AN ASSESSMENT OF SPATIAL VARIABILITY IN WATER LEVEL OBSERVATIONS AND SUSCEPTIBILITY TO INUNDATION FROM COASTAL STORMS IN A DEVELOPED ESTUARY, RARITAN BAY, NEW JERSEY

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ABSTRACT OF THE DISSERTATION

An Assessment of Spatial Variability in Water Level Observations and Susceptibility to Inundation from Coastal Storms in a Developed Estuary, Raritan Bay, New Jersey

by JOHN F. DOBOSIEWICZ, Ph.D.

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Coastal flooding is an integral part of the development of natural estuarine ecosystems but also threatens human populations living along estuarine shores. A study was conducted on the Raritan Bay, New Jersey shore to determine the spatial variability of elevated water levels from coastal storms and the physical controls on susceptibility to inundation. Raritan Bay is used as a study site because it is a developed estuary with a high population density and a variety of flood mitigation strategies in place. Water levels are identified from wrack (debris) lines on field profiles 200 m apart over 10 km of shoreline for five storms. Elevations on the field profile are referenced to a standard datum for comparison throughout the study area. The greatest spatial variability of water levels between sites from the observed storms was 1.7 m. Variability in water levels at the same site for different storms is used to evaluate site-specific relationships between shoreline characteristics and storm conditions. Fourteen onshore variables are determined from the field profiles and include natural and human-altered geomorphic features. Thirty-three offshore variables, including bathymetry and fetch, are determined or calculated from data derived from digital nautical charts. Fifteen of the variables are significantly correlated to water levels, with only one variable, the maximum elevation of the profile, correlated to all five storms. Correlated variables were categorized into five susceptibility classes and combined to produce two susceptibility indices using a Geographic Information System (GIS). The first index uses onshore and offshore variables to determine susceptibility to actual inundation. The second index uses only offshore variables to determine susceptibility to potential inundation. Water levels are highest where hard, vertical shore protection projects exist, suggesting that these structures increase water levels and susceptibility to actual inundation of human structures landward of them. Marshes and nourished beaches reduce water levels and susceptibility to actual inundation of human structures landward of them. Site-specific coastal data analysis and the use of GIS are consistent with modern research objectives to develop and enhance digital coastal databases and advance current flood mitigation based on single flood elevations for entire shorelines.

Acknowledgement and Dedication

My dissertation advisor, Dr. Karl F. Nordstrom provided insight and guidance as well as patience and tolerance and deserves my sincerest gratitude. The expertise imparted by members of the committee, Dr. Nancy Jackson, Dr. Robert Hordon, and Dr. David Robinson, is also greatly appreciated. Dr. Nancy Jackson also helped in the early formulation of the proposal and with the initial field study. I would like to thank Valerie Spalding and Michael Craghan for assistance in the field. Chris Rasmussen of the United States Army Corps of Engineers graciously provided information for identifying benchmarks in the field and Bria O'Conner from the National Oceanic and Atmospheric Administration provided information on historical water level observations. I would like to acknowledge support from the NOAA Office of Sea Grant and Extramural Programs, U.S. Department of Commerce, under Grant No. R/S 950060. This dissertation is dedicated to my wife, Diana, and children, Hailey, Christian, Jack, and Faith, my parents, Julia and John "Chevy", and "Os Meus Sogros", for providing support and the daily motivation to bring this dissertation to completion.

