance in physically and statistically robust fashions. The historical shoreline data files include six digitized and rectified Metric Map shorelines from Coast & Geodetic Survey "T" sheets and aerial photography covering the 1830-1979 period (Clow and Leatherman, 1984) plus six aerial photographic derivations for the 1973-1995 period were provided by the U.S. Army Corps of Engineers, New York District (COE/NYD). Differentially corrected, mobile GPS transects along the shore between August of 1993 and September 1999 add 22 more digital files (this remains an ongoing, long-term research project and we hope to get funding to do storm event scale changes in greater detail). More GPS surveys of the landward margin of the beach to quantify the inland distance and persistence of wave dominance. Due to physical obstructions and recovery restrictions generated by the Threatened & Endangered Species Act, these measurements are of relative short alongshore distances and cannot be repeated frequently. Primarily they identify the dune toe/vegetation/sand fence line at the landward margin of bare sand but do include overwash fan delineation where encountered. Ironically, these data provide valuable information on the persistence of habitat for species at risk but the rules limit their gathering. We also gathered numerous files describing short reaches of the bayside shoreline by mobile GPS for future reference, this included mapping of the cross-island overwash fan extending into Great South Bay at Old Inlet, some of which will be shown to illustrate bayside changes with regards to island thinning.

The earlier historical surveys identified and mapped a High Water Line as observed in the field, extending from days to months and thus the shoreline is time-averaged over months, in some cases more than a year. Much of the guidance for mapping is not clear (Shalowitz, 1964) but wrack lines and other watermarks would suggest a runup limit. This limit would be landward of a MHW datum intercept on the foreshore after spring tides or energetic wave states so change comparisons can be considered conservative over a century of data gathering. Beginning in the 1930s, aerial photography provided a more synoptic basis for shoreline conditions. Generally, the mapped shoreline was the wet/dry line visible as a change in hue or gray-tone. Little consideration to tidal variability was made and some missions were for post-storm damage assessments on Long Island, e.g. September Hurricane of 1938, the Ash Wednesday nor'easter in March 1962, and Hurricane Gloria in 1984. Nevertheless, most digitally (or analogue) mapped shorelines between the 1930's and 1980's have been derived from photo-interpretation and is thus fundamental to the historical data record. This is true despite that at field levels of interpretation, the "line" is a subjectively identified *zone* migrating up (landward) or down (seaward) the foreshore, depending upon lunar tidal excursions and especially upon wave runup variability. Both Anders and Byrnes (1991) and Moore (2000) provide excellent reviews of the sources of error in the various shoreline measurement data sets.

To extend the period of comparable measurement in a similarly consistent way, we chose also to interpret the Mean High Water line as the visual wet/dry line as the senior author drove a GPS-mounted vehicle along the shoreline near the time of predicted Low Tide.

No corrections were made for spring/neap tide range variation due to travel planning needs. Wave runup could not be viewed as excessive—visually estimated as breaking wave heights were less than a meter for the highest third or the trip was delayed by a day—in one instance by five days. This visual reference is not the equivalent of MHW datum intercept and is subjective; it does have historical substantiation because of its data base support in mapping shoreline change trends. On steep beaches, which Fire Island usually possesses, tidal excursions and small wave runup add little more than a couple of meters to the horizontal error. Other than different subjective interpretations by different drivers, several traverse days have not allowed a clear resolution of the contrast definition to be subjectively interpreted by the driver, especially during coastal fog conditions. After several encounters and searching for another reference variable, this driver found that eye height was close to berm height while driving under normal conditions in the Suburban SUV vehicle used in foul weather. In fair weather surf conditions, no clear obstacles were noticed at low tide, other than a need to be very careful about advising the beach administrators and occupants who have little knowledge or concern for shoreline survey protocols in their regulatory constraints of vehicular access to the beach.

Shoreline changes are rapid and bi-directional whereas dune surveys are much more conservative indicators of directional and magnitudes of trends over longer time periods. Surveys of horizontal change in the dune crestline position, interpreted from stereo aerial photography, have been conducted at roughly 5-year intervals since 1976 (Psuty and Allen, 1993). A NPS-commissioned dune crestline mapping effort in November of 1992 to update the 1986 survey became obsolete within weeks because of the long-duration storm in December but was updated via interpretation of a late-December 1992 COE/NYD photographic survey that isolates crestline changes due to the storm. Because of high wave runup, photography was deemed unsuitable for shoreline change analysis but not for crestline change because it was not overtopped at the time. Additionally, we have surveyed dune/beach profiles annually at 28 sites to provide vertical change data, isolate human from natural processes, and provide additional control for crestline interpretation. Although not directly comparable, we have also utilized the above GPS technology to provide some "inventory" maps of the dune toe/vegetation line/fence line along the length of the island. Some of the overwash penetration sites have been monitored infrequently by the PI but have always closed within a year or two, defining a short period of bare sand habitat survival in upland areas driven by wave overtopping. This has some implications to public policy planning and expectations of dune recovery vs. extermination of coastal barriers.

The flood and ebb tidal flows and jetties at Moriches Inlet constitute a partial block, or a filter, to a westward-directed sediment supply to the downdrift barrier island. Dense and broad surveys of the ebb-tidal delta were conducted to identify its morphologic role in sediment bypassing. Bathymetric surveys took place in 1995, 1996, and 1999 with a survey-grade acoustic fathometer and real-time, differentially corrected GPS system for horizontal control, mounted on a FIIS-supplied vessel. Instruments and data reduction were provided and conducted at the Woods Hole Oceanographic Institution. Contoured bathymetric maps and spatial change analyses were conducted at EDC/URI and produced in ArcInfo.

All planimetric data sets describing MHW shoreline position and dune crestline position have been assembled into ArcInfo GIS for management and production of maps for visual and semi-quantitative comparisons. Maps, however useful subjectively (and some will be used in the discussion section later), have spatial scale limitations upon their areal coverage and visual limitations upon the number of shorelines that can be clearly interpreted at one time. ArcInfo also provides the capability of performing quantitative analysis of any two data sets (see Appendix I for programmatic methodology) describing shoreline or dune crestline changes. For a baseline of comparison, we use the 1979-reference shoreline of Leatherman and Allen (1985) because of its proven, ground controlled coordinate coverage. Both past and contemporary shoreline comparisons from this base are at fixed points separated by 50-m intervals, originating from the jetty at Democrat Point and measured eastward. Such a separation distance has been suggested by Dolan et al. (1992) to be the most efficient separation distance for shoreline change analysis given available computational, data entry, and spatial autocorrelation problems. This lag distance results in a total of 993 stable alongshore locations for statistical analysis of full shoreline surveys, inlet to inlet. Some surveys are spatially incomplete due to inlet migration, satellite constellation problems, power failure, or vehicular survey restrictions arising from Threatened & Endangered Species protection schemes. Nineteen files extend from inlet to inlet and the other ten exceed half of the island length. In only three cases (9/95-1/96, 1/96-2/96, and 1/98-4/98 do the compared file sizes incorporate slightly less than half of the total alongshore potential because of spatial biases—an eastward vs. westward lack of data overlap. When all sequential temporal comparisons (the end-point method for each) are made, they can be aggregated into an incomplete matrix of change in space and time at fixed points. This matrix of change can then be analyzed by a variety of statistical methods, including sub-sampling to analyze more local relationships in both space and time. Fenster and Dolan (1994) and Walton (1998) have discussed non-linear temporal interpretations of changes at a specific site to separate short-term variability from long-term trends. The former even identifies a reversal in shoreline change trends in 1967 for much of the mid-Atlantic coast towards erosion. There is a trend toward using denser databases of shoreline change to predict future positions (e.g. Douglas *et al*., 1998) but these assume that past forcing mechanisms will continue at the same frequency/magnitude rates. If global climate change is occurring from human activity, the long-term prediction is invalid from such an assumption; shorter-term variability in weather patterns at decadal, inter-annual, and seasonal time scales are well known and are not just “noise” in past end-point comparisons.

Although remotely deployed, laser-based surveys at highly detailed and very large spatial coverage of the nearshore bathymetry (irregularly since 1995 with limited success due to turbidity) and Airborne Topographic Mapping (since December 1998, at roughly yearly intervals), the recorded changes are outside the scope of this report. Nevertheless, research proposals to relate these patterns of change to nearshore and offshore controls have been forwarded from the USGS to the USACOE and are resident within their Reformulation Study Project Study Plan. Funding is uncertain despite the promise to improve the resolution of cause-effect relationships for coastal change that affect both natural and cultural resources at risk of undesired change.

Chapter 3. Results of temporal analysis of shoreline change.

Many previous analyses of shoreline change trends at regional scales claim long term rates as meaningful while acknowledging greater variability at more local scales in space and time (e.g. Eliot and Clarke, 1989; Morton *et al*. 1994; Lacey and Peck, 1998). Simple maps of shoreline changes can be informative at various time scales but are limited by horizontal resolution to small space scales. The following four figures depict shoreline changes in our data set at long and short-term scales for differently responding sections of Fire Island. The old shorelines identified in the legend are those supplied by the University of Maryland in an ASCII format for use in GIS instead of the Metric Mapping format. The shoreline of the colored polygons denoting land management is the 1979 data from the Metric Mapping project (Leatherman and Allen, 1985) The "FI" shorelines have the year of the 1990s then the number of the month as identification to identify the GPS surveys.

It is shown in Fig. 3 that the historical trend of change is of barrier thinning in the narrowest portion of Fire Island. Bayside erosion is obvious despite substantial bayside fill in the 1970s, in conjunction with dredging for ferry service to the Barrett Beach marina, which is now planned for removal by the NPS. Certainly the more extreme erosion on the east side of the marina is related to the extension of the structure far out from shore as well as the fact that the flanking wall is not as long as the western one. In the 1970s the area adjacent to the shorter wall was filled and planted with saltmarsh vegetation. It has not persisted. The more recent, detailed surveys of the oceanside show

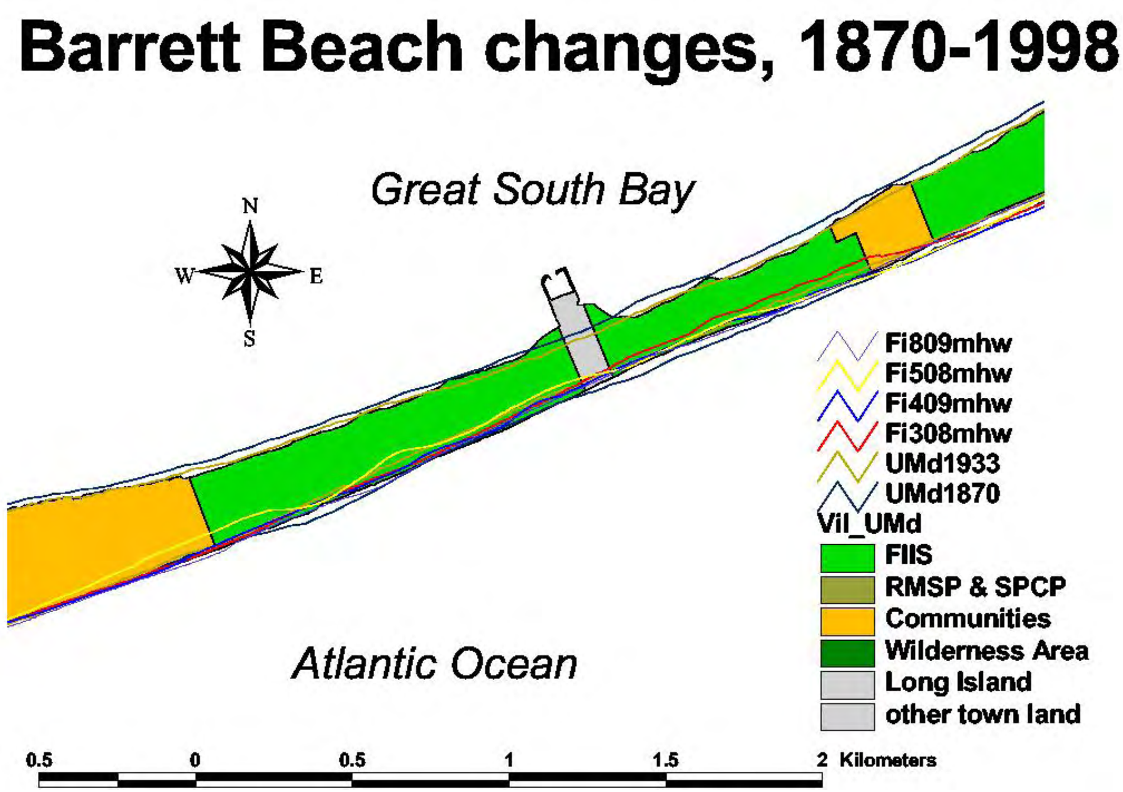


Figure 3. A century of shoreline change in central Fire Island with details for the annual regime of summer change in the 1990s.

migrating, cuspate indentations in the shoreline (and dune crestline, by extension), which are persistent over years in the early 1990s but move westward. This portion of the island is at a greater risk of breaching because it is thin, contains low elevations which can be overwashed, and it is out-of–phase with the present tidal inlets which leads to increased hydraulic stresses during periods of storm surge (Conley, 2000).

The more developed and wider western section of the island is shown in Fig. 4 to have severe retreat of the shoreline in the long term, owing to the migration of the Democrat Pt. sediment surplus, but also island thinning from bayshore erosion. The extension of the bayside spit into Clam Pond is one of the few geomorphic items testifying to the dominant direction of longshore transport of sediment along the bayside of Fire Island. The more developed and wider western section of the island is shown to have severe retreat of the shoreline in the long term, owing to the migration of the Democrat Pt. sediment surplus. The 1993 shoreline shows a large erosional embayment at Saltaire and Fair Harbor (Fig. 1 also). Many homes were lost because of this feature in the storms of 1992 and 1993. Despite being filled by beach nourishment, the westward migration of this feature into Kismet (the westernmost community) and NPS land can be traced through 1995. The erosional consequences to the dune system (and related to developed

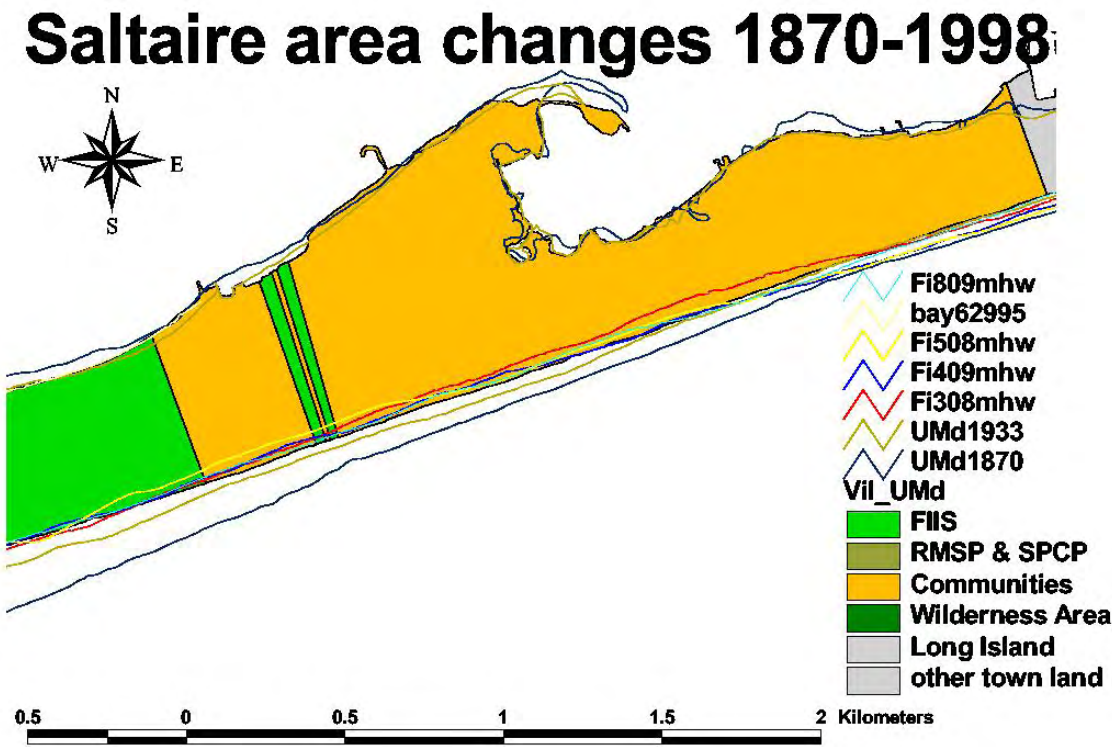


Figure 4. Shoreline changes in the western communities of Fire Island over the past century and showing local details subsequent to the storms of the early 1990s.

area problems) of the lack of a fronting beach are apparent and the area has conducted much beach scraping and even sandbags to repair the dunes.

Another example of barrier change is given in Fig. 5 where island thinning is driven by oceanside erosion but with landward transgression of the backbarrier associated with flood tidal delta creation with past island breaching. Saltmarsh colonization of these shoals provides large marshes in the eastern portion of the island. Bayside problems of geographic resolution in the 1870 data have been difficult to resolve. Old Inlet was open during the 18th century but the small tidal prism in eastern Great South Bay makes it unlikely to reopen. Again, the recent shoreline history shows major but migrating indentations in 1993 to 1996, which allowed overwash to continue after the major, cross-island events in December 1992 and March 1993. Note the bay shoreline accretion due to these overwash episodes. Dune breaching is unusual on Fire Island with only a few sites active at present during storms and this is the only cross-island site since the 1962 storm that we are aware of. The overwash fans are considered valuable habitat for some species at risk, unfortunately they are quite temporary as they normally revegetate soon after the locus of erosion has moved.

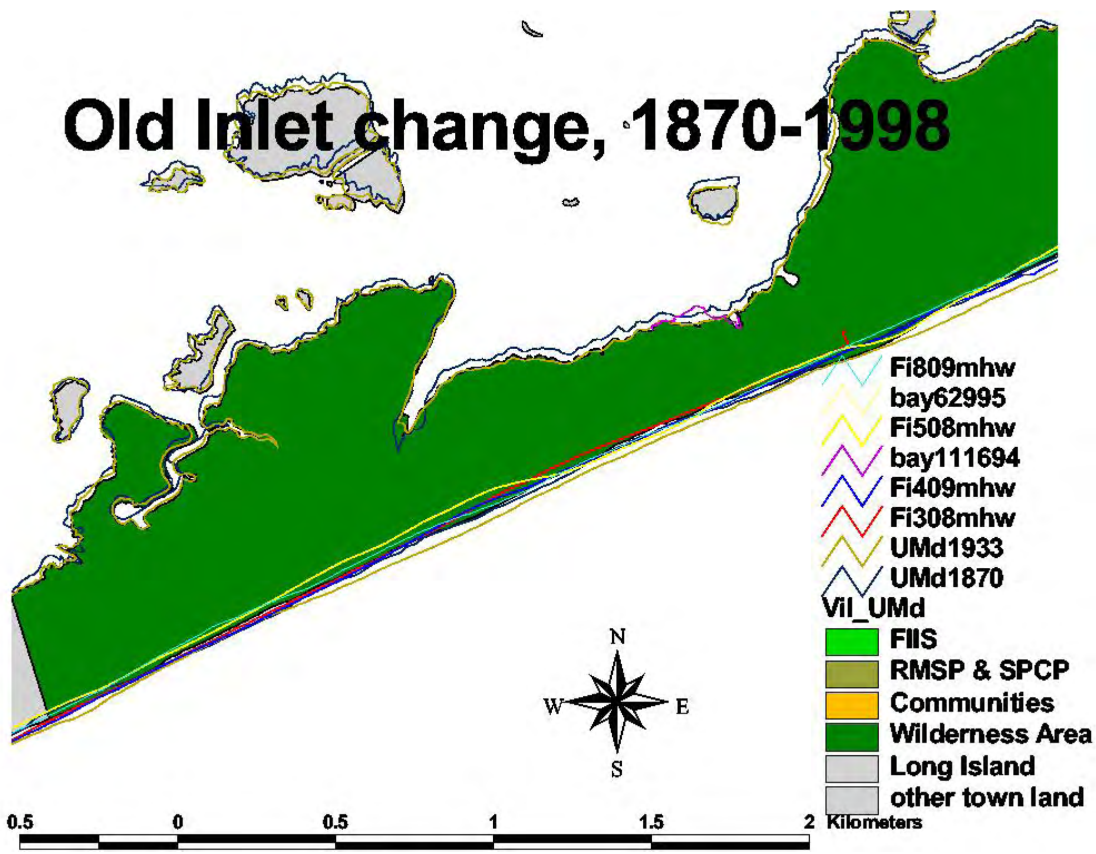


Figure 5. Long-term and recent shoreline changes at Old Inlet in the Wilderness Area, eastern Fire Island.

Shoreline changes at the eastern end of Fire Island are shown in Fig. 6 and several aspects are remarkable. The formation of a breach in the barrier island to form Moriches Inlet and its engineered control by jetties has led to updrift accretion in Cupsogue State Park but substantial downdrift erosion along Fire Island in Smith Point County Park over the past century but especially after inlet formation. Despite this long-term trend of erosion, a reversal to accretion is shown on the oceanside, at a site called Great Gun

Beach. This process-driven feature is quite recent in the data set but has persisted. The source of these sediments may be related to the development of natural bypassing of Moriches Inlet, given the location and persistence of the shoreline bulge during the 1990s. Some areas along the bayside have been relatively stable over the century-plus of data because of a restricted fetch in this area of Moriches Bay for wave-induced erosion but there has been a development of large areas of salt marsh after the formation of Moriches Inlet. To what extent this formation is natural colonization of flood tidal delta sediments or enhanced by landfill (because much of this area has been filled) is unknown but represents a major bayside gain.

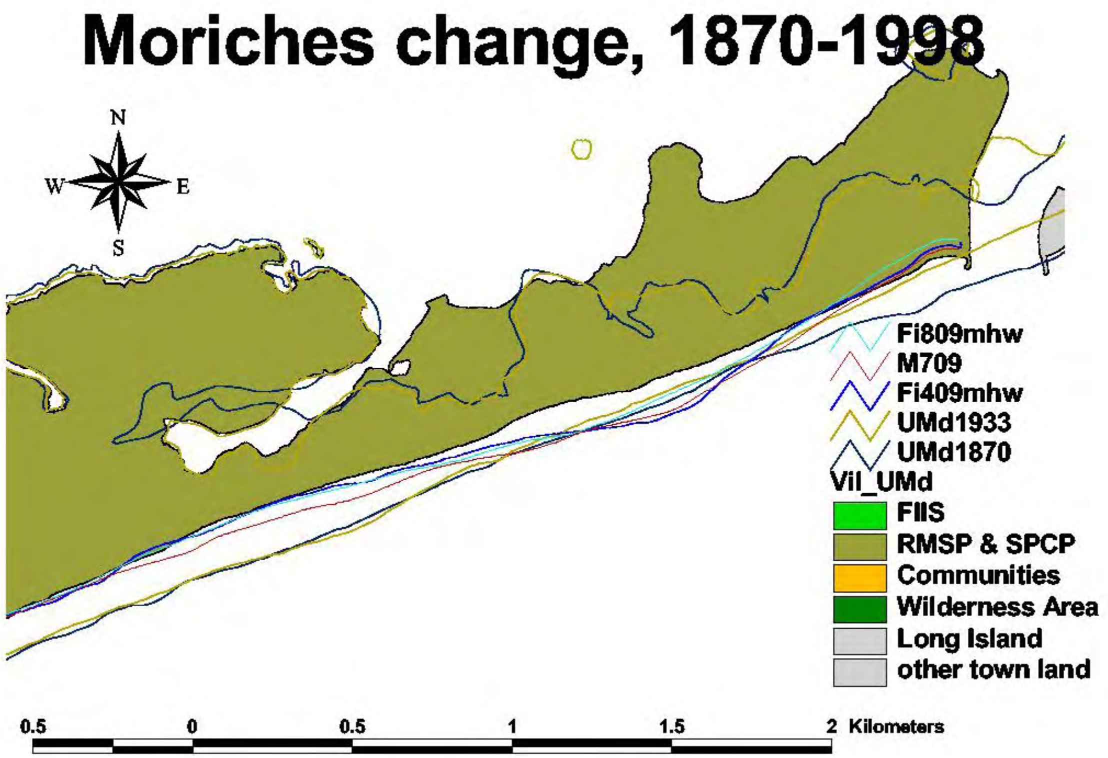


Figure 6. Shoreline changes adjacent to Moriches Inlet over the past century with added detail for the 1990s at the east end of Fire Island.

A GIS-based simple statistical summary of all qualifying temporal comparisons of Fire Island shoreline data is provided in Table 1. The long-term trend of change for the full barrier island is –0.4m/yr. for the 1870-1979 period. The density of data also shows, however, considerable variability at decadal, multi-year, inter-annual, and seasonal time scales. Perhaps more importantly, the table shows clearly that island-wide trends of change at multi-decadal, decadal, inter-annual and seasonal scales are overwhelmed by spatial variation, as measured by means and standard deviations respectively. Note that only 30 shoreline files are compared in Table 1. We have gathered more but several are problematic. Some of the files (*) have slightly less than one-half overlap but because their individual spatial coverage is substantial, their comparisons are included. An 1830 data set is not included as it is subjectively judged to be useful only for qualitative shoreline comparisons because its control point network was poorly resolved in today's coordinate system and one-quarter of the shoreline is missing in the west-central portion of the island (see fig. 4-3 in Leatherman and Allen, 1985). However, the 1830 data is useful for estimating directions and approximate magnitudes of change where changes are extreme, such as the westerly extension of Democrat Point and Fire Island Inlet. Files for shoreline positions on the 1938 and 1962 files are not considered to be quantifiably comparative to the other data sets because they were obtained within storm conditions of elevated water levels and wave runup and thus do not meet even subjective definitions of approaching the MHW target.

Table 1. Sequential change in 29 Fire Island shoreline surveys assembled through 1/99 (points # 1-993 is measured at 50m intervals east of the Democrat Pt. jetty).

Time interval	Mean, m	St. Deviation, m	Coverage (pt. #)
1870-1933	-29.5	67.2	103-993
1933-79	-14.1	58.6	24-993
1973-76	-6.3	19.3	1-993
1976-79	-12.9	15.9	1-993
1979-80	-20.7	14.1	1-993
1980-83	15.3	23.9	1-993
1983-84	9.3	21.5	1-993
1984-86	15.0	26.0	1-993
1986-8/93	-27.5	27.8	142-966
8/93-9/94	10.2	13.9	142-966
9/94-11/94	-14.7	7.1	174-993
11/94-4/95	6.8	16.3	174-795
4/95-6/95	-5.0	13.2	77-804
6/95-8/95	-7.5	12.5	173-993
8/95-9/95	0.6	10.0	1-829
9/95-1/96	6.2	17.7	1-435*
1/96-2/96	4.6	7.5	1-435*
2/96-6/96	14.5	15.0	259-993
6/96-8/96	1.0	10.1	259-993
8/96-9/96	-14.0	8.4	1-993
9/96-11/96	7.7	11.8	1-993
11/96-1/97	-9.7	10.0	1-993
1/97-5/97	13.2	10.3	1-993
5/97-9/97	2.2	9.3	1-993
9/97-1/98	-13.4	14.2	1-231, 665-993
1/98-4/98	5.6	17.6	1-213, 665-993
4/98-6/98	0.9	10.9	1-559
6/98-9/98	-10.3	8.7	1-560

The 1870 data set is believed to be sufficiently accurate and precise to be quantitatively compared, over long time spans, to more modern data sets. However it's full acceptance is hampered by a bayside offset of detailed marsh margins in the eastern portion of the island from more modern data. Unfortunately, this offset is nonlinear, ranging from 40 m to 17 m in the Wilderness Area, where testable by assuming reasonably stable marsh margins in very low energy environs (supported by the highly similar shapes in Fig. 5).

Leatherman (personal communication) suggests that this problem results from a focus on maximizing accuracy of the oceanside shoreline position instead of an overall or bayside emphasis. It may also be due to mapping error as this stage of Metric Mapping did not include control by the horizontal triangulation station of the C&GS. Nevertheless, any quantitative comparison must incorporate some caveat about potential error in shoreline position in 1870, well after Old Inlet had closed (by 1830) and the additional alongshore transport had accreted the eastern shoreline of Fire Island. The 1933 data files were digitized from high-accuracy US Coast & Geodetic Survey "T" sheets and the 1979 shoreline was photo-interpreted and rectified. Leatherman (1990) has discussed the metric mapping method, which forced root-mean-square solutions for the ground control points to <1.55m. One of the useful aspects of using GIS to manage the data is the ease of calculating areas of polygons to calculate areal changes: using an arbitrary baseline for examining the expansion of Democrat Pt. in 1870 from an area of ~1.5 million m^2, by 1933 the area was 3.1 million m^2 and in 1979 an area of 3.3million m^2. If this were to be supplemented by accurate bathymetric data, a decent long-term sediment budget could be calculated but excellent spatial resolution of hydrography at similar times is lacking. Even the area of increase in 1979 is inaccurate because spillover of the jetty had already started but was not mapped. All subsequent shoreline data were obtained by differentially correcting files from mobile GPS surveys as discussed in the methodology section.

Chapter 4. Results of spatial analysis of shoreline change.

Graphical Analysis. Figure 7 shows the island-wide, quantitative comparison of shorelines for 1870 and 1933 and it displays a pattern of variation at several spatial scales. This period characterizes natural change patterns in the 19th century prior to opening of Moriches Inlet and is thus physically and analytically meaningful in a system-wide comparison. Major erosion in the west is associated with a western migration of the positive sediment budget at Democrat Point, the balance of the western half of the island retreats about 25m but with substantial spatial variability, and the eastern half of the island is accretionary, on average but again the spatial variability. Loss of 100m of beach at the eastern boundary is directly attributable to the processes associated with the formation of Moriches Inlet.

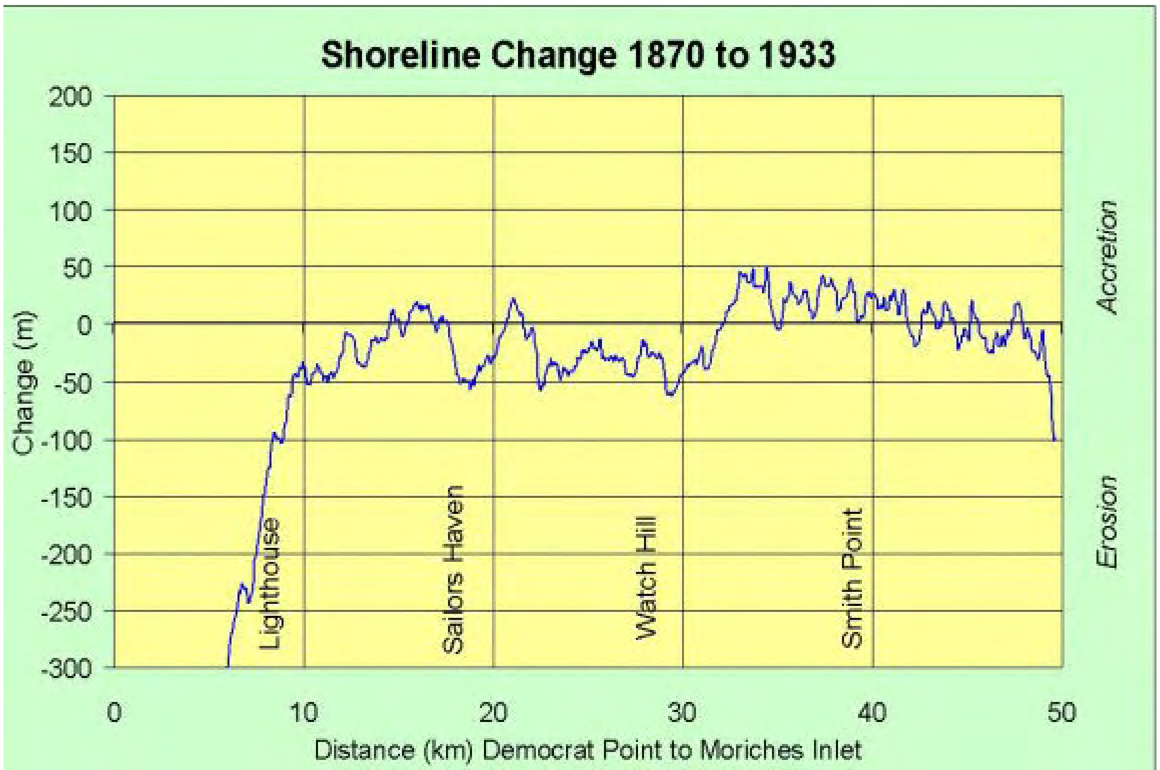


Figure 7. Shoreline changes calculated in ArcInfo for the 1870-1933 period. Four sites in the Seashore provide reference locations.

The interval of 1933-79 is instructive because it represents the period of opening of Moriches Inlet (1932) and the 1940 attempt to halt migration of the Democrat Point/Fire Island Inlet couplet. This pattern (Fig. 8) of shoreline change characterizes human-disturbed changed regime of the mid-20th century. Erosion in the east is associated with sediment starvation due to interception of alongshore transport by tidal forces at Moriches Inlet (see Section 3). Major accretion in the west is due to onshore sediment advection and interception of sediment by the Democrat Pt. jetty, long since filled and long ineffective in denying sediment shoaling into Fire Island Inlet. Again there is a westward migration of the zone of sediment surplus resulting in a deficit and erosion, spatially lagged. The central portion of the island is accretionary to stable but with wave-like variability at 5-10km intervals. The eastern portion of the island is quite erosional, likely due to the effects of sediment interception at Moriches Inlet leading to a sediment deficit extending over 15km downdrift.

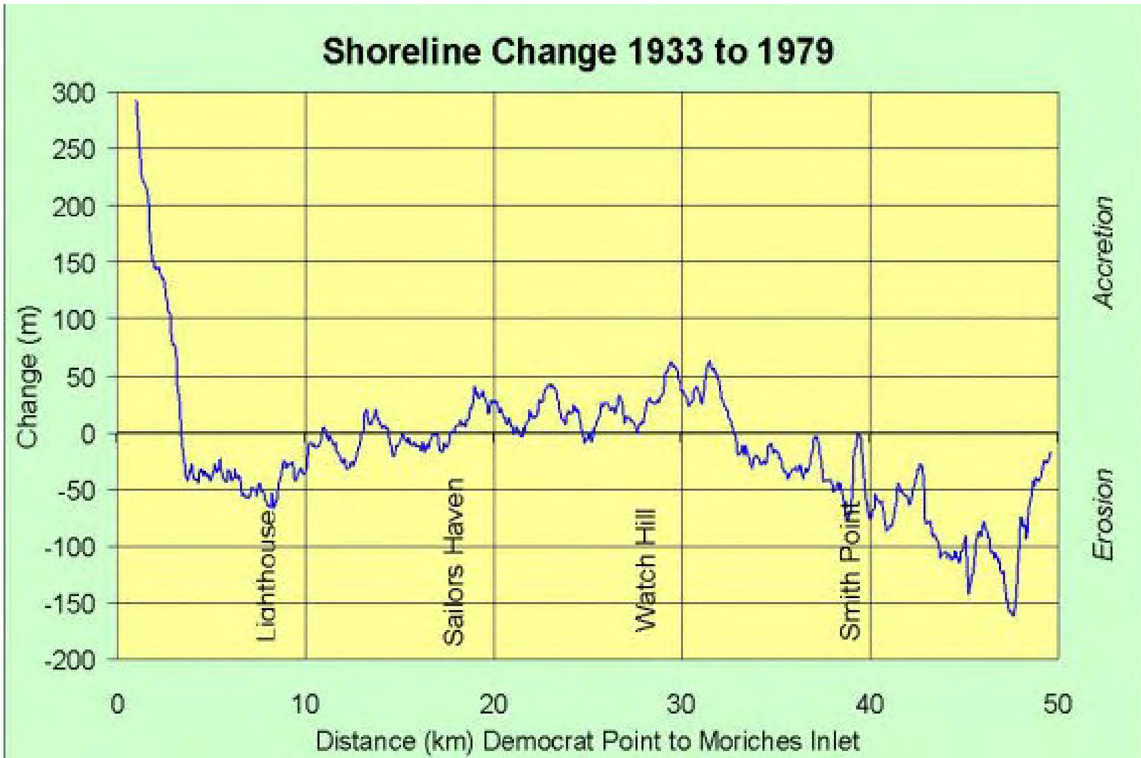


Figure 8. Shoreline change pattern during the mid-20th century along Fire Island depicting the sediment deficit-driven erosion in the east, net accretion in the center, and the melange of migratory depositional/erosional patterns accompanying the westward migration of Democrat Point/Fire Island Inlet after the construction of the inlet jetty.

A series of USACOE, NYD shorelines digitized via "soft photogrammetry" from aerial photographic surveys in the 1970s and 1980s provide a higher frequency, but still at annual to multi-annual comparisons and have unknown errors associated with them. They meet COE standards for shoreline comparison as they have been used in several projects but what these standards are is unknown because no metadata was supplied. Although specifics of quality control is absent, these data sets are very useful for identifying conditions overlapping the historical Metric Mapping and (below) GPS data sets and providing improved temporal resolution of key developments. For example, Figure 9 indicates that between 1979 and 1986, the shoreline at Fire Island accreted over most of its length (a maximum of 100m near Long Cove, about 4km east of Watch Hill, with a retreat at both ends, especially in the east. The latter is interpreted as being due to a continuing sediment deficit because of sediment interception at Moriches Inlet. Again, high frequency variability dominates along the island and there are also local sites of extensive erosion in the Wilderness Area, just east of Watch Hill and just west of Smith Point.

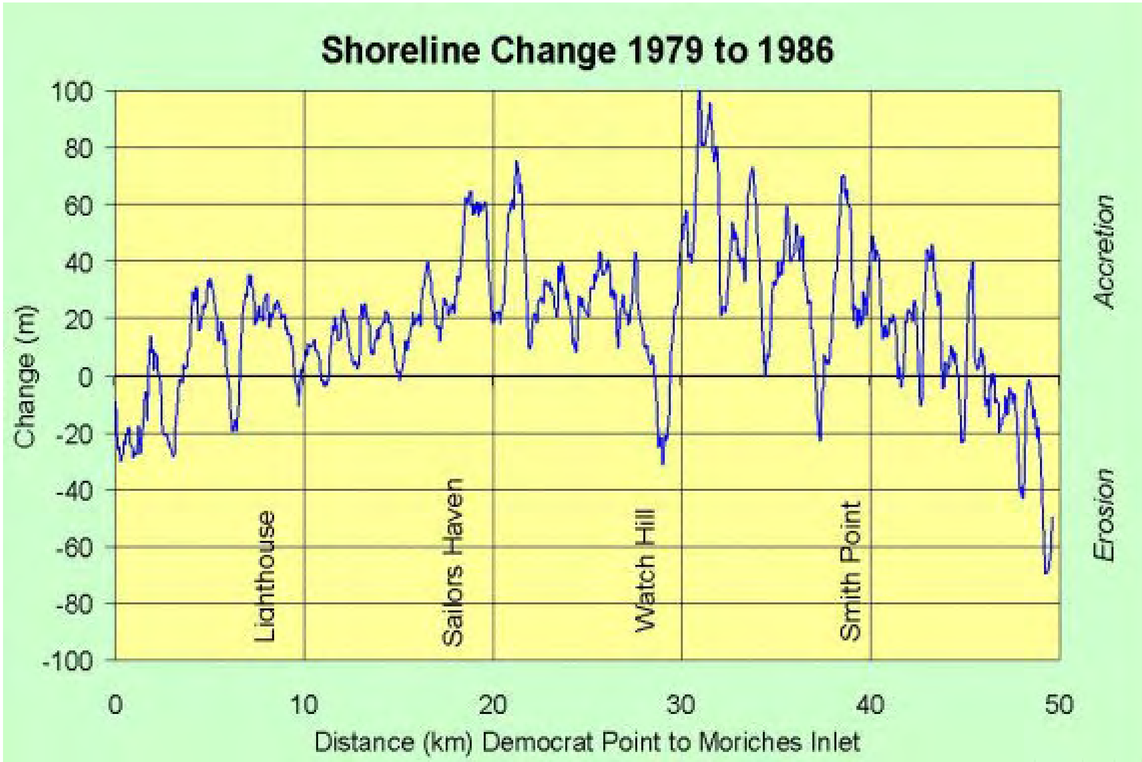


Figure 9. Shoreline changes along Fire Island for the interval of 1979-86. The erosion at the west end related to sediment deficit from the trapping effects of Moriches Inlet is evident but there is large spatial variability in any inferred trend from the COE/NYD aerial photo data.

Highly accurate GPS surveys have been obtained since 1993 for Fire Island and are used to update both the historical shoreline mapping data as well as to provide another baseline comparison for the COE data. Because the GPS data provide post-storm conditions to the other two data sets, they provide much of the foundation for this study of shoreline change and the threat of breaching, given both trends and variance over time. Fig. 10 compares the changes between 1976 and 1994 and the pattern is much different from the Corps's shoreline update. This figure provides information upon decadal scale changes after the storm impacts. There are three items of high interest, which are related to different geological processes. In the western half of the island change is dominated by a series of very large amplitude waves, which Schwab *et al.*, 2000 speculate is related to offshore bathymetry and onshore sediment flux from the inner shelf. East of the accretion at Watch Hill there is a negative slope to the change rate culminating in substantial erosion in Smith Point County Park. This might be related to the spatially mobile effect of past sediment starvation from Moriches Inlet processes. Two kilometers west of Moriches Inlet there is a major (120m) accretion of the shore and the present dune is now where the shoreline was in 1979. This may be related to a recent equilibration of inlet processes and natural sediment bypassing subsequent to 1986, when no growth was noted, and will be discussed in more detail later in this report.

The higher frequency GPS surveys also allow for the temporal elucidation of persistence and migration rates of localized erosional impacts, as opposed to shoreline re-entrants

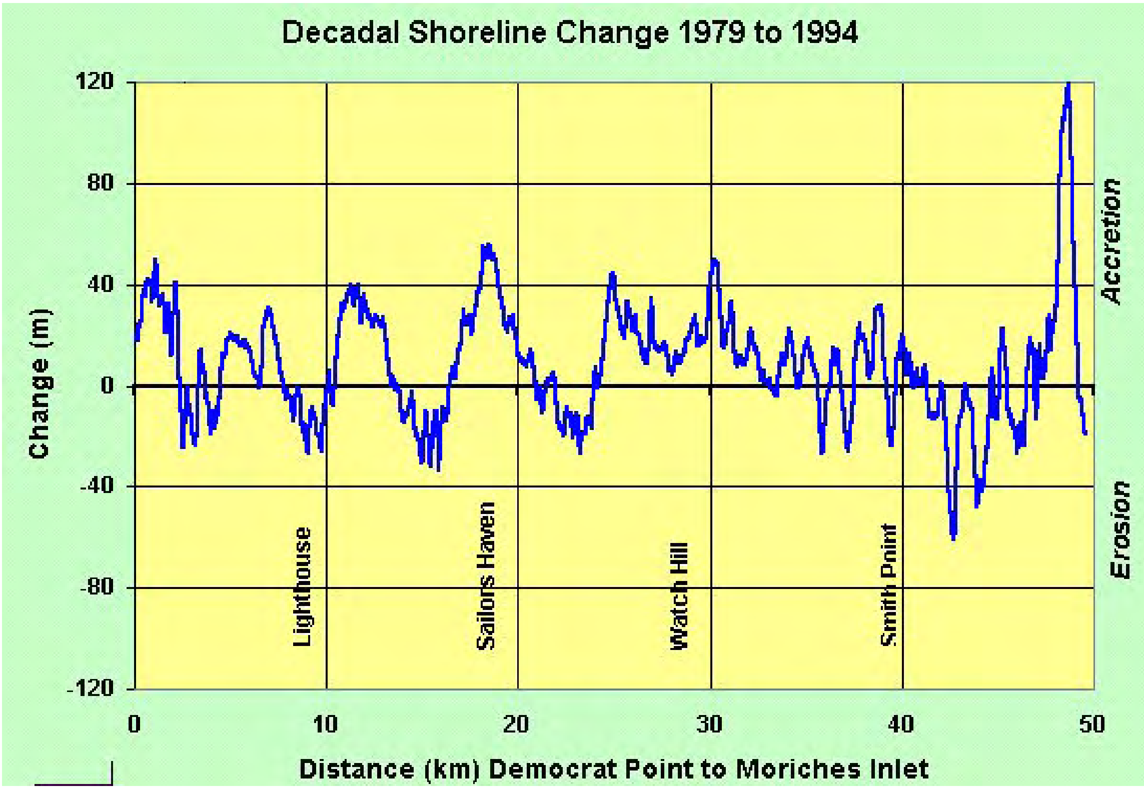


Figure 10. Decadal scale, GPS measured shoreline change after the series of storms in the early 1990's. The east is dominated by large "waves" of erosion/accretion and accretion (inlet bypassing?) at km 48t.

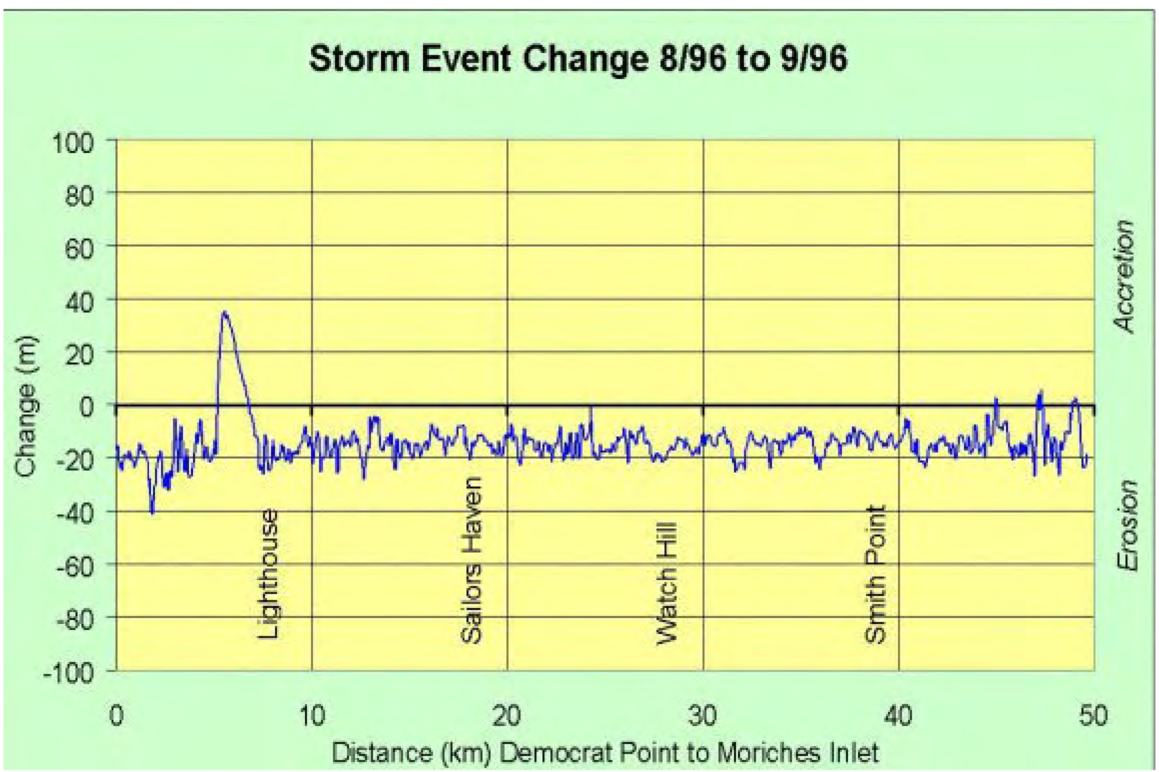


Figure 11. GPS-measured storm event scale of shoreline change at Fire Island during the offshore passage of Hurricane Edouard in 1996. The accretionary spike in Robert Moses State was induced by emergency beach fill.

poorly resolved at longer time scales. This allows for some analysis of spatial dimensions and persistence as well as of temporal dimensions for these so-called "hotspots" of shoreline change, with the main interest being in the erosional aspects. Inter-annual variability is high because late summer storms do pass offshore; seasonal variability is also high but dependent upon storm frequency and magnitude in the winter energetics. Individual storm impacts can be measured but Fig. 11, which shows the effects of the offshore passage of Hurricane Edouard in early September 1996, suggests that the spatial variability was relative low about the mean change. Neither long periodicities of change nor intense "hotspots" are noted in this storm impact upon the shoreline position.