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Problem Statement

Modern coastal hazards research recognizes that a diverse set of variables must be assessed to determine where coastal hazard mitigation should take place (Heinz Center 2000). In physical geographic research (Bray, Hooke, and Carter 1997; Owens, Richards, and Spencer 1997; Agnew and Spencer 1999; Thomas et al. 1999) and coastal research (Bartlett, Devoy, and Scalise 1992; Kaluwen and Smith 1997; Pope 1997; Hubert and McInnes 1999), collecting data at local scales is critical for evaluating the physical variables that cause variability in the susceptibility of shorelines to storm inundation. Numerous research studies exist that assess flood hazards from geographical perspectives including cost-benefit analyses (Palm 1990; White 1988; Cutter 1994; Hewitt 1997; Heinz Center 2000; FEMA 1997), personal coping strategies and human adjustments (Hewitt 1997), decision making and policy response (White 1973), human behavior (Kates 1985), response based on experience (Smith 1992); societal and temporal context (Mitchell, Devine and Jagger 1989), geomorphology (Gares, Sherman, and Nordstrom 1994) and the connection and operation of social systems (Blaikie et al. 1994). Some research focuses on coastal flooding using specific geographic issues or methods such as social justice or gender (Zoleta-Nantes 2000), planning and evacuation (Van Willigan et al. 2002), the relationship between gender and evacuation (Bateman and Edwards 2002), mapping (Leatherman 1983; Pilkey and Neal 1993; Dolan, Fenster, and Holme 1992; Pajak and Leatherman 2002) and Global Positioning Systems (McDermott and Hatheway 1997). Even greater emphasis in coastal hazards research is given to coastal erosion studies (Mitchell 1974; Sorensen and Mitchell 1975; Phillips 1985, 1986; NRC 1990; Dunn, Friedman, and Baish 2000; Heinz Center 2000; Zhang, Douglas, and Leatherman 2000) and the vulnerability of shorelines around the world to accelerated sea level rise associated with climate change (Barth and Titus 1984; NRC 1987; IPCC 1990; Gornitz 1991b; Titus et al. 1991; Bray, Hooke, and Carter 1997; Kaluwen and Smith 1997; Capobianco et al. 1999). Recently, Tropical Storm Floyd caused enough damage on the East Coast of the United States to spur specific research in flood insurance (Gares 2002) and mapping (Wang 2002). Within this extensive research framework in physical geography and coastal flood hazards, a clear need remains to generate general and site-specific research to evaluate coastal storm impacts along both ocean and estuarine shorelines, on local, state and federal levels (Wood 1990). Estuaries have been neglected in coastal hazards research because of the perception of low risk (Gornitz et al. 1994).

Risk is often used as an all-encompassing term in hazards research (Hewitt 1997). Risk has been used to signify the probability and magnitude of physical processes occurring at locations (Mitchell, Devine, and Jagger 1989) or losses due to a hazard event (Heinz Center 2000). Vulnerability has been used to signify the ability of the human and natural characteristics of an environment or population to incur losses from an event (Mitchell, Devine, and Jagger 1989; Hewitt 1997; Heinz Center 2000). Susceptibility is a term similar in definition to vulnerability but rarely used in the literature. This dissertation addresses a research need to identify spatial variability in inundation along a developed estuarine shoreline. The susceptibility to inundation of specific sites is influenced by the exposure of the shoreline to storm conditions and onshore characteristics that control the propagation of water inland. Susceptibility to inundation is a suitable term for this dissertation because the analysis conducted is contingent on actual water level observations and offshore and onshore characteristics documented at study sites and not probabilities of losses incurred by populations or damages to infrastructure that are speculative. Risk and vulnerability are used in this dissertation in reference to other studies that address these other aspects of coastal hazards.

Storm-Induced Water Levels

Coastal storms cause elevated water levels along ocean and estuarine shorelines in the form of storm surge. Storm surge can be categorized as a long gravity wave (Murty and Holloway 1985) and the waveform is modified by nearshore and foreshore conditions. Coastal flooding in estuaries is caused by external (ocean) and internal (within estuary) forces (Ward 1978). Storm surge produces elevated water levels upon which waves will propagate, and water levels are further modified within an estuary by local winds (Miller 1988). Elevated water levels cause geomorphic change high on the profile of sandy beach and dune systems (Kriebel and Dean 1993) (Figure 1.1) and along developed estuarine shores where shoreline protection structures such as bulkheads are placed at the foreshore (Figure 1.2).