A spatial-temporal integration and graphical portrait of the high frequency spatial changes during the 1990's, relative to the 1979 baseline position, is given in Fig. 12.

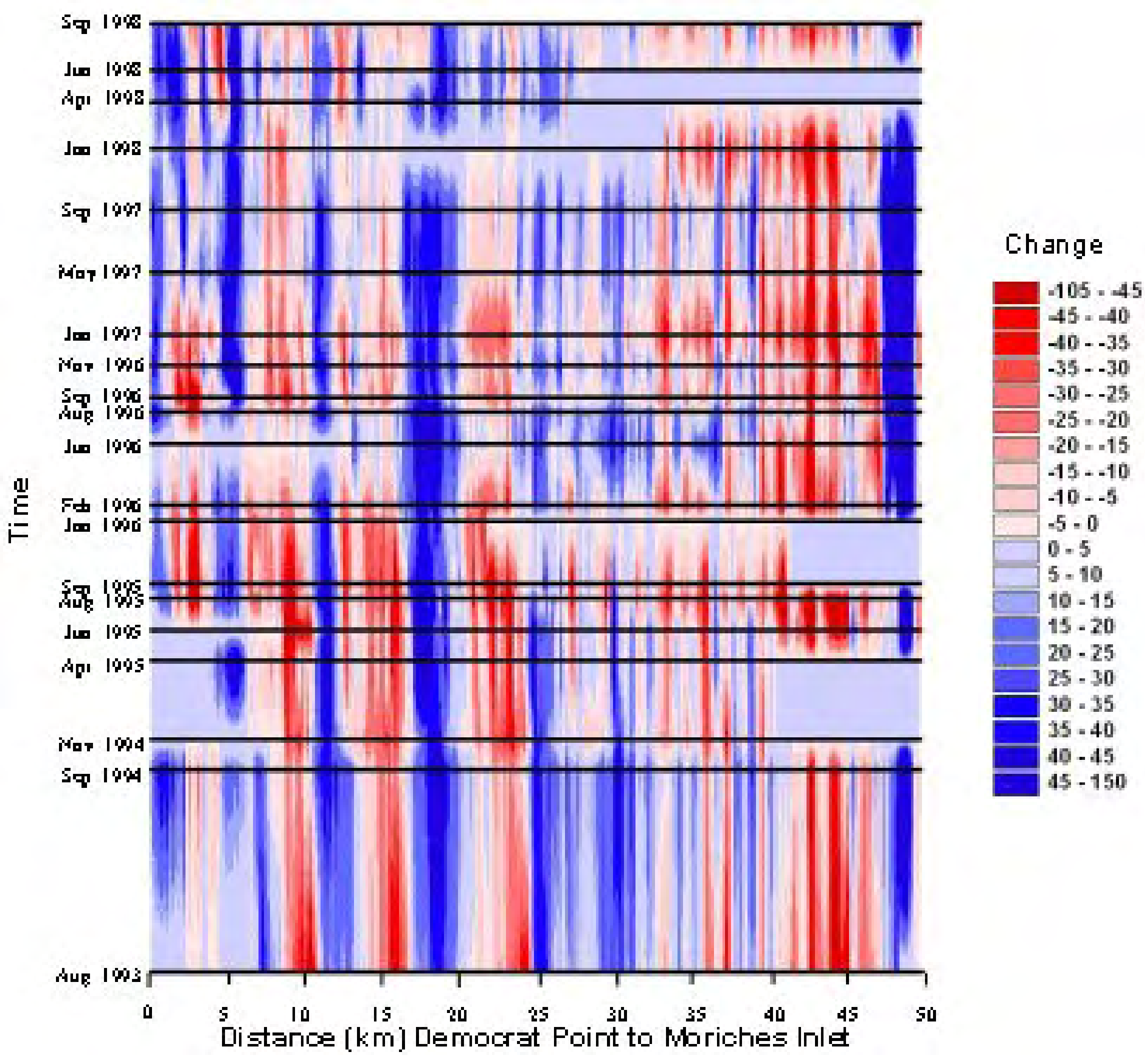


Figure 12. Timestack of shoreline change measured by GPA field surveys at Fire Island during the 1990s, as created by the TIN routine in ArcInfo. Spatial/temporal stability is substantial indicated but the broad, light blue area contain no data, *e.g.* km 40-50 in Nov 1994-Apr 1993.

Gaps in the database are visually apparent, such as in the east between April and June 1998. The western “waves” of accretion and erosion so apparent on Fig. 10 are shown to persist. Similarly, the more localized areas of accretion and erosion in the east tend to persist. Both suggest that offshore bathymetry is controlling the shoreline processes because of this stability of pattern but the larger dimensions in the west suggest a relationship with the oblique offshore ridges whereas the more local disturbance scale in the east suggests a relationship with the more mobile nearshore bar morphology. Both antecedent geology and the overall sediment supply are related to the continuity of these erosion/accretion cells. The persistence of accretion at Great Gun Beach is apparent and it widens, again suggesting effective bypassing by both natural and anthropogenic processes. There is some temporal intermittence in the Wilderness area at km 29 and 36 and at the Smith Point pavilion, near km 40. A burst of erosion at km 3 in 1995 and 1996 changes to accretion by May 1997 and this sediment surplus extends westward in the next year. In general, the scale of the graphic does not allow for tracking of migration of erosional cusps such as in Fig. 3. Beach nourishment also does not stand out as being substantial and persistent—the exception of a substantially wider accumulation zone at km 48—probably because most fill projects in 1993, 1994, and 1997 were also scraped to rebuild dunes for greater flood and wave protection in the communities.

Statistical analysis. The matrix of shoreline change data at 50m intervals, by time sampling, can also be addressed statistically. Simple statistics of change for all surveys since the Metric Mapping data of 1870 are graphically portrayed in Fig. 13 and the mean rate of change line highlights the 6 km-long wave forms of alternating accretion and erosion in the west, high frequency variability in the east which is dominated by erosion, and major accretion downdrift of Moriches Inlet. The plot of the standard deviation is relatively flat at 20-25m over the century-plus data set and indicates fairly homogenous shoreline variability. However there are three significant peaks approaching 70m, two in the west at Robert Moses State Park and one in the east. These are associated with the extreme shoreline changes in the historical record shown earlier: the peak at km 2 is due to interception of sediment by the Democrat Point jetty since 1940, the peak at km 6 indicates the large amount of erosion following migration of Democrat Point between 1870 and 1933, and the peak at 48 km represents the rapid accretion at Great Gun Beach sometime between 1986 and 1994.

Although the simple statistics describing change in temporal comparisons (Table 1) of the columns of the matrix of change, or the alongshore spatial distribution (Fig. 13) of the row data are valuable, more robust and objective statistical tools are available to analyze the data. Principal component analysis (PCA) is basically the same as empirical eigenfunction analysis with the only difference being that PCA is restricted to a covariance or Pearson correlation matrix. Empirical eigenfunction analysis has been used

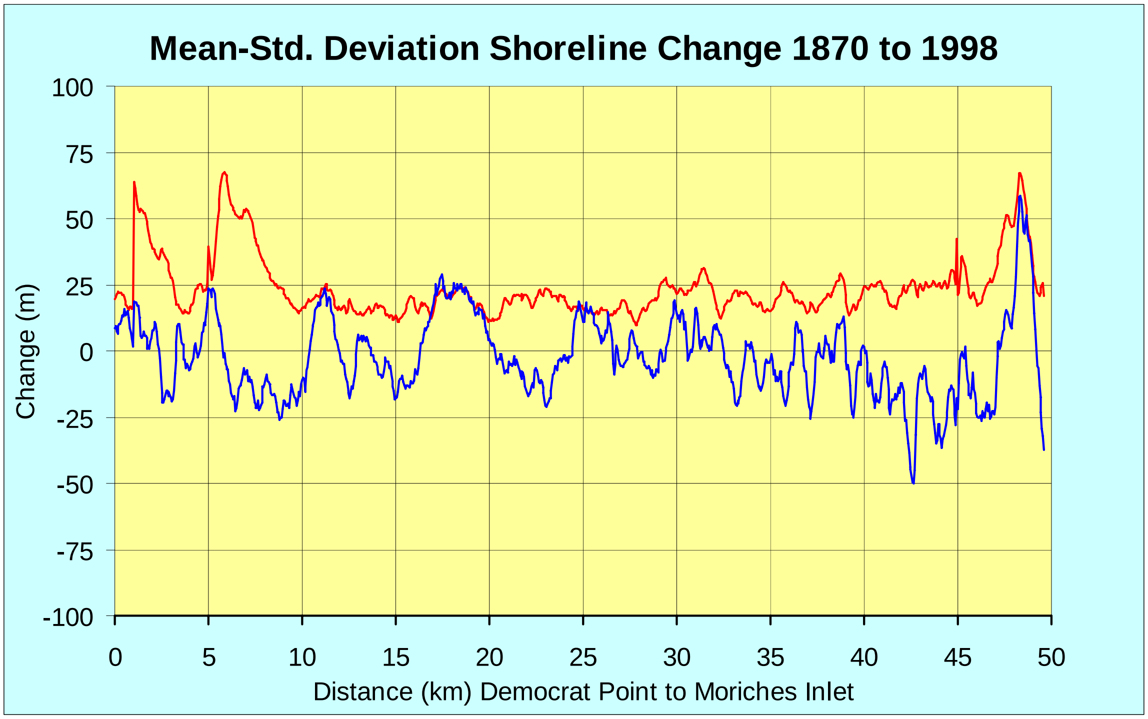


Figure 13. Simple summary statistics of shoreline change at Fire Island for the full data set at each of the 993 measurement locations. The mean change is given in blue; the standard deviation of change is given in red.

by several to investigate changes in beach profile networks and offshore bathymetry. Wijnberg and Terwindt (1995) provide a detailed review of past work and a unique application to a very large data set. PCA fits our matrix of MHW shoreline change data and is easily run in available statistical packages such as SAS. Our study design uses three different strategies to evaluate the matrix structure: 1) *maximum spatial coverage* which deletes the incomplete shorelines (15 surveys x points 0-993, n = 14,895, 2) *maximum temporal coverage* which ignores areas adjacent to inlets due to incomplete coverage or inlet migration (22 surveys x points 174-829, n = 13,684), and 3) *maximum matrix size* (19 surveys x points 143-966, n = 15,656). Effectively this is a sensitivity test but also of different hypotheses about the strength of explanation within the matrix despite the relatively small difference in numbers of elements. The 1870 data was not analyzed because of its restrictive scale and the extreme migration of Democrat Point with Fire Island Inlet, 1933 onward was solved for maximum temporal coverage. The correlation matrices in all cases were more highly loaded for the GPS survey dates (1993 and later), which is not surprising given their smaller intervals.

Although the SAS code solved for the top eight principle components (or eigenvalues), Table 2 presents the largest three eigenvalues of the correlation matrix describing the principal components of each matrix solution and it is clear that spatial maximization (MSS) by its top three is most efficient, followed by matrix size (MMS) and temporal coverage (MTS) respectively. However, the first component tends to represent something similar to a central tendency and the order is reversed for it. But the physical interpretation of what these components represent in reality at Fire Island is problematic.

Table 2. Three largest principal components, eigenvalues, and cumulative proportion of contribution to the three matrix optimization solutions by PCA.

Principal Component	Eigenvalue	Cumulative ratio
MSS1	8.180	0.545
MSS2	1.839	0.668
MSS3	1.249	0.751
MTS1	10.701	0.486
MTS2	1.935	0.574
MTS3	1.754	0.654
MMS1	8.653	0.455
MMS2	2.378	0.581
MMS3	1.481	0.659

Given the previous historical and island-wide database, we attempt to understand the significance of only the top two components by offering two different but spatially oriented approaches.

The first expression is a bi-polar plot of the eigenvectors of the component plotted against each other and color-coded for some spatial identity as to where the outliers are on Fire Island. In Fig. 14 it is clear that there is a large cloud of co-loadings at the center but that significant differences between components one and two exist at the east end, points 800-993. Confusingly, this area displays values on both the negative and positive ends of both components.

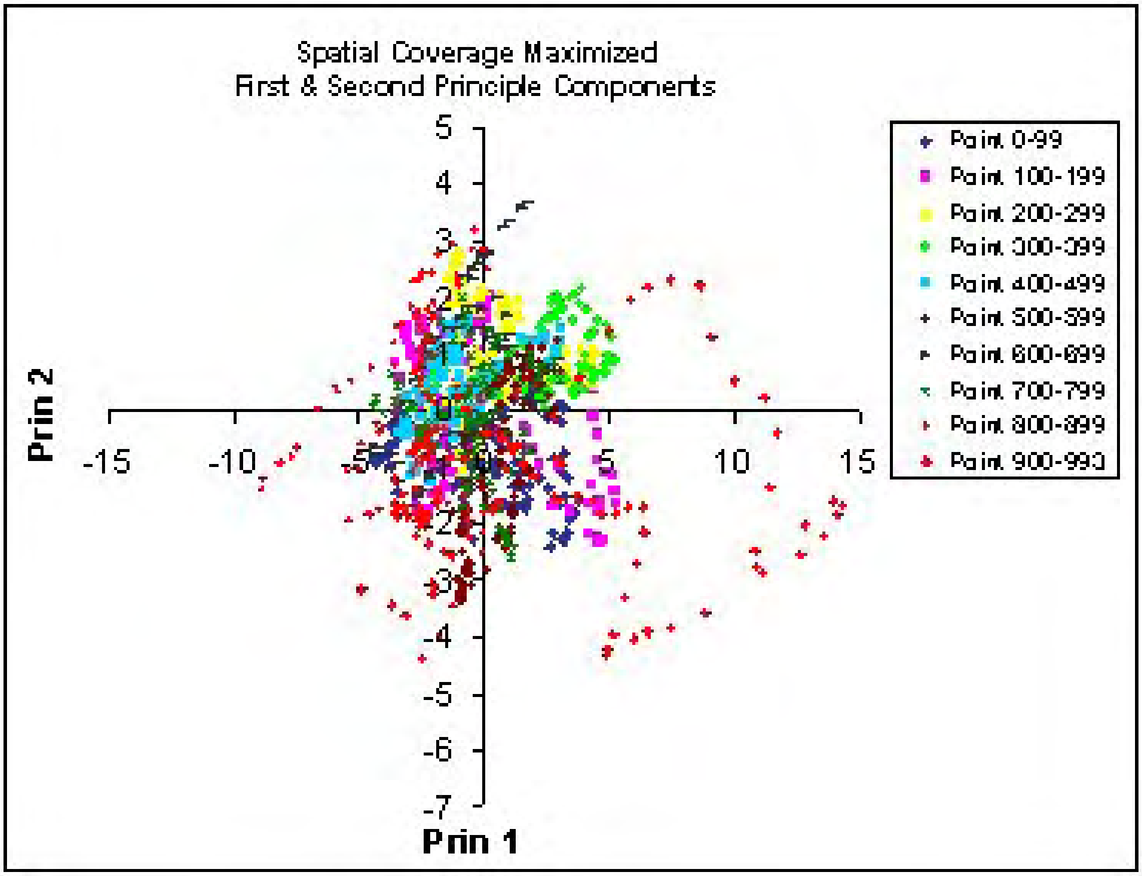


Figure 14. Bipolar plot of eigenvectors for the first two principal components of maximum spatial coverage PCA solution. The largest values are for the first principal component and it is oriented horizontally, as with the identifier in the graphic. The spatial coding begins at the western end of the island and increases towards Moriches Inlet, to indicate alongshore position of where outliers occur.

A bivariate visualization (Fig. 15) of eigenvector values displayed against the alongshore distance at Fire Island adds much signal to the confusion of Fig. 14. The first component is shown to essentially replicate the 1979-94 changes as dominating the variability in the matrix when analyzed inlet-to-inlet: western "waves" of change and eastern erosion except for the accretionary spike downdrift of Moriches Inlet. Component two is more difficult to interpret in that it seems to be largely in phase (spatially) with component one but with an antinodal relationship, thus seems to indicate the areas of higher shoreline variability. If the past patterns persist, these are also the locales of higher risk of dune breaching and island breaching where the island is narrow or there is sufficient imbalance to the tidally forced hydraulic head.

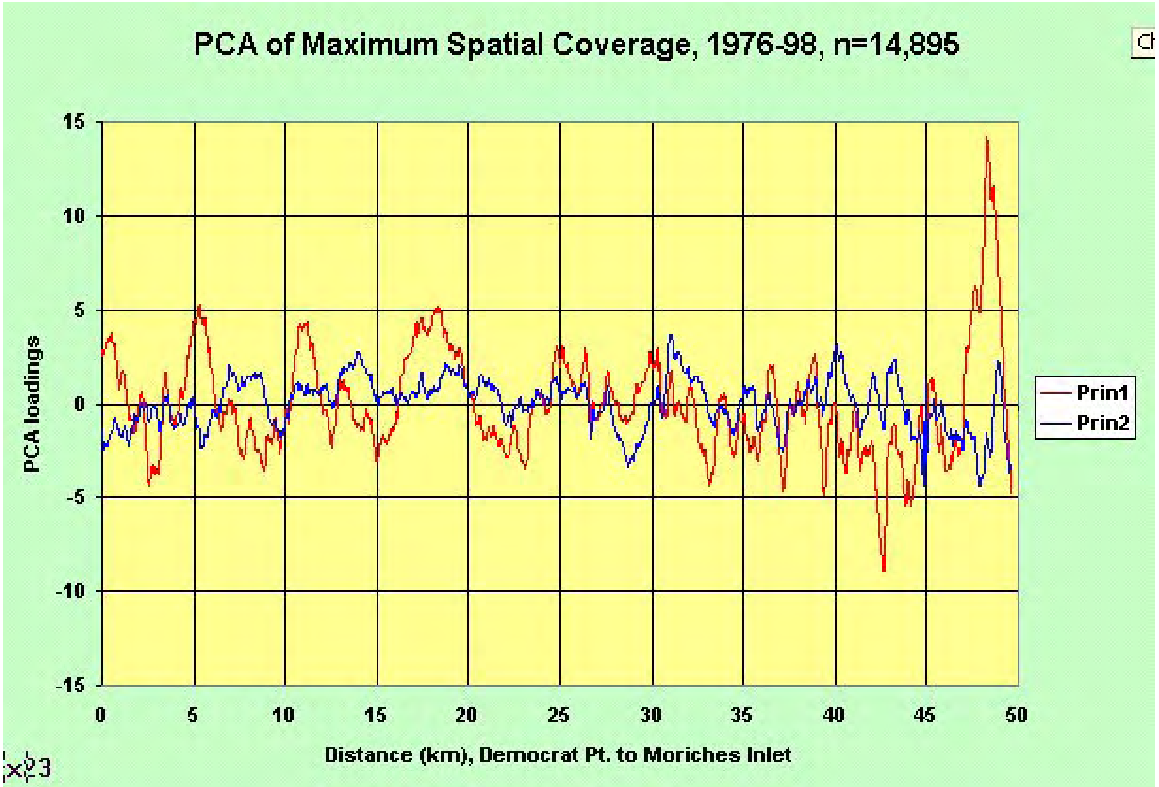


Figure 15. PCA of the spatially maximized matrix with the top two components plotted against alongshore distance at Fire Island.

By solving for a maximized temporal scale, the bipolar Fig. 16 does differ with the patterns shown in Fig. 14 because the eastern end is excluded. Now the extreme eigenvectors are located in the west at 174-299 also in the east at points 600-799. Their values are in opposition for component two but both are spread longitudinally along positive and negative values of component one. Again, what is meant by the spatial responses of shoreline change at Fire Island is not clear from this plot but the statistical importance of these localities, as standing out from the rest of the island response is clear. The bivariate plot in Fig. 17 of spatial variability along Fire Island possesses more geologically interpretable information. In this case, the western end, especially points 174-299 and the west-central portions of the island dominate oppositely on component two but are spread along component one on both positive and negative values.

The third maximization, of matrix size thus number of elements, is more similar to the bipolar depiction for spatial maximization. Although the inlet margins are excluded, the eastern response is visually dominant in Fig. 18. There appears to be some other segregational groupings in the inner and dense mass of eigenvectors but this is difficult to interpret other than being the difference in shoreline response between eastern and western Fire Island, with the former retreating more rapidly but with more spatial variability and randomness. The latter is better specified spatially and temporally only when compared to the other two models conjunctively, which is not surprising. Each of the other two models gives more detailed explanation within their own limits.

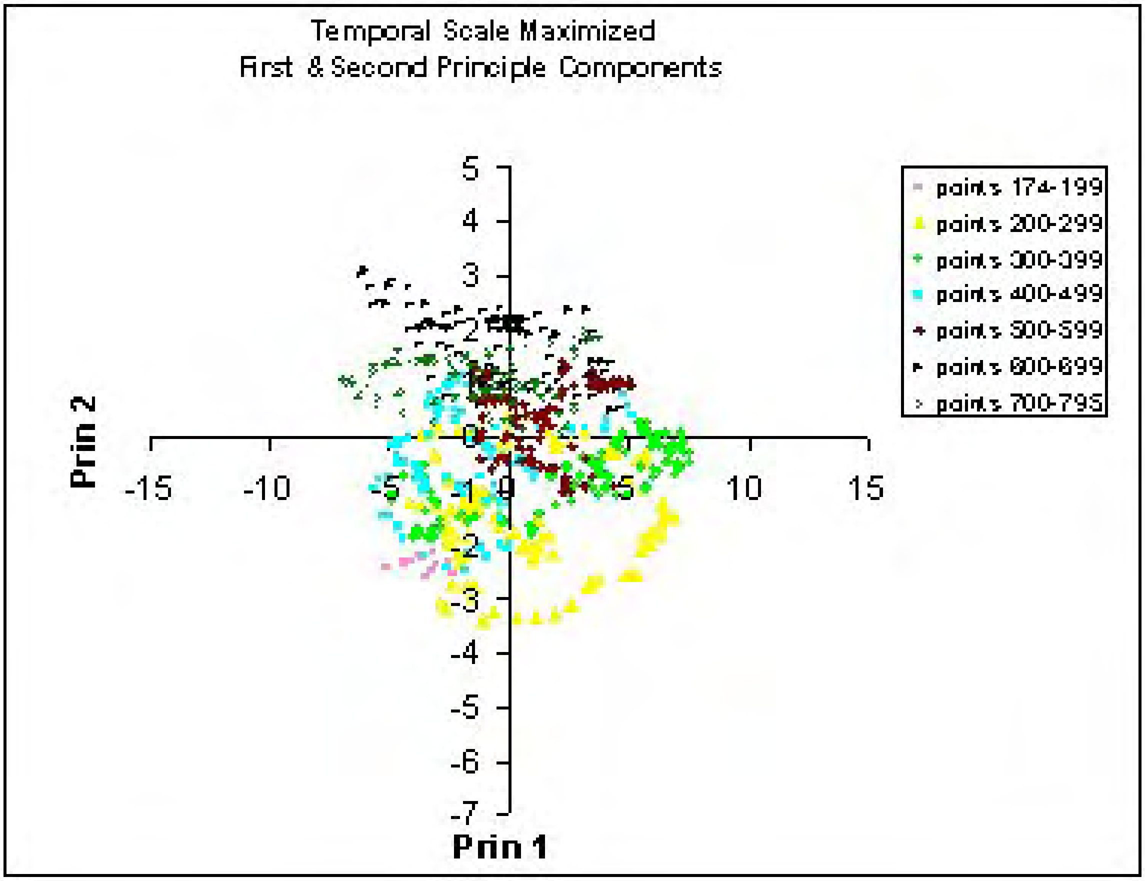


Figure 16. Bipolar plot of the first two principal components of a matrix sampled for maximum temporal resolution.

The alongshore, spatial variability in the eigenvectors for the maximum matrix size solution are given in Fig. 19 and it provides further evidence for understanding the dominance of the decadal scale pattern of shoreline change at Fire Island but does not provide anything new. The distinct differences of shoreline behavior and barrier island dynamics between the western and eastern ends of Fire Island that were first subjectively identified by Leatherman and Allen (1985), are given statistical power of the existence and persistence.

What is clear is that the spatial similarity of solution of the shoreline change matrix, over various elements of space and time, show a pattern that has predictable erosion and accretion locations. If the past trends continue, as argued by the physical controls of the oblique offshore ridges upon both cross-shore sediment transport relations with the shoreline as well as wave refraction concentrations during large storms, there are locations at greater risk of erosion than others. Specifically these would include sites (measured from the Democrat Pt. jetty) near km 3 in Robert Moses State Park, km 8 near Kismet, km 15 near Point O'Woods, km 23 near Fire Island Pines, and km 43 in Smith Pt. County Park. Each of these locations is much wider than overwash has been able to penetrate in the data of Leatherman & Allen (1985) and several have high interior elevations also suggesting that physical overwash to the bay has a low probability. If these patterns of shoreline change on Fire Island are controlled by the offshore ridges, the

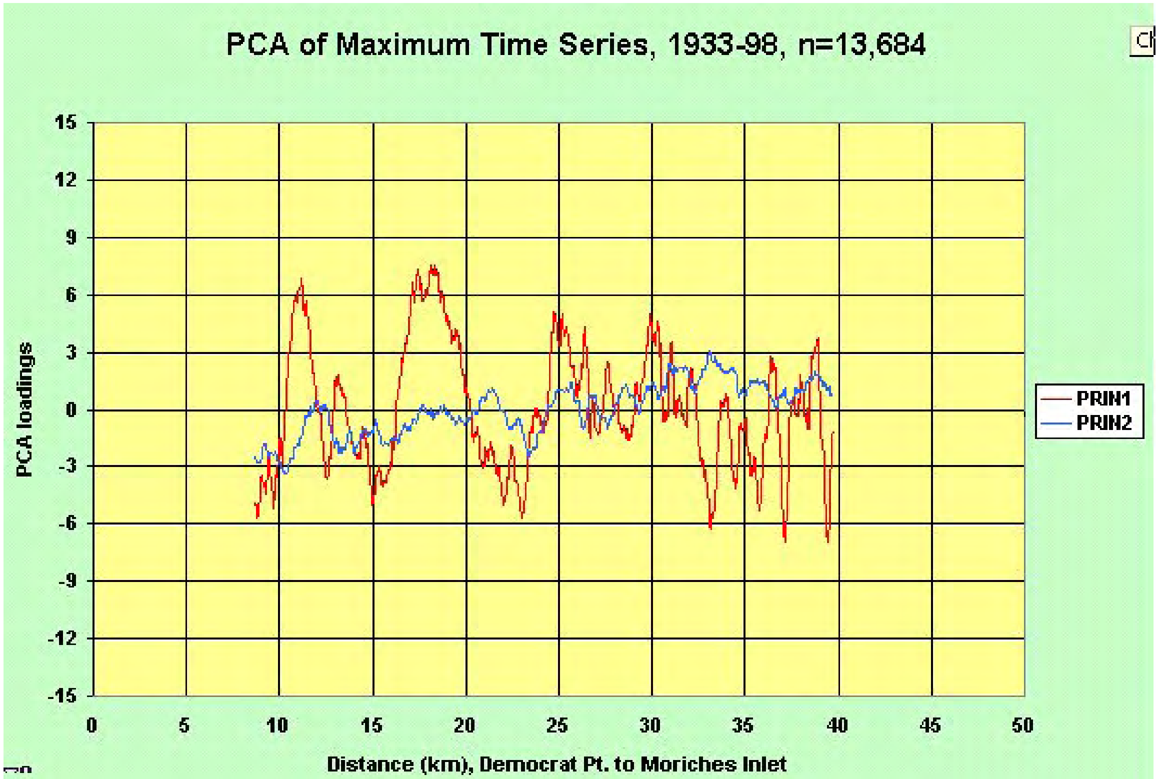


Figure 17. The first two principal components of the maximum time series coverage of the change matrix plotted against alongshore distance at Fire Island.

next question is, are the ridges stable or migrating in terms of continuing the past response pattern? Westward migration would change the pattern of shoreline response in terms of naming communities at risk but the physical pattern would be retained albeit with an alongshore phase shift with similar morphologic response to the “waxing and waning” pattern of dune response to migrating shoreline undulations as interpreted by Psuty and Allen (1993) for a specific site. The appropriate time-series data to verify offshore controls on alongshore migration are yet unavilable.

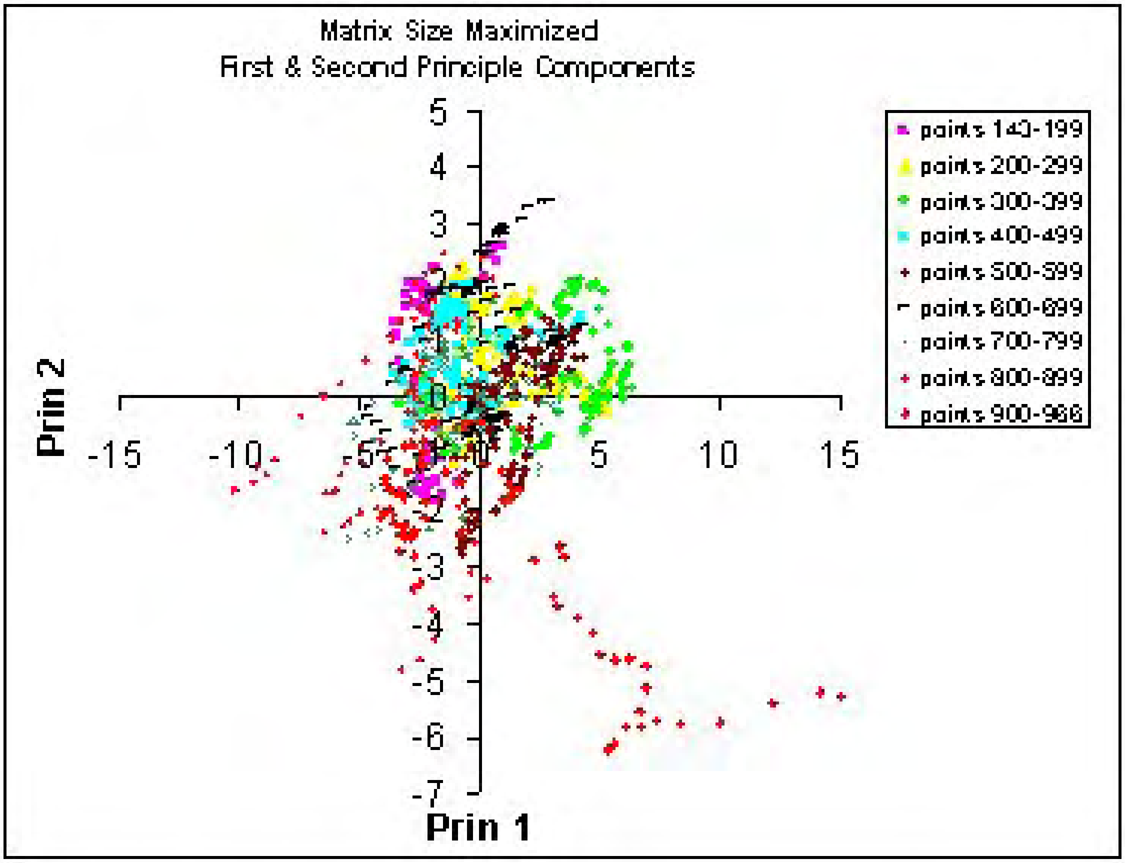


Figure 18. Bipolar plot of the first two eigenvector values in the maximum matrix sized solution.

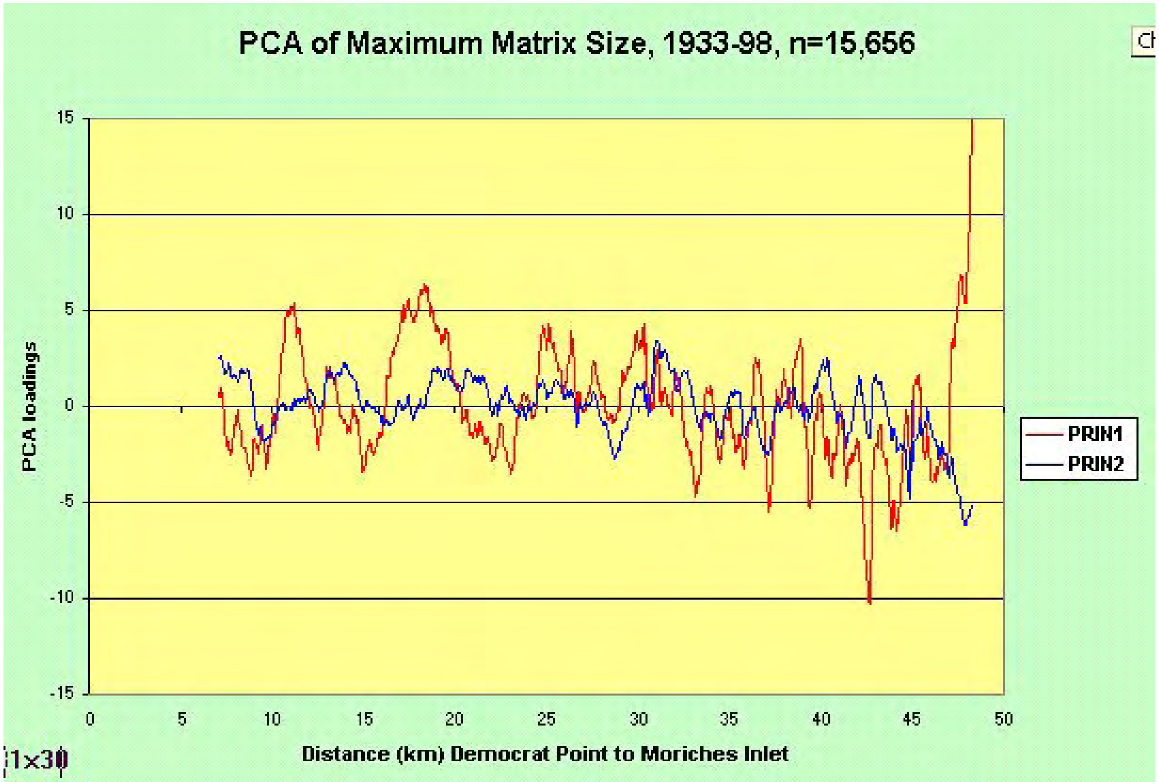


Figure 19. The top two principal components of the PCA solution to maximizing matrix size, graphed against alongshore distance at Fire Island.

Chapter 5. Recent dune changes.

Dune changes are a more conservative estimator of barrier island behavior than are shoreline changes because these landforms are less dynamic in the short-term and their change directly impacts upland development. Even beach strollers use visual recognition of dune forms to locate themselves. Psuty and Allen (1993) provide a multi-scale, dynamically based model of spatial change in the dune system at Fire Island for 1976 to 1992. Their statistical analysis of harmonics in dune crestline changes between 1976 and 1992 indicated a nested hierarchy of response with alongshore periodicities related to coastal geology and processes ranging along length scales of tens of km to hundreds of meters, and with stochastic processes involved at even smaller dimensions. The processes and linkages to the typical variations of nearshore morphology (Allen & Psuty, 1987) are unusual, if not unique, in terms of apparent associations between nearshore/shoreline/dune crestline behavior. Human interactions confuse this somewhat but the signal does seem to overcome the noise because of the small scales of human activity in the cross-shore dimension. Alongshore bias is, however, much different in temporal scales and human effects because inlet dynamics dominated. Beaches recover quickly but the response of dune systems is more problematic in that dune scarps resulting from even huge storms may recover but where decimated, their replacements (if any) are displaced. Whether there is a geologically interpretable scarp in front of a recovering dune system or a major loss of high dunes leading to cross-island overwash in common storms is critical for management in terms of access to protect public safety and for historical recreational use. Obviously, both private and public structures may be at risk also to dune loss and island breaching in storms. Again, Schwab *et al.*, (2000) add understanding and hypotheses to the spatial variability of coastal change along Fire Island, especially when large waves drive shoreline change at decadal levels of either process re-occurrence or at a similar temporal scale of response.

A subjective comparison of topographic maps prepared for the COE/NYD from aerial photography in December 1979 and April 1995 reveals major changes in the dune morphology at Fire Island. Many dunes have suffered erosion of their oceanside and have lower crest elevations. At one example, a dune fronting Old Inlet has narrowed and its dune crest elevation decreased from 9.7m to 4.6m. These values are relevant to a normal elevation for the foreshore berm crest and backbeach elevations of approximately 3m, resulting from deposition by wave runup during “normal” storm conditions. Backbarrier elevations are even lower and narrowing of the foredune brings these elevations closer to the shore and increases the risk of dune breaching. Although breaching of the foredune has occurred at only a few locations in the past few decades, it is a threat to inland flooding and can lower the barrier to where it could breach in a very large storm. On the other hand, overwash also provides sediment that can lead to vertical accretion of the island and, if totally cross-island, can lead to bayside accretion. Although there are several locations in Fire Island where overwash has taken place in the past decade (near the Lighthouse and several sites in Smith Pt. County Park are examples), the only area that has been large in area and contains cross-island transport is at Old Inlet. It has been inactive in recent years and has largely revegetated. A basic question of dune erosion is whether it is persistent or reversible in the natural environment. Dune reconstruction in form and volume, if not function, is certainly possible by mechanical means such as beach scraping (whether the sand is derived from either a natural beach accretion of from a nourished beach). However, if the locality is retreating faster than its surroundings, these projects possess a short period of survival. Many localities in the communities have rebuilt their dunes by beach scraping and sand fencing to encourage the regrowth of dune faces via the natural process of aeolian deposition has been used in all areas of the island (federal, state, county, and local).

The dune crestline position for the developed area between Kismet (the westernmost community) and Davis Park (the easternmost one) has been interpreted from aerial photographic surveys in 1976, 1981, 1986, and 1992 in support of the Dune District Management plan for the Seashore. Total change in this timeframe is shown in Fig. 20, using the same format as for shoreline change to place dune changes in a similar context. The most notable aspect is a correspondence to the decadal pattern change in shoreline position (statistically reinforced by the PCA) of wave-like changes. The sites (km 11, 16, and 22) of major retreat of the dune crestline fit the same spatial pattern. The magnitude of crestline retreat is remarkable in these locales, 20 to 40m. Although the beach can recover rapidly due to incident wave processes, seaward advance of the crestline is less common. In our experience, the *face* of the dune may be rebuilt by natural processes (at several locations on Fire Island it was possible to see a dune scarp dating from the March 1962 storm, perhaps the largest in recent history, but fronted by a lower incipient vegetated dune. To our knowledge, dune *crestline* advancement at Fire Island has been accomplished only by either mechanical rebuilding or by sand fencing.

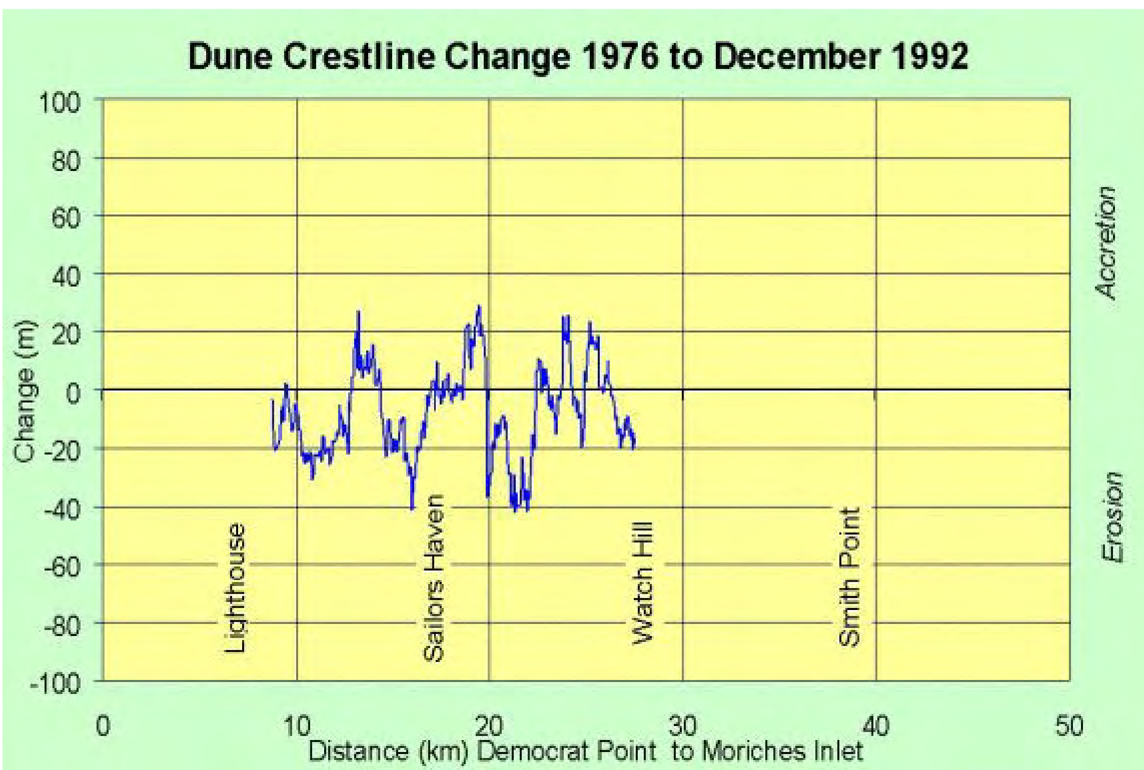


Figure 20. Cumulative change in dune crestline position in the community-dominated area of Fire Island as mapped for the Dune District program. The positive advances result from anthropogenic activity such as beach/dune fill, beach scraping, and dune fencing in the communities.

Because the last funded update of the Dune District crestline monitoring project was done from aerial photography conducted in late November 1992, it became moot within weeks due to the December 10-14 storm effects. We have used COE/NYD aerial photography from late December as a source to remap the crestline in this area and the results are depicted in Fig. 21. It is clear that the sites of major retreat, as documented in the long-term envelope of crestline change, are largely due to the impacts of this single event. The correspondence in spatial pattern is essentially perfect but the magnitude of change is less, peak losses of about 20m. The contribution of this storm alone to the pattern of dune crestline change is major and interesting because its long duration, and a peak storm surge equivalent to a 20-25 year storm recurrence probability, based on tide data analysis for the Sandy Hook tide gage, suggests that there is a decadal level of association of process and morphology response in the area. Typically, annual storms do not drive dune changes of large magnitudes although local dune scarping may occur.

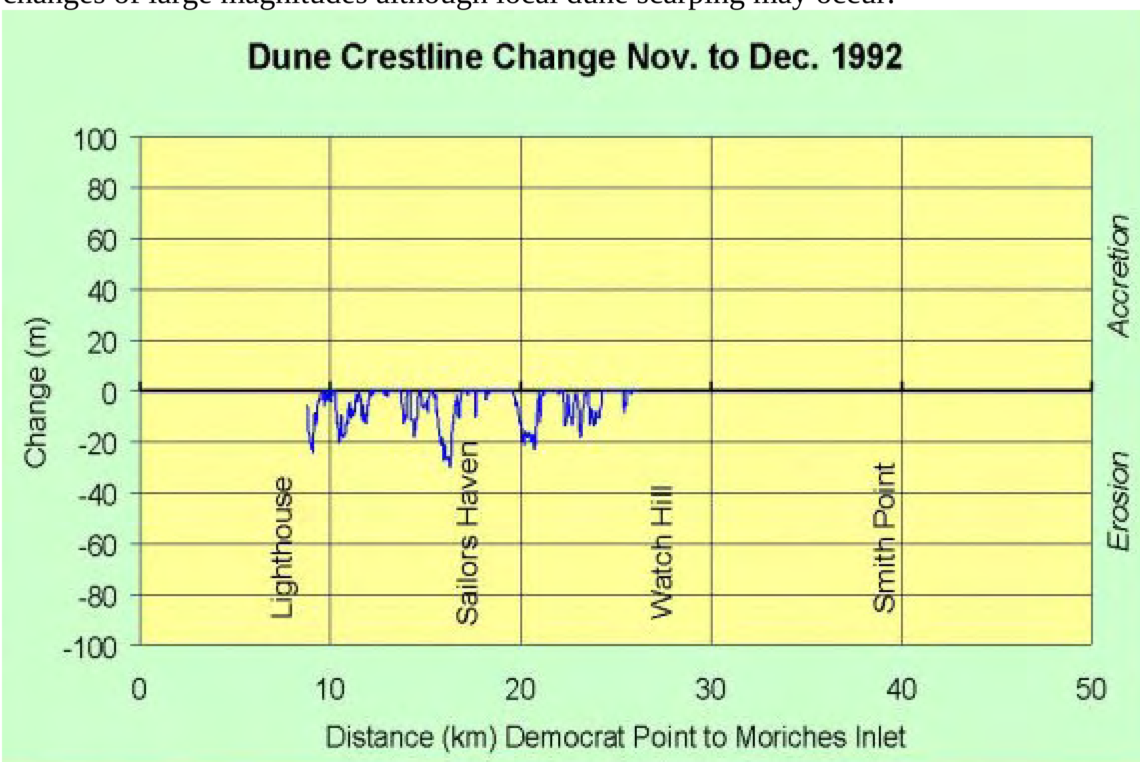


Figure 21. Dune crestline change between November and December 1992 as digitized from interpreted aerial stereo-photography. Again the same graphic scales are used to place the change into the long-term dune change reference and for comparison to shoreline change dimensions.

Spectral analysis of the storm response pattern of dune change (Fig. 22) shows that a significant pattern exists at about a 3.6 km interval in the data of Fig. 21. No other frequencies are suggested to be dominant but there are hints of smaller scale periodicities in the alongshore data. Although the visual signatures coinciding with the decadal scale changes in shoreline position are clearly associative, this is a more rigorous solution that has a suggestion of sub-harmonic interaction at the spatial scale but no known mechanism is apparent or inferred.