Establishing the storm surge penetration line following coastal storms appears to be critical for coastal management (Dolan, Hayden, and Heywood 1978b) and its value should be assessed in the field. The development and propagation of storm surge in estuaries is complex (Miller and Wei 1987) and is a function of broad, meso-scale storm parameters and local, microscale shoreline parameters (Dolan and Hayden 1981;

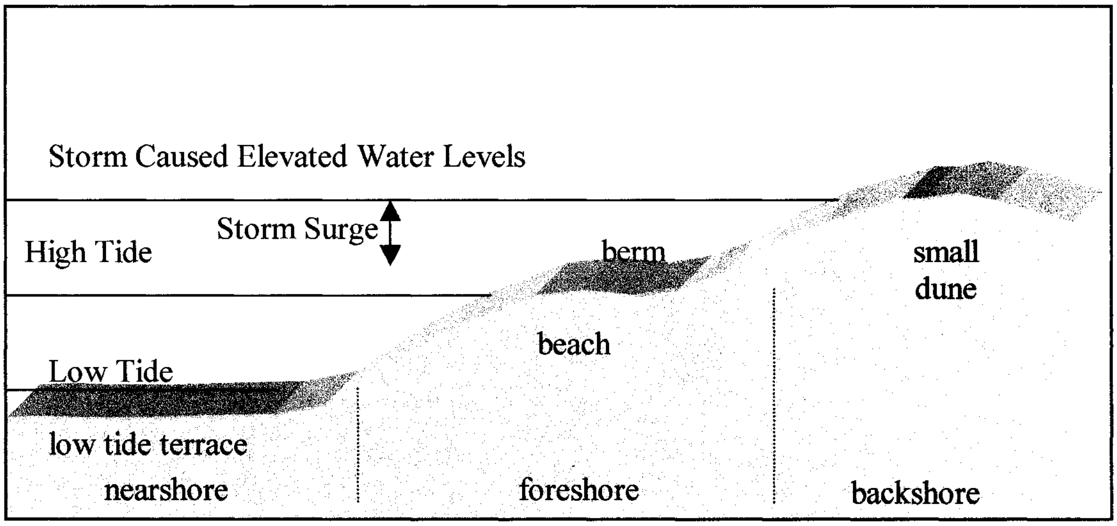


Figure 1.1 - Locations of nearshore, foreshore and backshore for a natural, sandy estuarine shoreline.

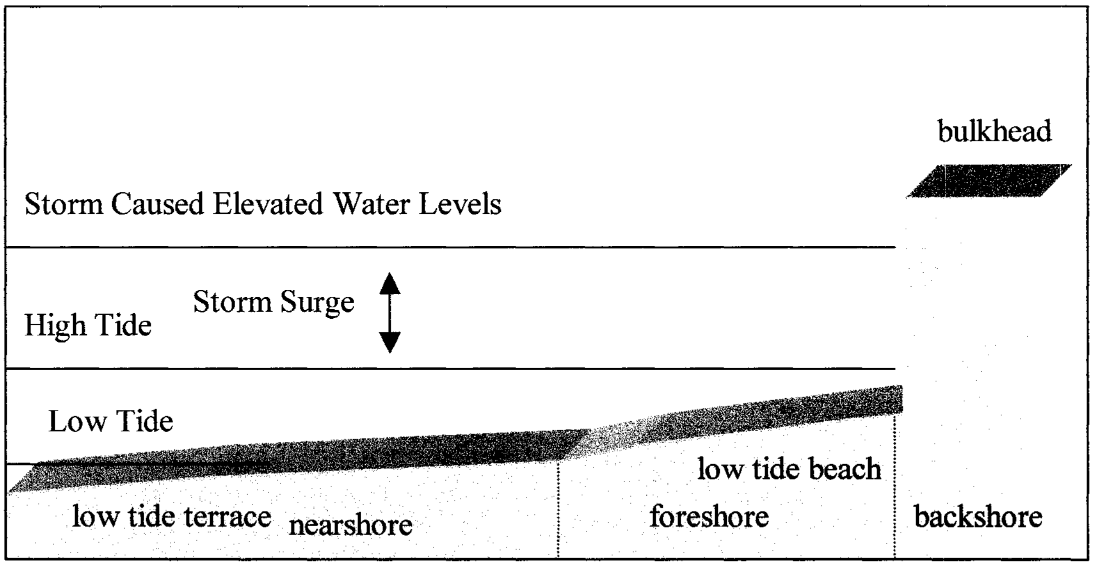


Figure 1.2 - Locations of nearshore, foreshore and backshore for a developed estuarine shoreline with a bulkhead.