Subsequent changes to the crestline position have not been monitored in a similar fashion but cross-sectional profiles at 28 sites have been conducted on an annual basis to allow

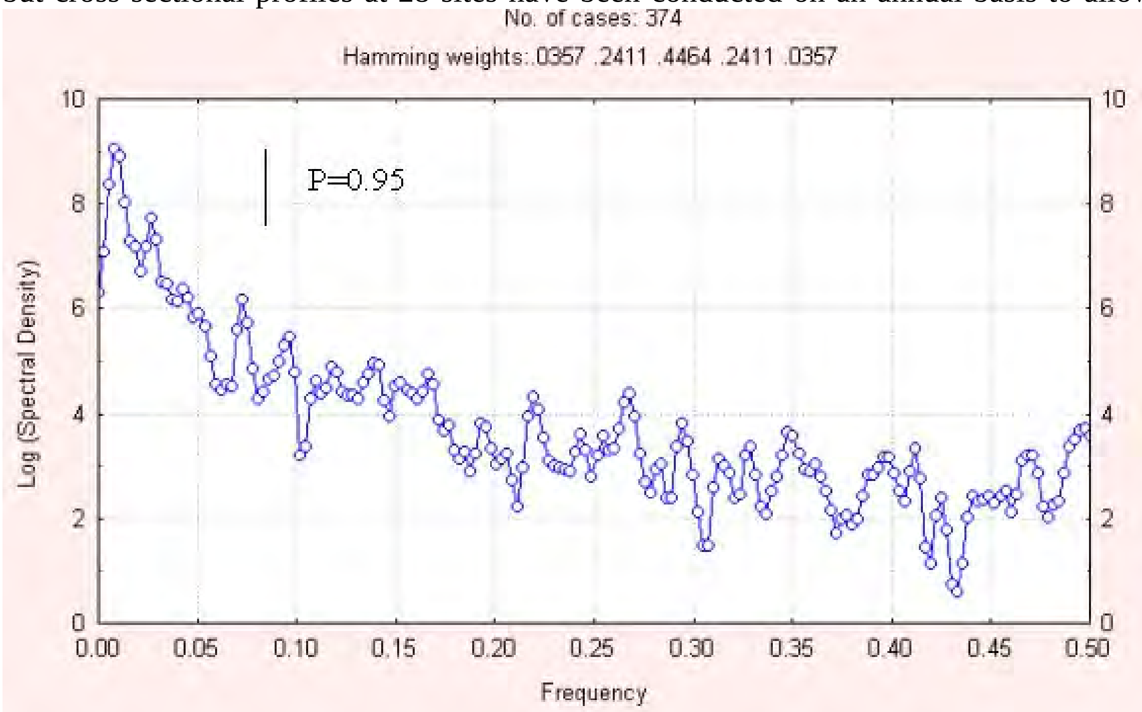


Figure 22. Spectral analysis of the changes in dune crestline position for the storm of December 1992. The significant peak at a frequency of 0.01 equates to an alongshore distance of approximately 3.6 km over the 18 km of change analyzed at 50m intervals.

for some site-specific tracking of change in dune morphology. At several sites where the dune has been severely eroded (km 9--east of the Lighthouse vehicle access road, km 17--west of the Sailors Haven access road, and at km 24--Barrett Beach), denser surveys of the 3-dimensional topography have been conducted in the annual survey regime. The Lighthouse and Point O'Woods areas were apparently driven by local "hotspots" of erosion (Gravens, 1999) associated with a narrow beach and a gap in the nearshore bar. The Barrett Beach (also termed Talisman for the NPS-associated infrastructure) project was conducted because of the major changes in dune morphology including relocation of the NPS Superintendent's residence, overwash under the VIP house, and loss of some of the recreational surface at Barrett as a consequence of the 1992 storm, as well as concern for the fate of the site given its narrow width, some areas of low elevation close to the beach, and the threat of island breaching. However, The first two areas were also impacted greatly in the 1992 storm event.

The change in foredune/beach morphology, between Kismet and the Lighthouse vehicle access site, between 1994 and 1997 is evident in a visual comparison of the modeled topography in Fig. 23. The dune has been lost in the east, adjacent to Kismet, and narrowed in the west. The rest of the dune has retreated and the seaward slope has been scarped. These responses were cause by the passage of an erosional embayment in the beach. However, overwash of the system has been minimal and led only to flooding of the access road in the fall of 1997. The residents of Kismet do view this as a flooding

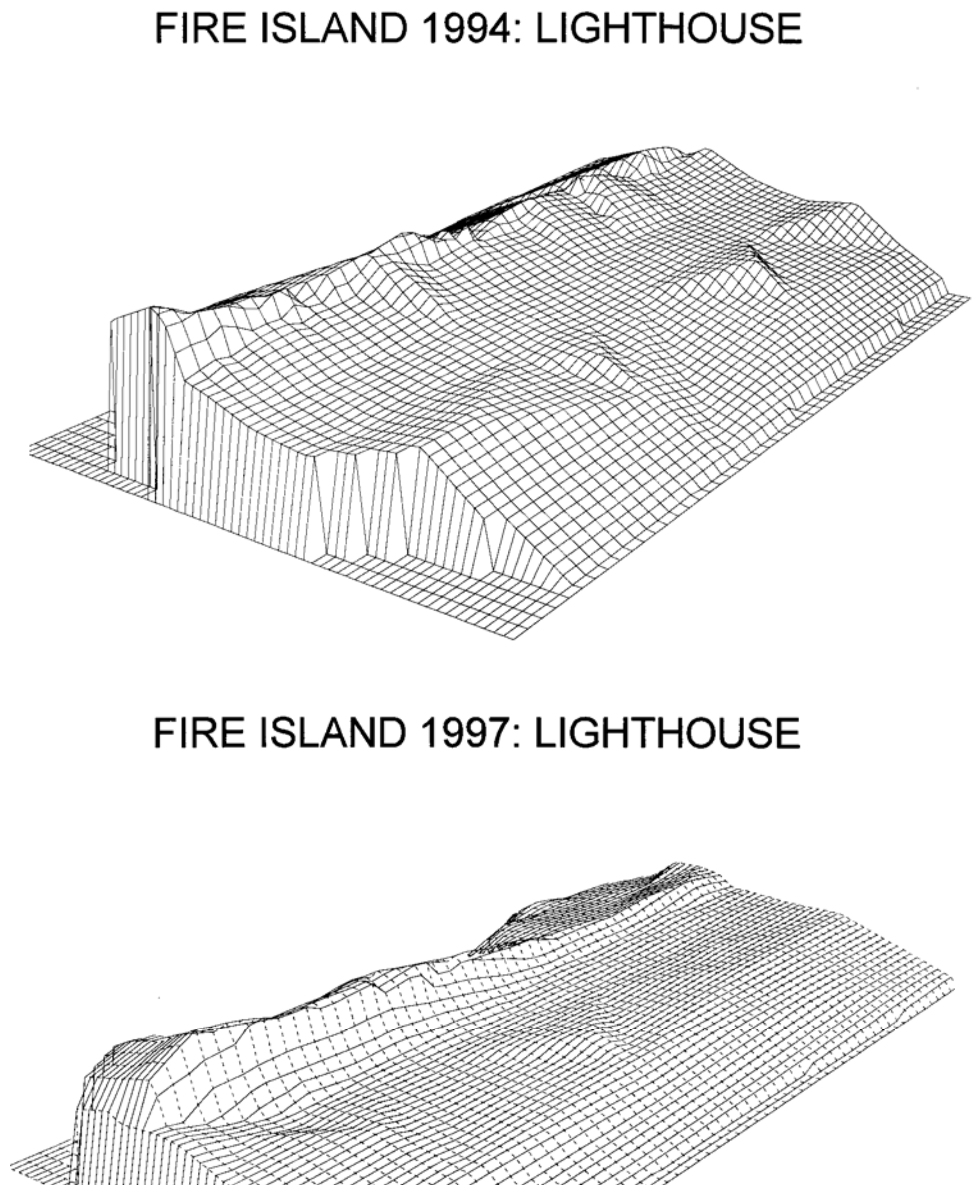
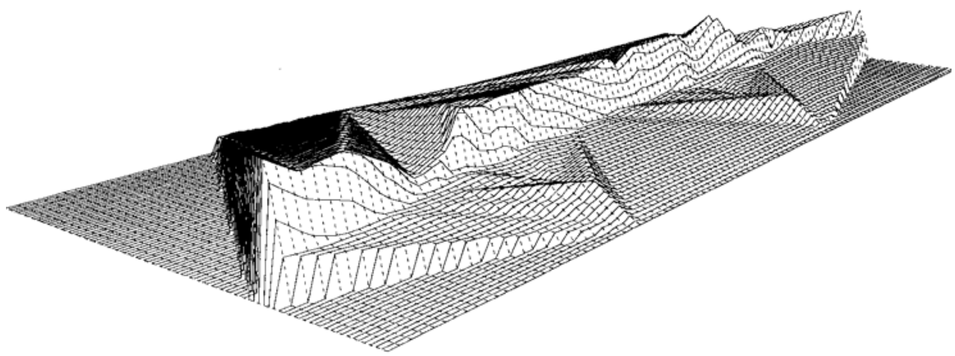


Figure 23. Topographic models of the 3-dimensional beach/dune landform between the Lighthouse vehicle access site and the Kismet border, western Fire Island. Note the loss in dune volume in the east (right) and lowering of the backbeach with dune scarping during the previous winter storms. Dune-crest lowering adjacent to the vehicle cut on the western (left) side is evident but the beach cusps are not relevant to long-term trend interpretation.

threat to their residences. The loss and lowering of the dune system also presents a threat to island breaching during storms. The island is low (~1.5m NGVD) in much of the area landward of the dune site but also relatively wide (nearly 1 km) so the threat of island breaching would seem to be low. However, the ebb tidal flow out of much of Great South Bay is directed toward the site before being deflected westward out through the inlet (see data of Conley, 2000) and this could provide severe flooding and direct hydraulic forcing across the bayside during a large storm, promoting ebb flow across the site. The width and surface roughness are contrary to breaching but the direct route of hydraulic efficiency suggests a hazard and the abandonment risk of the causeway makes this even more serious for human use in the future. The illustrations of the topographic models also show changes in beach form (a series of cusps and a wide, steep beach in 1994 but a narrower, lower gradient beach slope in 1997) but these are a result of processes operating during the preceding days, not the progression of a long trend over three years.

There is more complete data analysis for the Talisman/Barrett Beach surveys. The simple topographic models for 1994 and 1997 shown in Fig. 24 do not follow the same trend of change as noted for the Lighthouse site. At the Talisman area, the deep hollow in the dune system on the left (west) was in front of the VIP residence but it has recovered substantially with the use of fencing to intercept wind-blown sand. Similarly, the steep scarp face of the foredune has changed to a lower gradient slope with accumulation of sand at the toe of the dune, advancing the toe seaward. The beach morphology was not modeled well in 1994 due to a widely spaced sampling interval and some complexity of topography due to the presence of beach cusps. Continued monitoring of the Talisman/Barrett Beach area has been conducted because of the breaching risk due to narrow width and the possible removal of the marina. Fig. 25 shows an overlay of selected quadrants of analysis of dune change and the typical density of survey points as gathered in 1997. It is also important to note that there is a wide backbarrier tidal flat behind this narrowest portion of the island. Planning for removal of the marina is underway to re-establish natural processes of sediment advection on the bayside. There is concern that removal of the hard structure might make the area more susceptible to breaching but there are mitigation strategies to fill the lower elevations with removed sediment. Identification of the direction and rate of dune alteration are a high priority to park management.

FIRE ISLAND 1994: TALISMAN



FIRE ISLAND 1997: TALISMAN

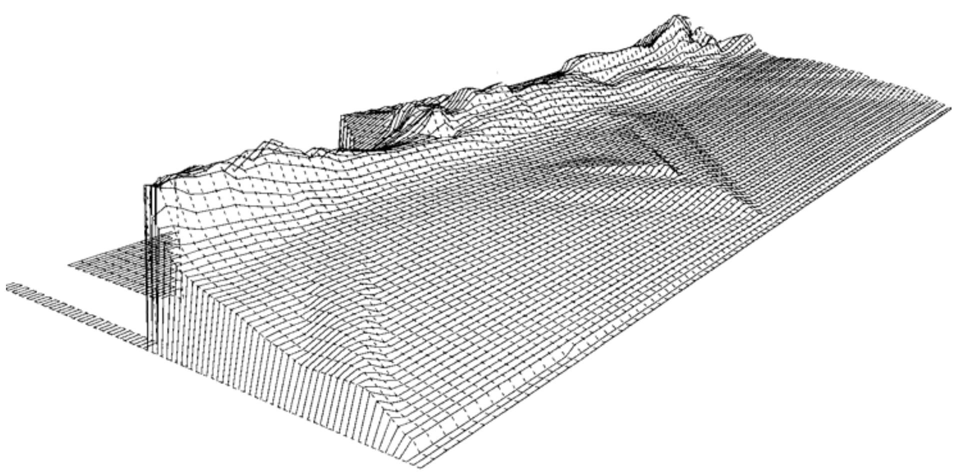


Figure 24. Topographic models of the beach/dune system at the Talisman/Barrett Beach area in central Fire Island. The western margin is just west of the present location of the Superintendent's residence (now called the Beach House) and the eastern end is just past the vehicle access road. Dune accretion about 1/3 from the left is evident and the "wedges" are coarse survey artifacts of the beach face.

Figure 25. The Talisman/Barrett Beach area of high breaching risks at Fire Island. The quadrats for detailed analysis of changes in the 1990s are identified along with some survey points shown for 1997.

Changes in the dune/beach profile in area 2, just west of the Barrett Beach complex and in front of the VIP residence, are depicted by the annual profiles gathered in the mid- to late-1990 as shown in Fig. 26. The dune system shows a clear trend of recovery with only sand fencing employed, with a lag time of a couple of years. The crest elevation has increased by 1.5m and the seaward face has also accreted by several meters. Unsurprisingly, the foreshore location on the beach has vacillated greatly but the seaward growth of the dune is a clear trend. Most likely, this is possible because there have been few winter storms in the latter years of observation and those have not been particularly energetic.

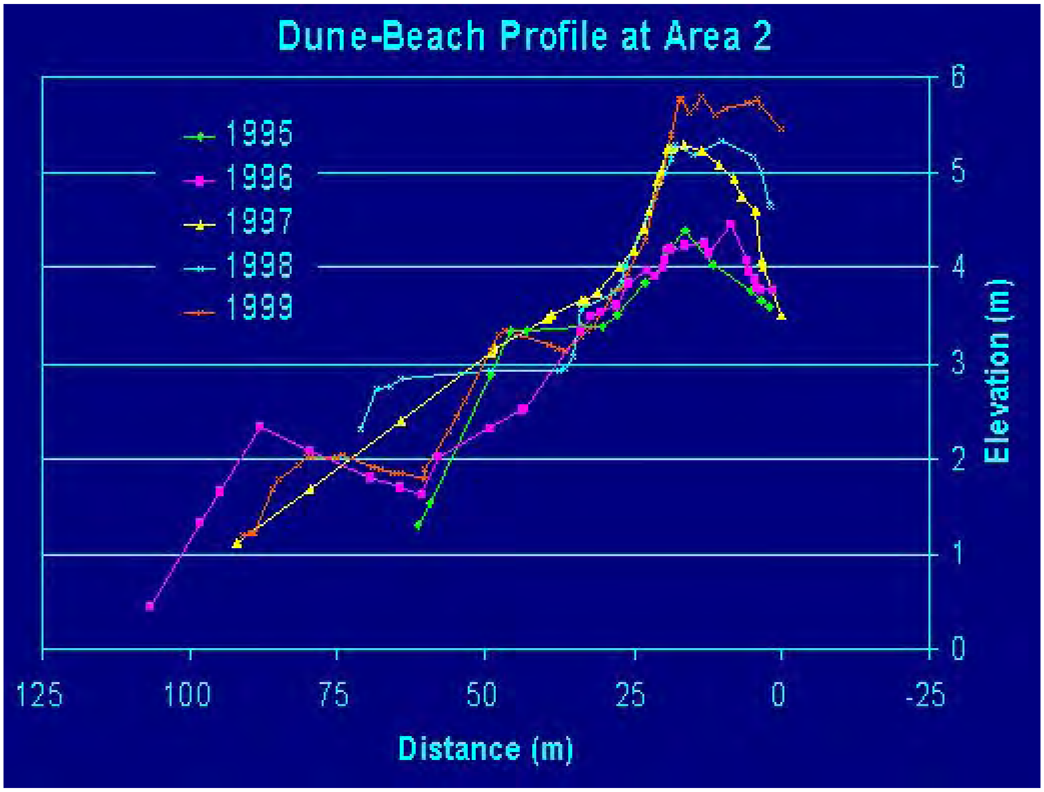


Figure 26. Annual beach/dune profiles in the Talisman/Barrett Beach area 2, surveyed between 1995 and 1999, showing major vertical accretion and seaward growth.

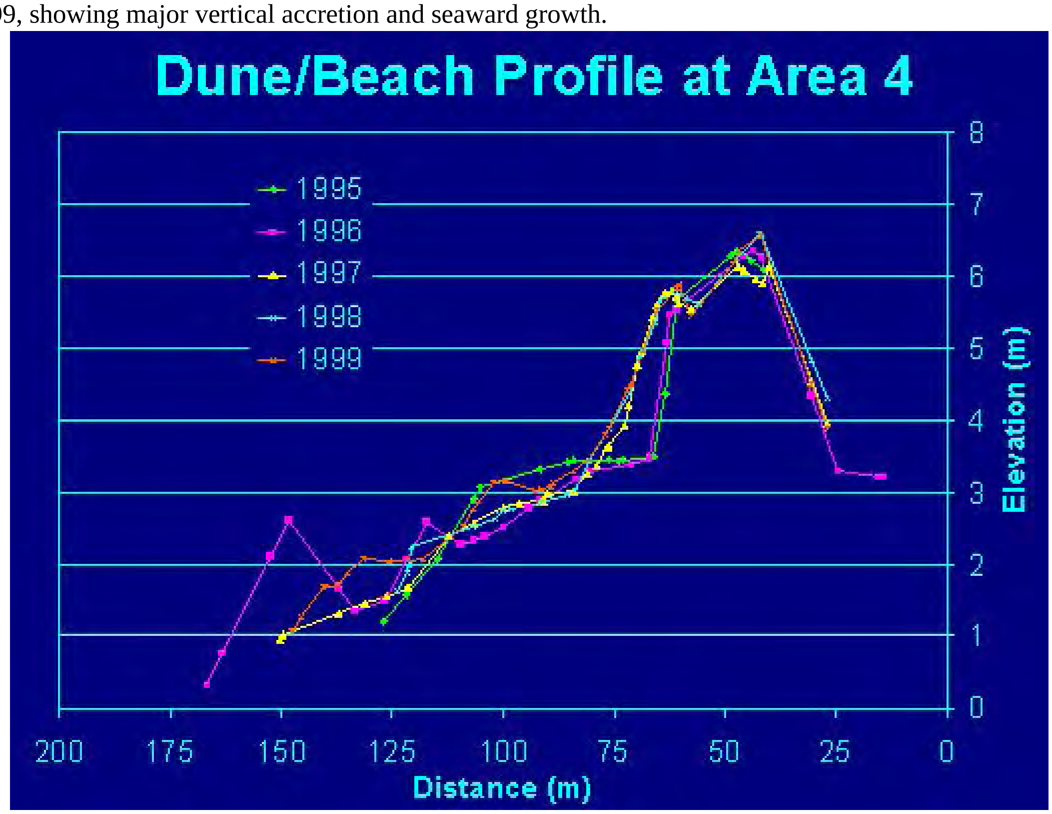


Figure 27. Annual beach/dune profiles in area 4 at Barrett Beach showing the seaward growth of the dune face in front of the paved recreation area.

Dune change in area 4, just to the east of the Barrett Beach complex, is depicted in Fig. 27. Over the 5 years of survey data obtained in late spring of each year, it is apparent that this higher elevation, remnant dune has changed primarily by accretion on the seaward face, resulting in more than 10 meters of advance. The previous scarp has a lower gradient with maximum horizontal change at the toe of the dune. No change is clear, however, in the dune crest elevation. Again, sand fencing was used at the toe of the dune to trap sand stripped from the beach by wind. Variation in beach morphology is apparent also with the 1996 foreshore being well in front of other measurements, different gradients, but with a consistent backbeach/dune toe elevation >3m NGVD at this inter-

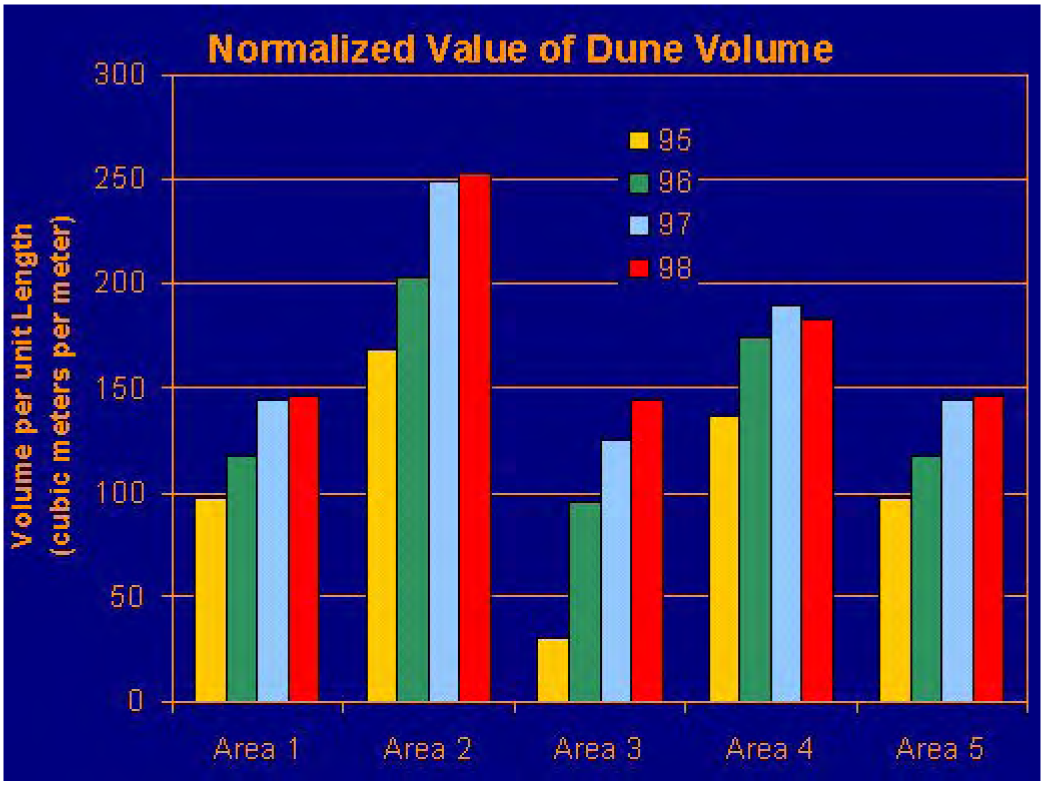


Figure 28. Bar graph of changes in dune volume for quadrants 1-5 at the Talisman area, normalized as cubic meters per annum, in four years of measurement.

annual time scale of monitoring. Fig. 28 shows that a rapid growth in dune volume occurs in all quadrants but the rate of accumulation declines after the first couple of years. Absolute magnitudes of recovery are dependent upon pre-existing topography. Where dunes are largely absent (such as area 2), gains are large. Where there are high backshore elevations (remnant dunes or where fill has been placed, the gains are less. The increase in dune volume due to aeolian processes alone range along the area from 40 to over 100 m^3/yr. per meter of shoreline.

These changes in dune morphology and crestline position show that storm-induced, erosion changes can recover partially but only over a time scale of years. Many of the dunes on Fire Island are remnants of past processes associated with human activity. Photos taken by local residents document large areas of bare sand during the 1930s and

1940s, which had to have been a consequence of extensive grazing and clearing by the occupants. This surface would have been reworked into tall dune features. Major beach/dune nourishment to repair the system after the March 1962 storm, as well as in the 1990s via beach scraping, has also amplified the presence of a prominent foredune morphology to protect island residences and to decrease the likelihood of island breaching, which would temporarily increase the threat of mainland flooding during periods of elevated sea level (storm surge). The highest dune on Fire Island is +15.4 and several others in the Wilderness Area exceed +13m but, while close to the beach, they are really the interior extension of the foredune system. The highest foredune in the Talisman area is +10.3m, at Sailors Haven it is 13.0m, and in the Lighthouse tract one peak is +11.6m. Most communities have leveled interior secondary dunes, which also provide substantial protection, but there is a relict dune 13m high in Fire Island Pines and another at the Water Island/Barrett Beach border is +11.7m and which is undergoing erosion from bayside processes. It is important to notice that dune change is much less frequent than shoreline change and with a lesser magnitude, but that the locations of major disruption mirror those of extreme shoreline change. This is true for both the 6-km long wavelengths in the western communities; however, at Great Gun Beach the foredune is now where the shoreline was in 1979.

Chapter 6. Recent change of the ebb-tidal delta at Moriches Inlet.

The growth of an ebb-tidal delta at an inlet is forced by a dominance of tidally driven forcing in microtidal regimes (range < 2m) is enhanced via a channeling of outward flow through dredged channel and jettied margins. These constrict the flow into a narrower and deeper channel, thus decreasing the effects of friction restriction. Growth of the ebb-tidal delta is at the expense of sediment bypassing to the downdrift beach, which results in a localized deficit in the alongshore sediment budget and beach erosion. Without these features, flood tidal processes dominate but the inlet still intercepts a portion of the longshore transport regime. The magnitude of the downdrift erosional impact, in both time and space, depends upon both wave and tidal forcing of sediment advection (Fenster and Dolan, 1996). This chapter focuses on recently obtained data describing the changes associated with the ebb-tidal delta at Moriches Inlet, at the eastern end of Fire Island.

As was shown in several earlier figures, major accretion of the shoreline at Great Gun Beach, about 2 km west of Moriches Inlet, occurred between 1986 and 1994 and has continued (Allen and LaBash, 1997). This suggests that substantial natural bypassing of the inlet, stabilized by jetties in the early 1950s, is now taking place. If so, the ebb-tidal delta would be approaching an equilibrium size and no longer would intercept littoral drift from Westhampton to Fire Island. To test such a hypothesis, we conducted dense bathymetric surveys (tracklines spaced ~60 m apart) of the bathymetry of the area in June 1995 and August 1966 to establish the morphology, volume, and changes at the interannual scale. Fitzgerald (1987) has identified three mechanisms of sediment bypassing for the "mixed energy" conditions which are also found at this site: inlet migration and spit breaching, stable inlet processes, and breaching of the ebb-tidal delta. On a policy basis bypassing is important because several agencies are interested in promoting bypassing by various engineering schemes that may be unnecessary. Volume captured, which would have been available to buffer the effects of erosional forces on the shoreline location along Fire Island, is highly relevant to National Park Service policies which allow for mitigation of human-caused alterations to the natural longshore transport rate to Fire Island causing downdrift erosion. How much impact and how far downdrift is the impact are key questions for mitigation strategies. Shoreline change data are inconclusive on the downdrift impact distance but this study focuses on the inlet interception impacts to the Seashore. Policy-wise, this would equate to allowing beach nourishment, somewhere in the park, of an equivalent amount of sediment entrapped on the ebb delta. This key volume is elusive as most assessments differ by a factor of two or more: 3.6 million m^3 in 1955 and 4.0 million m^3 in 1978 (USACOE, 1983) and 2.08 million m^3 in 1967 and 2.38 million m^3 in 1979 (Vogel & Kana, 1985), although growth proportions are similar. Even though the temporal data describing an interception rate (inlet growth and downdrift erosion) are limited to a few surveys, some (see above and the undefendable speculations of the Westhampton Beach groin field as also contributing directly to erosion on Fire Island by Spencer & Terchunian, 1997) assume a continuing linear rate of interception.

The latter concept, attributing continued erosion on Fire Island to updrift machinations is poorly substantiated and contrary to a scientific appreciation of the concept of natural equilibration, let alone far-field impact limits. In theory, the ebb-tidal delta cannot grow forever at the same rate due to eventual limits imposed by natural feedback. Furthermore, this stabilized inlet has not behaved as designed as evidenced by alternative sites being selected during storms in 1980 and 1992 (see breaching discussion by Headland *et al.*, 1999; inlet history review by Smith *et al.*, 1999). Accordingly, the NY Department of State's Coastal Zone Management Program and the US National Park Service agreed to conduct another bathymetric survey in 1999 for more data to clarify the issues involved with the calls for more effective inlet management programs.

Methodology.

In June 1995, August 1996, and April 1999, bathymetric surveys were conducted with a survey grade (acoustic) ODUM^{TM} Hydrographic System Fathometer (Echotrak Model DF-3200 Control Unit with Dual High Frequency (24 kHz, 200 kHz—we used the latter) Transducer, Model 210-33/9-19). Manufacturer's stated accuracy is within 2.5 cm in seawater. Horizontal positioning control is provided by a real-time, differentially corrected Geographic Positioning System (DGPS) receiver with a manufacturer's accuracy of 2-5 m (although we commonly achieve accuracy of 1 m or less on the water with no cross-reflection to complicate phase resolution).

All surveys were led by Wayne Spencer (then) of Woods Hole Oceanographic Institution, in a boat operated by Fire Island National Seashore staff. The initial study design was to completely cover the ebb delta form with transects spaced at 60m intervals and into deep water on both sides and offshore (see Fig. 29). Subsequent surveys tried to duplicate the same ship tracklines of the 1995 effort and we added westward transects because initial analysis of the 1995 survey suggested that detailed resolution of an accretionary area was incomplete, and we used the same survey hardware on each voyage. We were largely successful in transect replication but the sea states and the growth of a very shallow bar (crest depth measurements of 1.5 m at high tide) westward along the ebb-tidal delta limited complete duplication in 1999. To best approximate the real bathymetry, the estimated depths were artificially entered as coarsely spaced points into the empty coverage area of the corrected data.

The surveys are much broader in spatial coverage than the dredging verification surveys for USACOE/NYD projects and more densely detailed: the 1995 survey has n=35,635, in 1996 n=36,049, and in 1999 n=37,213 bathymetric data points (x,y,z), tidally corrected to NGVD NAD 1929. Rigorous analysis of these very large, irregularly spaced, three-dimensional data sets was conducted in a common Geographic Information System, Arc/Info 7.1.1 running on an Intel Pentium Pro-based computer. 1) a triangular irregular network was fitted to the complete data set using the CREATETIN subroutine to develop a bathymetric surface model with boundaries fitting both 1999 and 1996 survey coverage and augmented by a 1996 GPS shoreline survey for a landward MHW reference. 2) the TIN model was then converted to the raster GRID model using the TINLATTICE procedure to create a best fit surface composed of 5 x 5 m squares (see Fig. 30 for this synthetic morphology). 3) GRID bathymetry was then passed into ArcView Spatial Analyst 1.1 wherein contoured models (Fig. 31, 32, and 33) were produced to assess the morphology of each data set and provide a quantitative basis for evaluating patterns and forms of morphological change between the data sets. 4) sediment accretion and erosion

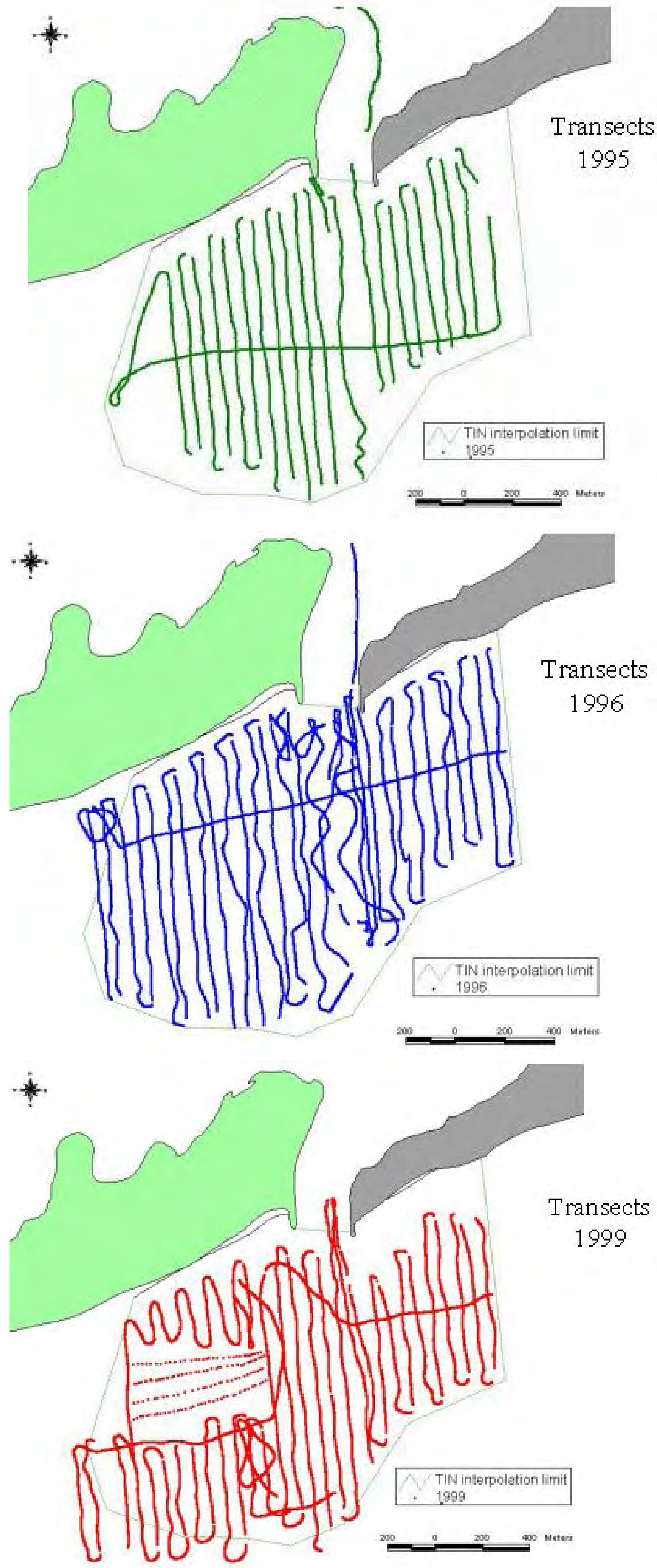


Figure 29. Vessel tracklines and comparative polygon outline of surveys in the three years.

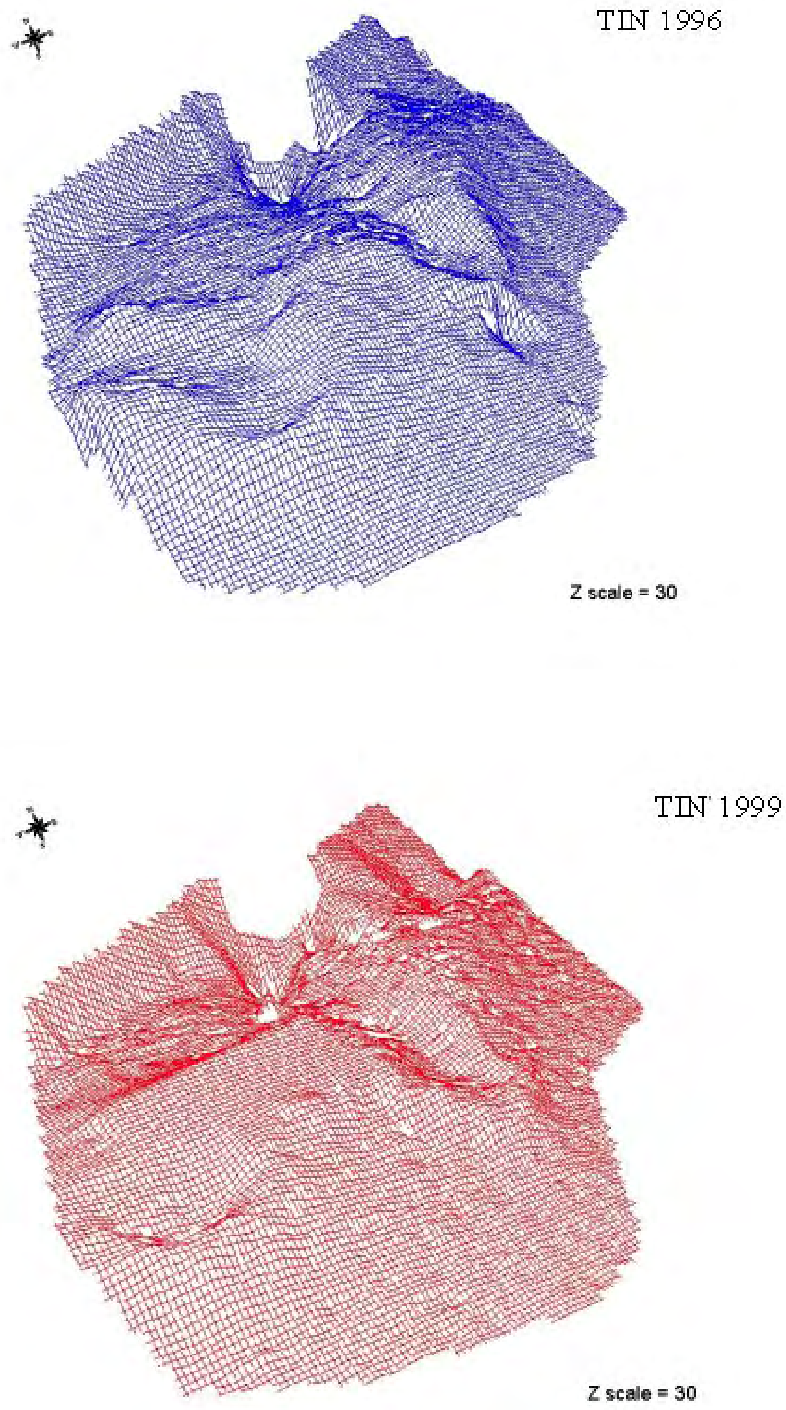


Figure 30. Examples of oblique view of wire-frame bathymetric models from GRID of the ebb-tidal delta.

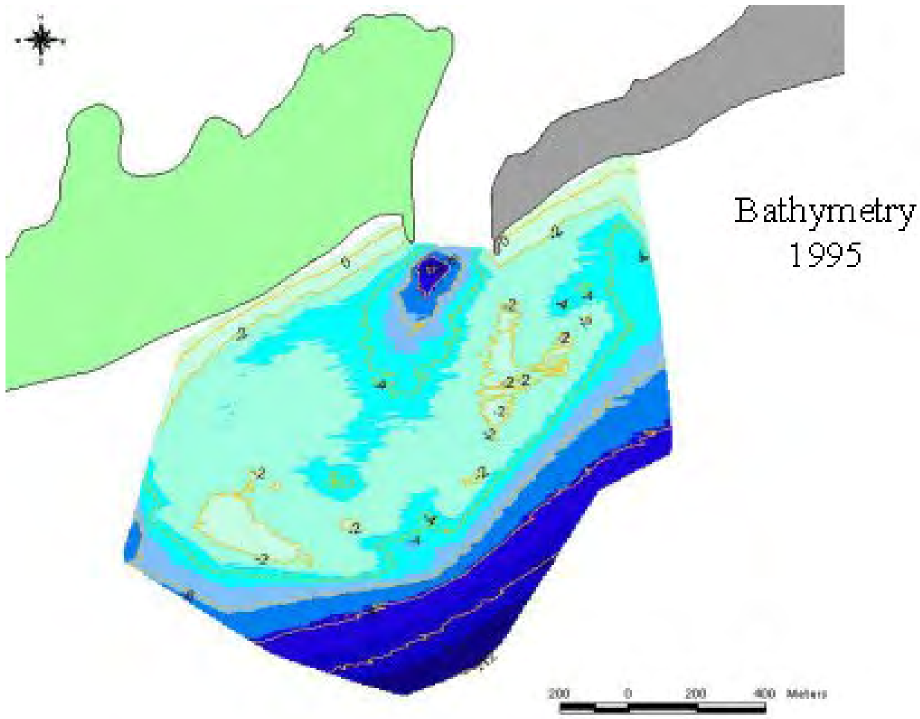


Figure 31. 1-m contour interval map of ebb-tidal delta bathymetry in 1995.

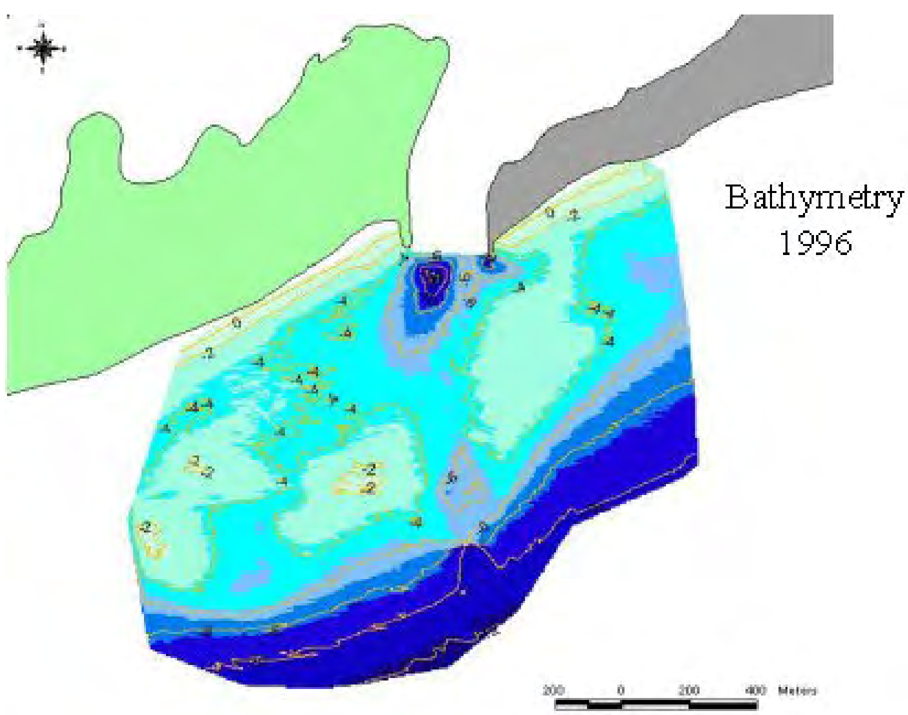


Figure 32. 1-m contour interval map of ebb-tidal delta bathymetry in 1996.

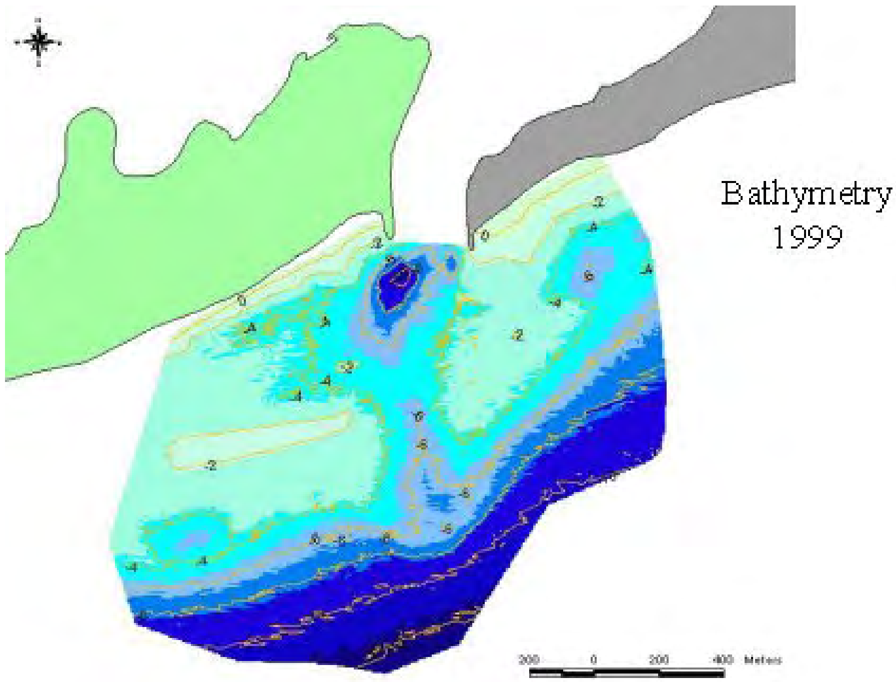


Figure 33. 1-m contour interval map of ebb-tidal delta bathymetry in 1999.

Estimates between surveys were calculated using the ArcInfo CUTFILL routine. This produced quantitative measures of the volumetric change while the resulting GRID data set identifies where the changes took place. The output changes for the 60,00 to 70,000 grid cells are mapped (Fig. 34 and 35 in terms of the standard deviation (s.d.) about the mean. We assume that the theory of large numbers results in a Normal (Gaussian) Distribution; this means that +/- 1 s.d. incorporates 68% of the distribution and that +/- 2 s.d. incorporates 95% of the raw values of change in each cell. This allows for a semblance of confidence estimates in significance of bathymetric change at quasi-probabilistic levels.

Results.

The 1995 survey was obtained after a decade of no dredging so the morphologic associations were relatively natural. The results indicate that the ebb-tidal delta has: 1) an asymmetric form skewed to the west (in accordance with the net westward direction of the annual regime of littoral drift), 2) the vertical relief was characterized by a very deep inner basin (scoured by a strong ebb-tidal jet between the jetties) and a shallow outer bar (where the ebb-tidal jet diffused and breaking wave-driven transport became important), and 3) contained a volume of approximately 2.27 million m^3 relative to the adjoining shoreface morphology in 1995. By 1996 the volume had decreased by about 190,000 m^3, very close to the volume of 180,000 m^3 removed in a spring, 1996, maintenance dredging project and westward migration of shoal-like features on the outer bar was apparent. The short- and long-term effects of the dredging project design as a form of inlet management, whether or not substantial natural bypassing is present, was unknown.

Change of the ebb-tidal morphology between 1995 and 1996 is shown in Fig. 34. For the 63,346 grids cells compared, the mean change was erosion of 0.83m with a standard deviation of 1m. This means that 68% of the cells experienced very small change that attests to either substantial variability of small-scale bedforms or represents error due to the inability to filter out the presence of surface gravity waves in the data (although the boat is large enough to partially dampen wave distortions). Large changes result from natural process of sediment transport and human activity. Accretion on the western margin of the delta has expanded the feature downdrift. The prominent outer bar has

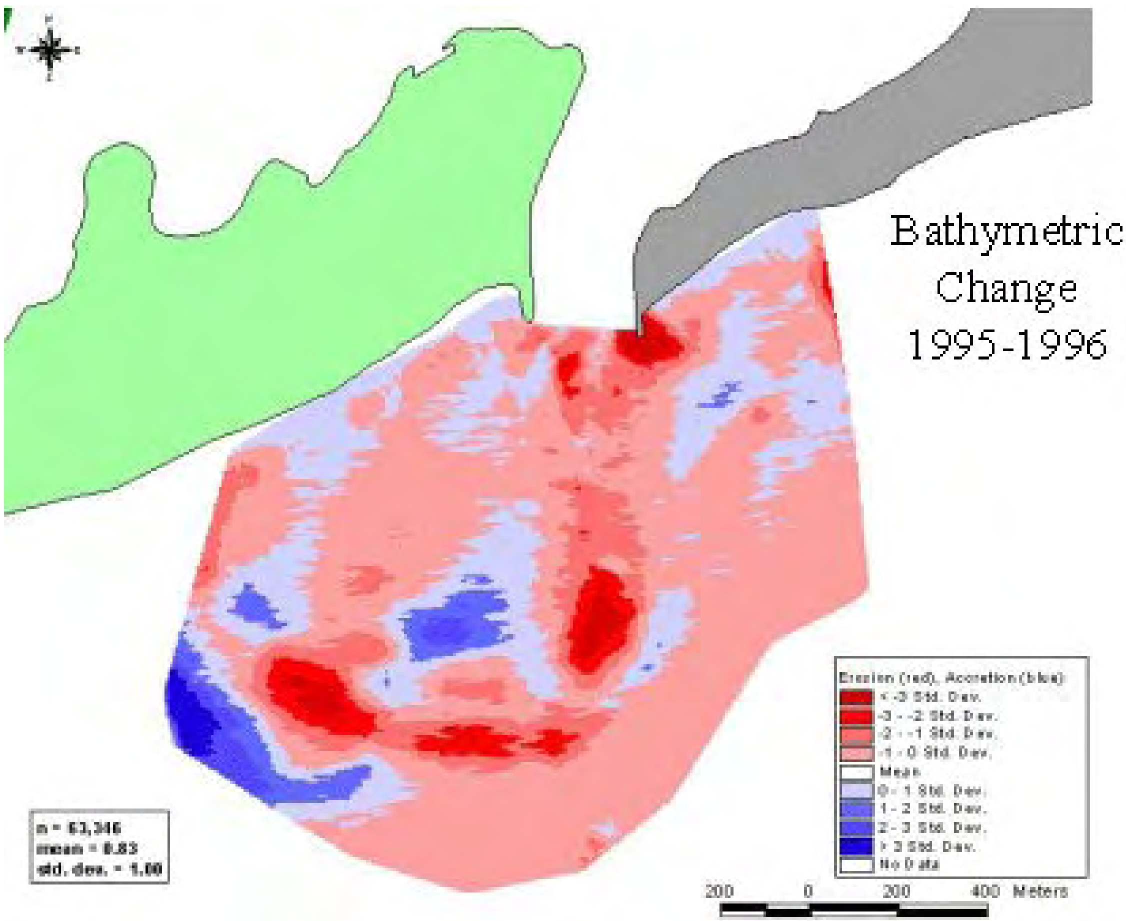


Figure 34. Bathymetric map of change between 1995-1996 where the value in each cell is expressed as by the class of standard deviation about the mean, n=number of cells compared. Erosion class is in red, accretion class in blue.

eroded substantially on the western side, which has provided for the westward extension but also discrete shoal units are migrating westward and landward. There is also some minor accretion on the eastern, updrift margin, likely associated with longshore and offshore transport. Navigational dredging cut through the outer bar, deepened the channel just seaward of the jetty ends, and the project created a deep sediment trap off the end of the east jetty with a presumed strategy to increase the time before dredging would be needed again.