Dendrou, Moore, and Myers 1985; Sheffner, Borgman, and Mark 1996; Bode and Hardy 1997). The evaluation of vulnerability to elevated water levels from storms in developed estuaries is complicated by the persistent modifications of the environment by people (Roman and Nordstrom 1996). The engineering strategies used to combat coastal erosion, such as armoring the shoreline with shore parallel structures, are often used to reduce storm flood damages (Pope 1997). Estuarine shores may not flood during normal flood tides because of these protection strategies (Ward 1978). Studies have not evaluated the spatial variability of elevated water levels from coastal storms at the site level and the connection between susceptibility to inundation and storm conditions and shoreline characteristics, including human modifications. An evaluation of the spatial distribution in flood water levels determined from statistical analysis of water levels from tide gages indicates that storm-caused water levels vary between sites kilometers apart in a large, funnel-shaped developed estuary (Dobosiewicz 1997).

This dissertation is designed to evaluate both the spatial variability of elevated water levels within a developed estuary and the storm characteristics and shoreline parameters that cause this variability. Variables that represent offshore, nearshore, foreshore and backshore characteristics that affect the distribution of storm surge and the propagation of water levels up cross-shore profiles along a developed estuarine shoreline are correlated to elevated water levels. The dissertation helps fill the research need to integrate data in coastal area vulnerability assessment (Capobianco et al. 1999), with a focus on integrating offshore and onshore characteristics and storm conditions with post-storm water level observations in the field. The results of this study advance current flood mitigation by producing information about the physical controls on elevated water levels at local scales. Current flood mitigation is typically based on a single statistically derived flood elevation employed over a large spatial scale, such as an entire estuarine shoreline.

Coastal Hazards and Mitigation

The portrayal of coastal hazards, hazard mapping and mitigation is in need of evaluation because of outdated maps and the lack of detailed coastal data (Monmonier 1997). Mitigation is defined as a sustained action that reduces or eliminates the long-term risk of people to a hazard (FEMA 1997). Site-specific post storm data is not frequently collected and used for policy-making, and since the United States has no formal national policy in response to coastal hazards, public and private efforts are often mixed together with little insight to when action, such as mitigation, is taken (Platt 1994). There is a need to document and address factors, e.g., mitigation, that reduce coastal vulnerability over time and space (Pulwarty 1999).

Often coastal management is not mitigation but short-term response, as in scenarios that follow catastrophic hurricane storm surges and wave damage (Wiegel 1987). Sand bags and loosely configured revetments are used as emergency measures and often left in place as a solution. Shoreline protection strategies in developed estuaries have not been accurately identified in databases used for coastal management because many small-scale projects by local residents are not documented (Deaton, Noble, and Chappell 2003). More effective response or mitigation is contingent upon accurate identification of structures and a detailed understanding of the interaction between physical processes and human impacts (Wiegel 1987). One of the key components that shape a coastal zone is the local effect of large storms encountering the shoreline (Godschalk, Brower, and Beatley 1989). Detailed site-specific studies that have the spatial resolution to assist coastal zone management are lacking. There is a need to produce site-specific research to assess coastal hazard impacts at local, state and federal levels (Smith and Piggott 1987; Handmer 1999; Wood 1990).