A following survey in 1999 is informative about changes in shape and volume over a three year period, which was relatively quiescent with only mild winter storms. The comparison of the 70,523 grid cells coincident in the two surveys over the three years yields a mean loss (fill required for 1999 to match the surface of 1996) of 0.23 m per cell, with a standard deviation of 0.92 m. This equates to a total loss in the surveyed area of 16,220 m^3 since the 1996 survey estimate of an ebb-tidal delta volume = 2.08 million m^3. The 1995 survey indicated a total volume of 2.27 million m^3 of sand in the ebb-tidal delta relative to the surrounding bathymetry assuming a smooth surface. The present volume is not measurably increasing substantially, and the changes are nearly equivalent to the amount of navigational channel dredging removal during the period of monitoring. This lack of measured interception suggests that there is a rough balance of sediment inputs and exports, despite dredging and modeling assumptions, possibly because dredged sediments are disposed of towards Fire Island. The results are also not dissimilar from the estimated longshore transport rate of 150,000 m^3 per year (but with substantial variability depending on the method of solution, Kana, 1985; Rosati et al., 1999). We know of no way now to test the modeling assumptions for objectivity, given only three samples in our data set, but are aware of the uncomfortably close balance of numbers in the equation.

The spatial pattern of change between the 1996 and 1999 surveys (Fig. 35) is clear if one ignores subtle changes less than one standard deviation. While the mean changes are important for evaluating changes in ebb-tidal volume and interception rates, two standard deviations describing variability about the mean can thus be thought of being both statistically significant at the rejection level of $P < 0.05$ and physically significant, given the long time period between surveys with the concomitant errors of each due to mobile bedforms and the presence of surface water waves which could not be filtered out. There is substantial sediment advection and accumulation westward around the end of the east jetty penetrated nearly across the inlet throat, filling the 1996 sand trap. A 1999 dredging project carved a small channel through this shoal. There is a westward and landward advection of material from the outer bar contributing to the enhancement of the longshore bar that was problematic for boating safety in the survey and this bar is the dominant nearshore morphologic state along Fire Island (Allen & Psuty, 1987). An erosional site on the west side of the outer bar had developed but shows no clear pattern of the destination site, which could be used to infer a process. Shoal detachments moving westward and landward are found again. There is a potential problem in that there is seaward deposition of sediment (a bypassing loss) in the form of a small pro-delta on the face of the ebb-tidal delta. We interpret this to result from the ebb-tidal jet enhance farther into the ocean through the navigational cut in the outer bar. It is clear that the conclusions of Fitzgerald (1987) about sediment bypassing and ebb-tidal delta dynamics do not apply well to what is happening at Moriches Inlet because there is adequate evidence that all are playing a role, at certain time scales and depending upon the frequency/magnitude of human interference of breaching the ebb-tidal delta.

It is apparent that there is a moderately well resolved and complex interaction between the natural forcing of sediment transport by tidal and wave driven processes for this jettied inlet because it’s volume remains reasonably constant and form is reasonable given the present constraints. Nevertheless, disruptions occur, some of which are easily explainable by dredging but others are not. The implications to inlet management solely by maintenance channel dredging with westward disposal of the enhanced jet through the outer bar, diverting more sand seaward by ebb flow into a sub-delta are troublesome. The creation of a sediment sink by dredging a deep hole off the end of the east jetty is shown to be quickly overwhelmed in a period of three years. The perpendicular pattern of the maintained navigational inlet does allow for a substantial amount of sediment to be effectively advected downdrift, unlike perhaps at Shinnecock Inlet where the channel is oblique to the SW where downdrift bypassing may be more difficult because of the blocking of the ebb jet and vortex development effecting sand diffusion over a large area.

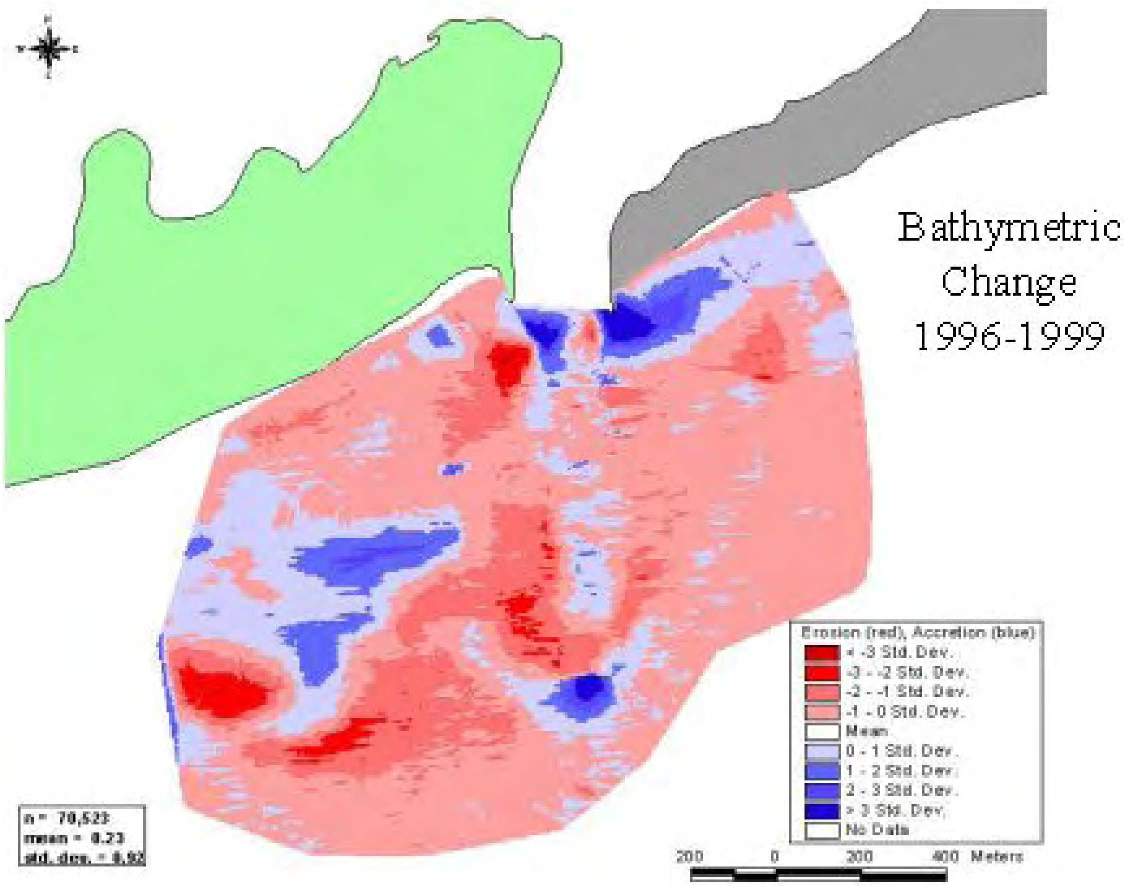


Figure 35. Bathymetric change in the ebb-tidal delta between 1996 and 1999 with cell values expressed in units of standard deviation classes about the mean, n=number of cells compared. Erosion class in red, accretion in blue.

jetty is inefficient in precluding littoral drift from filling the inner basin scoured by ebb-tidal flows. The results indicate that the ebb-tidally dominated inlet bypasses sediment in discrete morphologic units of shoals moving downdrift along the outer bar and that the updrift jetty is inefficient in precluding littoral drift from filling the inner basin scoured by ebb-tidal flows.

Chapter 7. Discussion and conclusions.

The results of our studies of geomorphic changes on the oceanside of the Fire Island barrier over the past decade reinforce some of the earlier interpretations in Leatherman and Allen (1985) about distinct differences in island evolutions between the eastern and western portions, roughly separated at the Watch Hill location. The eastern section continues to be dominated by inlet-related processes: it accreted after the closure of Old Inlet and the present beach dune system is well seaward of those inlet-related secondary dunes dating to the early 19th century. The formation of Moriches inlet in 1932 led to sediment starvation of the downdrift beach and the erosional impact is measured as far as the Wilderness Area, 10 km distant. The causal factor was the inlet interception sediment from the incident wave-driven transport regime during the initial period of flood dominance thence ebb dominance after being stabilized by 1953. It appears as though this "wave" of erosion has propagated westward by 1979 and may be seen in 1986. Between 1986 and 1994 (although there is a partial hint in the 1993 data), however, it is apparent that the inlet hydraulics and wave-driven transport had equilibrated to a quasi-stable ebb delta form and substantial sediment bypassing to Fire Island had developed and caused the major accretion at Great Gun Beach, two km downdrift. The eastern section of the island also has a very limited offshore sediment supply in that Holocene deposits are lacking and the bottom is dominated by Pleistocene age material (Schwab, et al, 2000) which are not readily transferable into beach sand. Cross-shore transport is thus limited only to beach/nearshore storm and swell exchanges close to the shore and the resulting pattern of shoreline change is a very high frequency alongshore oscillation at event, seasonal, and inter-annual time scales. As such, longshore transport is the principal sediment budget process of importance to maintaining shoreline position at space scales greater than 1-2 km.

Westward of Watch Hill, shoreline (both MHW and dune crestline surrogates) change along the barrier island have a very different pattern and this appears to be a function of both alongshore and cross-shore processes controlled by the offshore geologic framework (Fig. 36). The alongshore processes lead to a migration of sediment surplus loci into both the center of the island and the western end (Democrat Point) during the 20th century, as well as the migration of local erosional/accretional sand wave-like features over time scales of months to a few years. Large scale (~6 km) waveforms are also present in the shoreline change data since 1979 and have persisted with alternating erosional troughs and accretional crests. These forms are also present in the dune change measurements for the Dec. 10-14, 1992 storm. Because shoreline recovery takes place rapidly, the longer-term persistence must relate to either onshore or offshore transport patterns dominating over the long period, which is yet unknown. The pattern of dune erosion during the 1992 storm, mimicking exactly the decadal shoreline change pattern, is more likely due to storm wave energies. The insight into these two similar patterns but different processes has been provided by Schwab et al. (2000). Their findings indicate that there is a remnant of a former headland off of Watch Hill, composed of Cretaceous-age and Pleistocene glacio-fluvial sediment that provides a sand source, onto Fire Island. The delivery mechanism is a westward transport, to a series of oblique, shoreface-attached ridges. The ridges decline in amplitude westward and their connection in depths less than

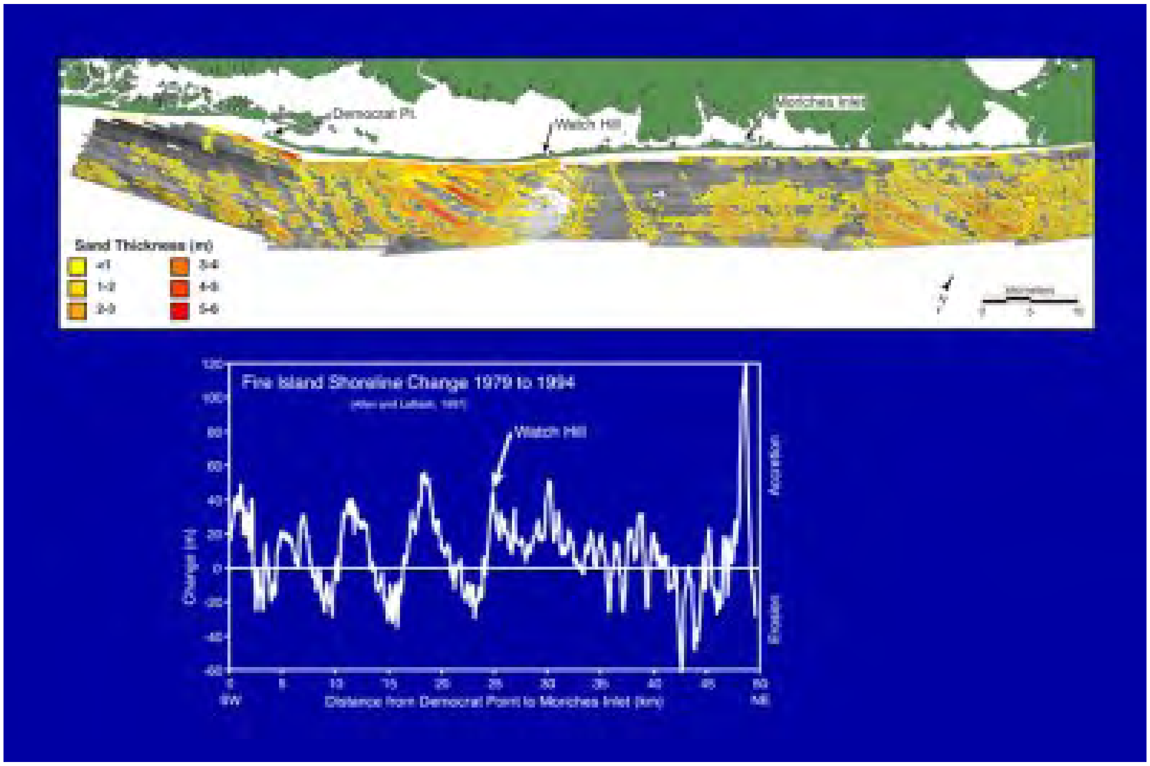


Figure 36. Offshore bathymetry and shoreline change along Fire Island in the latter twentieth century. From Schwab, *et al.*, (2000). The Cretaceous-age sediment source supplying sand westward to the oblique ridges and shoreline westward of Watch Hill is identified in white. Note the association between the ridges and the alternating "waves "of erosion and accretion in the west.

8m to the mobile longshore bar system is unknown. Their alongshore spacing is about 6 km so the correspondence in space with the shoreline change and dune crestline change patterns is the same. Because of the increase (>200,000m^3/yr) in the sediment transport rate from Watch Hill to Democrat Point/Fire Island Inlet, it was concluded that this is the source of additional sediment because budget analysis of the inshore/upland region does not support erosion of an equivalent amount. Rosati *et al.*, (1999) provide some evidence for a smaller transport rate but their various pathways also indicate substantial variance within the different theories of approach.

The directional vehicle for the cross-shore sediment flux has yet to be identified but the pathway seems to be along the axis of the oblique ridges. The pattern of dune erosion during the 1992 storm suggests also that the ridges, despite their depth, were important in controlling wave refraction with erosion occurring in alignment with the valleys between the ridges and less impact along the ridge axis. Again, this requires more analysis by both modeling of storm wave processes and correlation with field data. Especially needed is information about nearshore morphology during times when the shoreline is changing substantially. Localized "hotspots" of erosion have been related to gaps in the longshore bar (Allen and Psuty, 1987). Although most profile data in our unpublished reports indicate that the beach recovers in a week or two, these erosional/accretional waveforms migrate with the littoral drift and nearshore flow forcing a migration of the bar gap, and this turn results in an alternating temporal pattern of loss and recovery of the beach on a time scale of months at a specific site. The same pattern exists in dune scarping and dune loss and was explained in a similar forcing and temporal pattern for dune change by Psuty and Allen (1993) at Fire Island. A major issue is present here: are inland erosional phases resulting from standing (or migrating?) offshore ridges or from discontinuities in the nearshore system. This is of the highest relevance of shoreline change explanation at the present time. The former suggests a degree of determinism whereas the latter is more randomly driving erosion and property damage in both space and time.

Dune recovery after the erosional episode (whether a storm or passing of an erosional "hotspot" are a much slower process and can take years to decades, depending on the severity of the forcing mechanism. Natural dune recovery has been documented as being major within a few years at several areas in Fire Island. At Old Inlet, incipient dunes are forming after re-colonization of overwash fans and throats by vegetation within a year of cessation of overwash. In the communities, a combination of dune rebuilding from beach sands provided by either natural recovery or beach fill, invokes the human factor. Whether these rebuilt "dunes" function well is another matter. Their composition is neither tightly packed, fine grain sized sediment nor do vegetal root systems extend to the base of the dune, as would be the case in a natural dune built by aeolian processes. Although artificial dunes are often planted with beach grass (*Ammophila breviligulata*), the way a natural dune would have grown vertically with a concomitant vertical extension of the plant system, the internal strength of the sediment composing them is relatively weak. Mycorrhyzal fungi are also common in natural dune systems and further bind sand grains to resist erosion but, unfortunately, inoculations have not been done during dune rebuilding on Fire Island. Whereas humans have restored dune form to some extent of elevation design, they have not provided for the full integration of dune strength to resist erosion during storms and thus their protection against flooding is more perception than real.

Moriches Inlet is shown to be an unstable and complex system providing evidence of non-linear spatial behavior, through time, and is not responding simply to morphologic carving for navigational safety. More shoreline/dune and bayside monitoring is needed to provide a better understanding of what the implications are in the future and to begin to address how to improve the present simple management plan that emphasizes onshore controls on reconstruction of property and protection. Such dense surveys should indicate how bathymetric change in the intervals is strongly influenced directly and indirectly by navigational channel dredging. These data would suggest that management alternatives should be explored to improve navigation and still provide sand bypassing to Fire Island. Alternatives to the present design of channel dredging/downdrift disposal should be evaluated to improve the bypassing efficiency by natural processes. It is necessary to improve the present scheme because better data than available in the past are needed to assure that adequate sediment volumes are being received at Fire Island. Dense and broad bathymetric surveys are required to evaluate the stability and variability of the inlet under present conditions for optimal inlet management. New technologies such "jet ski" mounted survey gear or the USA COE SHOALS (aircraft based, laser/GPS survey system) for bathymetric monitoring would increase the density of data over what we have produced. The cost would likely increase but the data value would also if captured under optimal conditions (low waves and low turbidity respectively).

Despite the fact that Fire Island is the only developed barrier in the nation without a road running through it, breaching of the island would greatly disrupt access for maintenance, construction, power and telephone utilities, and public safety patrols. All of these rely upon the beach for a transport corridor and protection, and the structures at the breaching site would be destroyed. According to Conley's (2000) modeling data the increased flooding threats would be limited to within a few km. On the other hand, most of the people and supplies utilize water access to the island and this is a viable alternative also, along with splitting access locations. Determination of likely sites of island breaching at Fire Island is a complex task that has resisted a simple resolution based upon field conditions, let alone simplistic modeling exercises. In various draft reports supporting an interim project of storm damage reduction at Fire Island, the USACOE has modeled scenarios with regional applications and are quite simple in their assumptions. The unpublished reports address risk threats at coarse intervals with a smooth offshore bathymetry compared to a "design" elevation or volume that can be compromised in a storm. These models are too simplistic for application in a known environment of great complexity and of great value. Of course, some areas of the island are at more risk than others, such as where the island is narrow and contains low swales between the recurved dunes that could facilitate cross-island flow (Talisman to Water Island). Other areas that are wide but relatively low (very narrow dune system backed by elevation barely above MHW) and in the path of ebb flows during bay/ocean imbalances in water surface elevation (such as the Fair Harbor to Lighthouse area). Any location where there is a vehicle cut through the foredune and there is no secondary dune or high upland from fill is at greater risk (Long Cove, Atlantique Beach).

Despite geomorphic evaluations of relative risk levels, considerations of storm tidal hydraulics are also important to the breach threat. A geographical understanding of the Great South Bay regarding the differences in tidal prism and phase relationships is fundamental to evaluating whether a storm breach would become a permanent inlet. This makes the center of the island more hazardous than the eastern end where there is a limited tidal prism and the shallow depths that led to frictional forcing of the closing Old Inlet nearly two centuries ago, remain today. The report by Conley (2000) addresses simulated breaches at Talisman/Barrett Beach and suggests that major changes in the circulation of Great South Bay would occur. On the whole, water quality and flushing would improve but there would be local disruptions to existing habitat. Effects upon existing inlets of a new breach were not simulated but most other studies agree that the reconstructed tidal circulation would lead to increased sedimentation in Fire Island Inlet and Moriches Inlet, increasing their unpredictability of behavior. One of the major implications of this report is the present concentration of ebb flow directly at the bayside of Fire Island near the western area of the developed zone and where there is a substantial phase difference in tidal elevations between bay and ocean. During a major storm, with highly elevated water levels, this could be a problem of water egress across the island cutting a breach. Whether the breach would survive to become an inlet, *i.e.* tidal hydraulics overcome wave-driven sand transport is not evaluated in this report.

However, it is clear from both published NOAA tide charts and Conley's study that flooding effects are limited to near-field distances (~3-5km) but Conley indicates that substantial changes in the physical circulation of Gt. South Bay would ensue. Westward migration of any new inlet, as in the historical past, is predictable because of the net littoral drift direction. Unfortunately, the physical range of erosional impact cannot be predicted without knowledge of what alterations might happen at the two existing inlets or the speed of response at the new inlet. It is clear that implementation of the Breach Contingency Plan, although difficult and costly, would be done rapidly for nearly any location other than the Wilderness Area. There, the threat of true inlet formation is small due to physical hydraulic factors such as a limited tidal prism and frictional constraints.

Our focus has been on change in the oceanside shoreline as driving barrier island dynamics of inlet migration, dune erosion and breaching, and shoreline accretion patterns. However, it has been shown also that island thinning, west of the marsh at Davis Park/Watch Hill, is also a response to bayside erosion. Leatherman & Allen (1985) first established the spatial and temporal patterns of bayside erosion at Fire Island in their Fig. 4-4, which showed bayside erosion west of Smith Point at 1 km samples in the historical interval of 1834-1979. The only exception was for the interval of 1873-1933 wherein accretion at Democrat Point's recurved spit led to progradation of the shoreline. They also showed that the bayside is rarely affected by progradation from island overwash. A bayside monitoring program was established in the 1990s for park staff to provide better detail on temporal change issue at inter-annual and seasonal scales, utilizing park staff and the distance from an arbitrary benchmark to a consistent bayside morphological feature: the break in slope separating the low tide terrace/foreshore slopes. Retreat of 0m to 1.55m per year was observed. Unless very large storms occur (as in the winter of 1992-93), thick mats of dead eelgrass dampened shoreline retreat. Because these mats are removed on many bayside sites to clear the beach for human use, these sites eroded more.

Bayshore erosion at Fire Island has been identified as a physical threat and a managerial problem, if not dealt with in detail herein. However, mention must be made of both an ongoing bayshore monitoring program (with no analysis yet). Furthermore, a NPS/NSF-funded study of bayshore processes, sediment flux, and morphologic response was conducted in late winter of 1992 to identify thresholds of bayside dynamics and to integrate the different processes and responses into a general model. Jackson *et al*. (1993) found that high water levels and waves >20cm drive sediment transport on the low tide terrace and foreshore of the beach and that onshore wind velocities >10msec^{-1} resulted in inland aeolian transport of bayside sediments. Low amplitude, oblique bars on the terrace are fairly stable in position but surficial sediment advection, from incident wave windows with nearly 180^{o} differences, results in clear morphologic change in the form of alternating gentle stoss and steep lee slopes. Sherman *et al.* (1994) analyze the sediment mixing depths from the tracer studies and scale them by environment and wave parameters. Mixing depths were greatest at the toe of the foreshore but were significant on the low terrace as well; the latter, driven by oscillatory waves, is sufficient to keep subaqueous plants from colonizing the tidal flat. Not only is this the landward inhibitor of SAV but also to have sufficient wave height, a large fetch is required. Fetch seems to be the principal reason why there is a sandy bayside beach system west of Watch Hill and saltmarsh dominates the bayside to Moriches, mainly because Smith Point separates the eastern portion of Great South Bay from Moriches Bay. Nordstrom *et al.,* (1996) summarize the findings more completely and it is suggested that offshore winds (W to N quadrant) lead to a regional setdown in the ocean (and bay) surface elevation, which dominates over wind setup across Great South Bay perpendicular to the Fire Island bayside. Despite this observed lack of substantial cross-bay water level setup by wind, east to west setup by longitudinal winds, along the bay axis, is well known by the local residents. The site of our 1992 experiment is long gone, two replacement benchmarks have been lost, and now the shoreline in the general location is monitored with GPS equipment because the difficulty of retaining fixed markers despite bayside shoreline erosion. The problem of bayside erosion is limited to the western end of the island where nearly all communities have wooden revetments and a few have bayside groins to stabilize the bayside shoreline, to protect inland development. Yet these structures, by denying the supply of sediment to adjacent areas, by reflecting waves to increase nearshore scour, and by their alongshore deflections of longshore transport exacerbate erosion of natural resources in the Seashore. Either a new method of dealing with the landuse obstructions or re-invention of old concepts—pilings and movable or disposable structures—require regulatory and legal exploration at several scales of political jurisdiction and implementation.

Over several decades, an edifice of laws and regulations has been developed for management of the coastal zone of places like Fire Island. Many relate to DOI agency responsibilities specifically. Yet policies to address the fact of shoreline change ignore the reality of it and remain parochial in interest and goals, absent national and state priorities of action. The concept of orderly retreat from erosional processes, endorsed in 1991 by the NYS Governor's Task Force on Coastal Resources and the Long Island Planning Commission, was rejected in 1994 when the Breach Contingency Plan was accepted on an interim basis. Erosion at Fire Island that was mis-perceived as due to USACOE projects, instead of resulting from natural processes in most places, has led to even more public and private investment in stabilizing a fixed position on an annual basis in several localities. Breaches can be closed if considered threatening but trying to stabilize the shoreline is expensive and a doomed action without a supporting philosophy and data, and a financial mechanism that does not depend on public underwriting. The inability of the NPS to acquire lands to restore a reasonable degree of natural protection to inland resources remains a key problem to restoring a natural viability to the system. Unfortunately, this solution appears to be confounded by local and national level politics, which are not addressed to the problem of a retreating coast but to the rights of the property owner instead of society as a whole. A key indicator has been the inability to gather political support for an update of the dune district management plan within the NPS jurisdiction, as required in the Congressional directive. Maybe adoption of the NYS coastal erosion philosophy may be better at the state level of acceptance but it lacks the physical clarity of definition and federal distinction of the existing NPS plan. Whether the state will ever accept responsibility within lands managed by the federal government is a question that is easy to answer in the negative.

In conclusion, science can provide accurate measurements of shoreline change and trends along with levels of uncertainty. However, our society that must decide what level of risk it is willing to live with and pay for, especially in coastal areas that are retreating and flooding in storms. The economic threat increases with the combination of more development, a relative rise in sea level, and possible increases in storm frequencies and magnitudes.

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Appendix 1. Shoreline Change Calculation Procedures Using ArcInfo/Arc View.
Shoreline positions are collected with a Trimble GeoExplorer coarse acquisition (c/a) code portable GPS unit (rover). Mounting the GPS unit on a 4-wheel drive (4wd) vehicle, collect MHW shoreline data under low Precision Dilution of Precision (PDOP) conditions (less than 4) and a data logging interval of less than 3 seconds for coarse mode mapping when traversing at speeds at or greater than 20 mph. The target is the wet/dry line visualized under low tide and low wave energy conditions to duplicate aerial photographic interpretations during the 20th century. When finer detail resolution is desired set receiver logging interval to "all" (0.7s) or 1s, depending on the equipment options (we use this as a default because a shoreline survey for the 50 km of Fire Island can be held in a GeoExplorer memory, if multiple files are needed, a lower frequency of sampling is required). For shoreline-related features not accessible with a 4wd vehicle, such as a dune crestline, dune toe or vegetation line, or bayside shorelines—marsh, beach, and structurally engineered--not accessible with a 4wd vehicle, set the data logging interval to 5 seconds and walk the feature.

Download raw (c/a code) GPS data (*.ssf file suffix) from rover unit using Trimble Pfinder Office software to a personal computer (PC). Obtain GPS base station reference files that correspond to the times of field data collection. (e.g., URI GPS Base Station Internet Site http://gps.edc.uri.edu). Differentially correct each raw file using Trimble PFinder Office software using the Smart Code and Carrier Phase processing option and specify output of corrected records only in Advanced options. Select the appropriate coordinate system and datum and Export an Arc/Info Generate (ASCII) formatted file. Fire Island data were standardized to Universal Transverse Mercator (UTM) Zone 18, North American Datum 1983 (Zone 19 for Cape Cod). Using Arc/Info, convert the Generate file into an Arc/Info line coverage using the Generate command and Build line topology.
Example:

```
Generate <out Arc/Info coverage name>
        input <Generate file>
        end
        quit
Build <out Arc/Info coverage> line
```

Reference Shoreline Generation
Select a reference shoreline. Reference refers to the shoreline from which temporal changes are measured. Ideally, the coverage of this shoreline should be complete with no missing segments. Since other shorelines will be compared to this reference, data gaps will produce erroneous measurements using the methods described herein. There are, however, instances where inlets create natural breaks in coverage. Gaps in the reference datalayer will require custom editing to ensure that shoreline changes are being accurately calculated.

This approach involves measuring changes along the shoreline from series offset positions. These offset positions are calculated through a technique known as buffering (Figure A1). The reference shoreline R is buffered in a seaward direction by a distance greater than the maximum distance between the reference shoreline and any comparison shoreline. The reason for this is the routine used to compute the distance will measure to the nearest feature in the comparison dataset, so it is necessary to standardize the direction of measurement to the landward side of the buffered shoreline. Buffering by this distance ensures that all measurements between the reference and comparison shorelines are computed in the landward direction from the reference. Directionally standardizing these measurements is key to this approach.

Buffering is accomplished with the Arc/Info BUFFER routine. In this example we are using a 1979 shoreline obtained from the University of Maryland and called umd1979d2.

Example:
Buffer <in-reference shoreline> <out buffered reference shoreline> # # <buffer distance> <flat> <left/right>.
Where:
<in_cover> - input reference shoreline
<out_cover> - output buffered reference shoreline
- accept default value
- accept default value
<buffer_distance> - distance to buffer
<flat> - option for line connecting endpoints of original and buffered lines
<left/right>
For Fire Island, we used a buffer distance of 150 meters. The buffered shoreline should be isolated in ArcEdit by removing unwanted line segments. Also, select all lines and invoke the Unsplit routine in ArcEdit to remove pseudo-nodes.

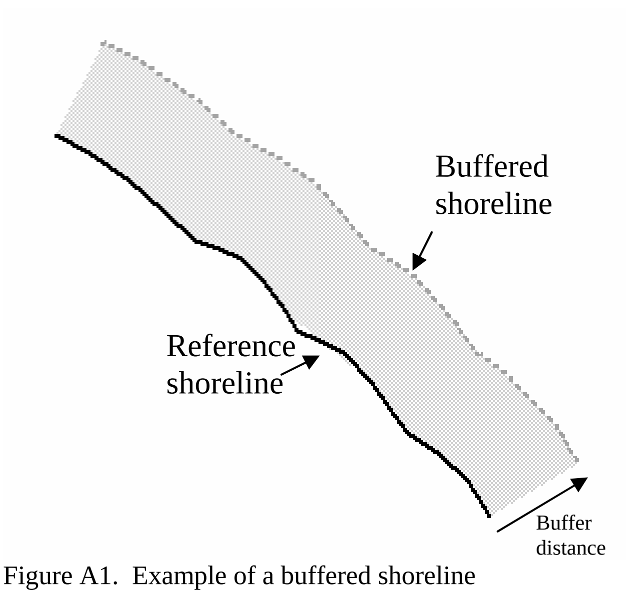

Figure A1. Example of a buffered shoreline

Once the buffered reference shoreline is created, measurement points at equal intervals along this line need to be defined. Distances to reference and comparison shorelines are measured from these points. A series of procedures that make use of Arc/Info's Dynamic Segmentation Model developed by Environmental Systems Research Institute (ESRI) aid in producing measurement points at equal intervals along a line segment (Brennan, email comm., 1996). First, a Route feature (with a corresponding Route Attribute Table) is created on the arcs that make up the buffered reference shoreline. This is accomplished in ArcEdit with the Makeroute command.

Example:
ArcEdit: Makeroute <subclass>
Where:
<subclass> is the name given to the route.
In this example we assigned the name int50m which stands for intervals at 50 meters.
Arcedit: Makeroute int50m

Next, an event table is created using an Arc Macro Language (aml) program. This event table defines the intervals that will be used to create measurement points along the buffered reference line.

```
/*A-------------------------------AUTHOR---------------------------------
/*
/*Original Coding:     ESRI
/*
/*N--------------------------------NAME---------------------------------
/*
/*INTERVAL.AML
/*Copyright 1995, Environmental Systems Research Institute, Inc.
/*
/*P------------------------------PURPOSE---------------------------------
/*
/*This macro will help a user to create a point event table.  It takes
/*a maximum number value (the highest measure of a route) and create
/*"stepped" records by an interval also specified by the user.
/*
/*U-------------------------------USAGE---------------------------------
/*
/*INTERVAL <interval> <max_value> {number_of_routes}
/*
/*V----------------------------VARIABLES--------------------------------
/*
/*int - the interval at which max will be divided by
/*max - the maximum or highest measure value of a route
/*num - the number of routes in the route_system
/*
/*C-------------------------------CALLS----------------------------------
/*
/*None
/*
/*===========================DISCLAIMER=======================
```

```
=========
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/*create derivative works of this AML for your own internal use.  All
/*rights not specifically granted herein are reserved to ESRI.
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/*possibilites of such damage.  This AML is not supported by ESRI.
/*
&args int max num

&if [NULL %int%] | [NULL %max%] &then
 &return Usage: Interval <interval> <max_value> {number of routes}

&if [NULL %num%] &then
 &s num 1

&if [EXISTS temp.eve -info] &then
 &s d [DELETE temp.eve -info]

&data arc info
ARC
DEF TEMP.EVE
ROUTE-ID,4,5,B
INTERVAL,4,12,F,3
[UNQUOTE ' ']
ADD
&do y = 1 &to %num%
&do x = 0 &to %max% &by %int%
%y%
%x%
&end
&end
[UNQUOTE ' ']
Q STOP
&end

&ret
```
Figure A2. ESRI Interval.aml. Subroutine for establishing measurement intervals along the buffered reference shoreline.

In the example below, we've supplied the following variables to interval.aml to produce a INFO database table:

Example:
Arc: &run interval.aml <interval> <maximum value>
Where:
<interval> - is the interval in distance units (m)
<maximum value> - distance over which intervals will be computed (m)

Arc: &run interval.aml 50 80000
Result: INFO table TEMP.EVE

ROUTE-ID,	INTERVAL
1	0.000
1	50.000
1	100.000
1	150.000
1	200.000
1	250.000
1	300.000
.	
.	
.	
1	80,000.000

The next step is to relate this event table to the Route Attribute Table established previously using Makeroute. This will create events at intervals specified in the event table (TEMP.EVE) along the buffered reference shoreline. The Eventsource command in Arc/Info establishes this intermediary relate environment.

Arc: Eventsource ADD POINT <source_name> <table_name> {database} {relate type} {route_key_item} {event_key_item} {measure_item}

Where:
<source_name> - name given to the relate environment to be established, this is arbitrary
<table_name> - event table
{database} – database file format of event table
{relate type} – sort order of the event key item
{route key item} - item in the Route Attribute Table from which the relate to <table_name> will be performed
{event_key_item} - name of the field in <table_name > which is related to the <route_key_item> in the Route Attribute Table
{measure_item} - an item in <table_name> which stores the interval data

In this example the following variables are inserted into the Eventsource routine:

Arc: Eventsource add point dist50m temp.eve info ordered int50m-id route-id interval

The next step is to apply the newly-established event environment to the buffered reference shoreline to create a coverage containing points representing selected point events in the event table. This is accomplished with the Eventpoint command.

Arc: Eventpoint <in_cover> <in_route_system> <event_source> <out_cover>

Where:
<in_cover> - buffered reference shoreline
<in_route_system> - name of route system created using Makeroute
<event_source> - name given to the event relate environment established with Eventsource
<out_cover> - name of the output point coverage

In this example the following variables are inserted into the Eventpoint routine:
Arc: Eventpoint usbu400m int50m dist50m ptsus400

The output point coverage contains points spaced at 50 meter intervals along the entire length of the buffered reference shoreline (Figure A3). Each point is coded with a ROUTE-ID and INTERVAL item in the point attribute table. A quality control check should be performed to verify and validate the results. This involves displaying the point coverage against the buffered reference shoreline and verifying the consistency of the INTERVAL item.

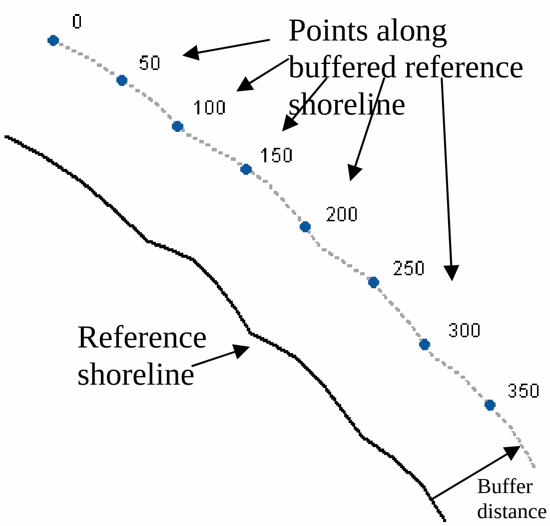

Figure A3. Results of Eventpoint showing points along buffered reference shoreline at 50 meter intervals.

Comparison shoreline preparation

Before running the program to calculate shoreline changes, it is necessary to prepare the comparison shorelines. In ArcEdit, edit the starting and ending points of the shorelines so that they correspond to the starting and ending points of the reference shoreline. Edit and remove spurious and out of range vertices in the comparison shoreline that can sometimes result from errors introduced through signal multipathing in GPS data. In ArcEdit, select all arcs and run the Unsplit routine to remove pseudonodes. Save changes and Build line topology at the Arc: prompt.

Calculating shoreline change

The algorithm used to calculate change is based on measuring the nearest distance from pre-defined points (i) at regular intervals along the buffered reference shoreline BR to the comparison shoreline T. Each distance measurement made at interval i from BR to T is subtracted from a corresponding measurement from BR to R at interval i. The difference is the net shoreline change between the reference shoreline R and the comparison shoreline T at interval i. To calculate change between a shoreline T and T^{+1} at interval i, subtract the change R to T from the change R to T^{+1}. Figure A4 contains a hypothetical example of this where:

R=reference shoreline
BR=reference shoreline buffered by 30m
T=comparison shoreline
T^{+1}=comparison shoreline mapped at a time greater than T
i=interval

Shoreline change at interval 0

from R_0 to $T_0 = (Br_0 - R_0) - (BR_0 - T_0)$
$10 = (30 - 0) - (30 - 10)$

from R_0 to $T_0^{+1} = (Br_0 - R_0) - (BR_0 - T_0^{+1})$
$0 = (30 - 0) - (30 - 0)$

from T_{i0} to T_{i0}^{+1} = (change R_0 to T_0^{+1}) – (change R_0 to T_0)
$^{-}10 = (0) - (10)$

Shoreline change at interval i

from R_i to $T_i = (Br_i - R_i) - (BR_i - T_i)$
$^{-}5 = (30 - 0) - (30 - {}^{-}5)$

from R_i to $T_i^{+1} = (Br_i - R_i) - (BR_i - T_i^{+1})$
$^{-}10 = (30 - 0) - (30 - {}^{-}10)$

from T_i to T_i^{+1} = (change R_i to T_i^{+1}) – (change R_i to T_i)
$^{-}5 = ({}^{-}10) - ({}^{-}5)$

Shoreline change at interval 2i

from R_{2i} to $T_{2i} = (Br_{2i} - R_{2i}) - (BR_{2i} - T_{2i})$
$20 = (30 - 0) - (30 - 20)$

from R_{2i} to $T_{2i}^{+1} = (Br_{2i} - R_{2i}) - (BR_{2i} - T_{2i}^{+1})$
$10 = (30 - 0) - (30 - 10)$

from T_{2i} to T_{2i}^{+1} = (change R_{2i} to T_{2i}^{+1}) – (change R_{2i} to T_{2i})

$^{-}10 \quad = \quad (10) \quad - \quad (20)$

Shoreline change at interval 3i

from R_{3i} to T_{3i} = ($Br_{3i} - R_{3i}$) – ($BR_{3i} - T_{3i}$)

$^{-}30 \quad = \quad (30 - 0) \quad - \quad (30 - {}^{-}30)$

from R_{3i} to T_{3i}^{+1} = ($Br_{3i} - R_{3i}$) – ($BR_{3i} - T_{3i}^{+1}$)

$^{-}20 \quad = \quad (30 - 0) \quad - \quad (30 - {}^{-}20)$

from T_{3i} to T_{3i}^{+1} = (change R_{3i} to T_{3i}^{+1}) – (change R_{3i} to T_{3i})

$10 \quad = \quad ({}^{-}20) \quad - \quad ({}^{-}30)$

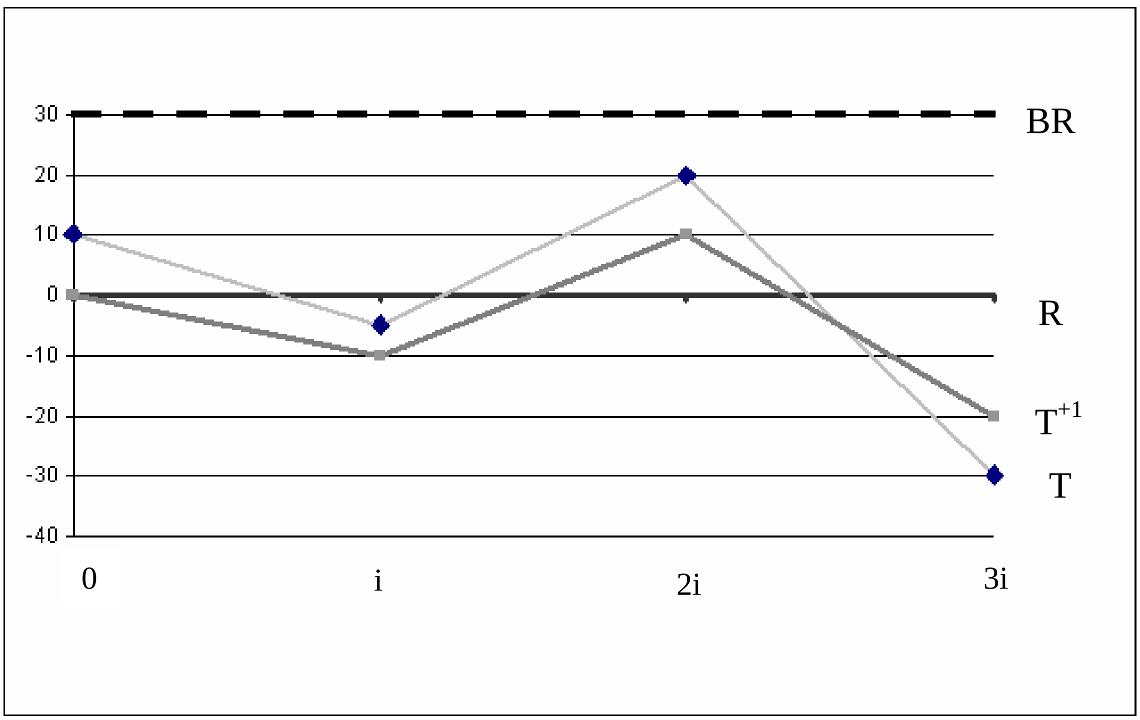

Figure A4. Hypothetical multi-temporal shoreline comparisons from a reference shoreline, R.

Shoreline change will be derived by measuring the distance between each buffered reference point to the nearest location along the arc of the comparison shoreline. This is accomplished with the Near routine.

Example:
Arc: Near <in_cover> <near_cover> {line} {search_radius} {out_cover}

Where:
<in_cover> - point coverage produced using Eventpoint
<near_cover> - the comparison shoreline coverage

{line} – topological feature to be searched from <in_cover>
{search_radius} – maximum distance in coverage units between <in_cover> points and <near_cover> arcs for which distance will be calculated.

Before running comparison shorelines through this procedure, it is necessary to first process the reference shoreline. In this example the following variables are inserted into the Near routine:

Arc: Near pts79b150 umd1979d2 line 160 near79b79 location

The Near routine adds an item called DISTANCE to the <out_cover> point attribute table. Output the values from the item DISTANCE in INFO to an ASCII file.

Example:
Arc: info
ENTER USER NAME>ARC
SEL NEAR79B79.PAT
OUTPUT N79B79.TXT
PRINT INTERVAL,DISTANCE
Q
STOP

Open and import the output of this using a spreadsheet application such as Microsoft Excel (see Figure A5, column D). To further validate the integrity of the buffered point reference shoreline, inspect the output of the distance values for outliers and to verify that distances are tight to the buffer distance, in this case 150 meters (mean 149.73, standard deviation 0.38, minimum 147.94, maximum 150.23). Retain this column for it will be used in the calculations as the distance from BR to R at interval i to n, where n is equal to the number of intervals or measurement points along the buffered reference shoreline.

Next, run a comparison shoreline (August 1996) through the Near routine and output the measurement results to an ASCII file. Import this file as a new column in the spreadsheet (refer to Figure A5, column E). To calculate shoreline change from the reference shoreline (1979) to the comparison shoreline (August 1996), create a new column (column F) by subtracting the column values containing the results of the comparison shoreline distances (column E) from the column containing distances from the reference shoreline (column D). Use the Chart tools in Excel to graph the changes.

To calculate "end point" shoreline change between two comparison shorelines (e.g. August 1996 and September 1996), subtract the results of change between both comparison shorelines and the reference shoreline (refer to Figure A5, column H4-F4). This column of differences represents changes resulting from a storm. Again, use the Chart tools in Excel to graph the changes.

	A	B	C	D	E	F	G	H	I
1		cumulative	cumulative	buffer		change		change	change
2	sample point	dist. m	dist km	ref to 79	ref to 8/96	79 to 8/96	ref to 9/96	79 to 9/96	8/96 to 9/96
3						D4-E4		D4-G4	H4-F4
4	1	0	0	149.463	114.008	35.455	129.431	20.032	-15.423
5	2	50	0.05	149.922	110.634	39.288	126.837	23.085	-16.203
6	3	100	0.1	149.613	109	40.613	124.573	25.04	-15.573
7	4	150	0.15	149.956	107.871	42.085	128.913	21.043	-21.042
8	5	200	0.2	150.164	106.606	43.558	129.821	20.343	-23.215
9	6	250	0.25	149.991	105.864	44.127	128.316	21.675	-22.452
10	7	300	0.3	150.181	107.4	42.781	128.933	21.248	-21.533
11	8	350	0.35	150.077	107.549	42.528	132	18.077	-24.451
12	9	400	0.4	149.978	107.18	42.798	128.937	21.041	-21.757
13	10	450	0.45	149.128	110.444	38.684	129.551	19.577	-19.107

Figure A5. Section of a Microsoft Excel Worksheet containing shoreline change data for Fire Island NS.

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