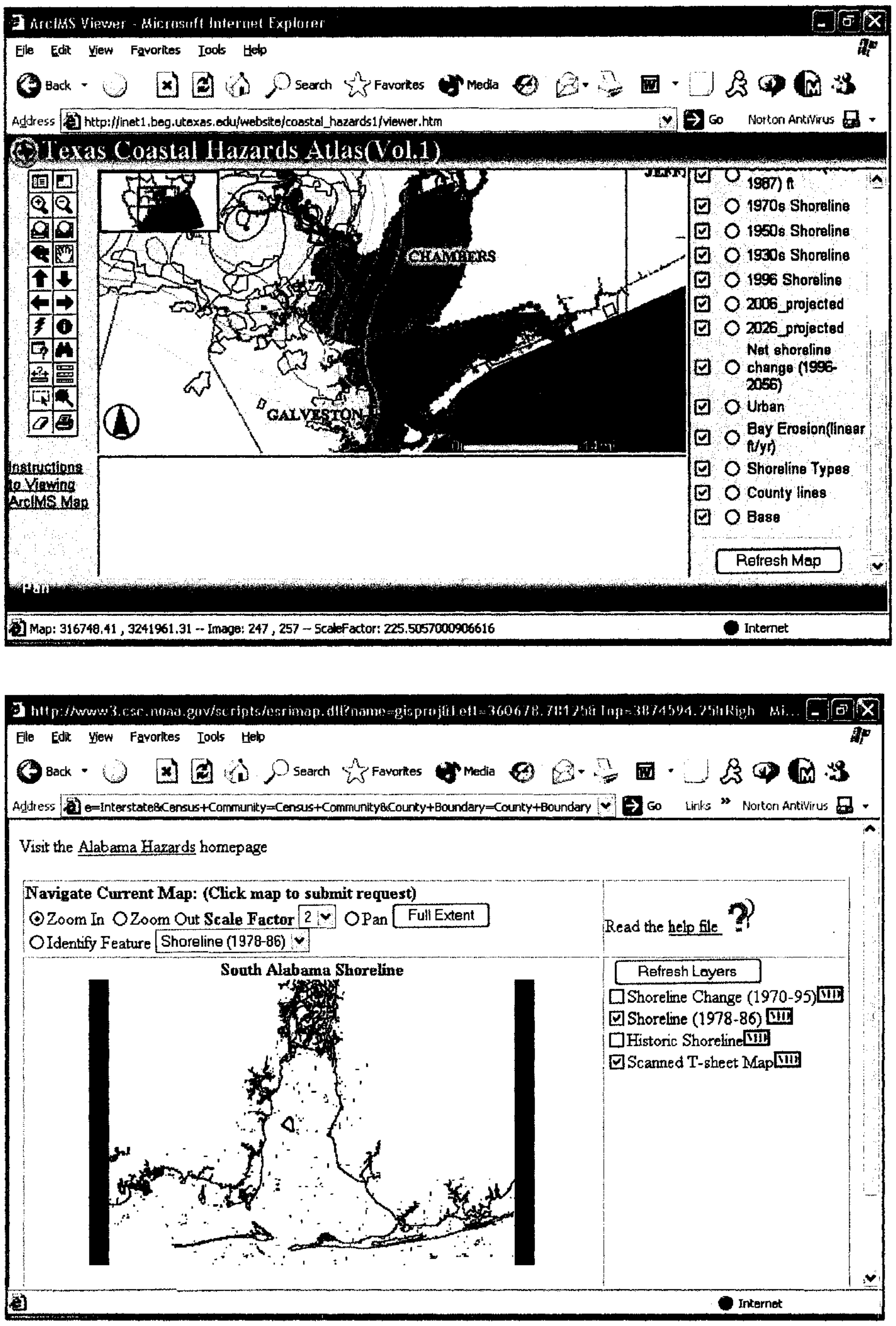
Mitigation policy and action are influenced by many geographic and coastal factors, but actual mitigation that is based primarily on knowledge of coastal processes is rare (Bush and Pilkey 1994). For instance, county or municipal borders and property lines are used as the boundaries for mitigation, rather than the spatial extent of the physical processes that cause risk and vulnerability (Slaughter 1964). Coastal data sets are limited by these boundaries (Bartlett, Devoy, and Scalise 1992). Different datum planes are used with no one standard adopted, for example, National Geodetic Vertical Datum of 1929 (NGVD 1929), and new shoreline protection structures are not adequately identified, which reduces the ability of municipalities to effectively respond to and mitigate hazards (Bartlett, Devoy, and Scalise 1992, NOAA 2003). Data within municipalities and counties and between shoreline reaches and sites must be integrated to overcome multi-scalar factors that limit coastal zone hazard assessment. Topographic profiles of cross-shore transects and water level observations following storms that are referenced to the same datum can be used to evaluate variability between sites throughout an entire study area.

People have three options for mitigating coastal flooding hazards; maintain nature, control nature, or give nature some latitude (Pope 1997). All three options are possible along estuarine shores as either retreating entirely to give nature its space, building up land and property on flood embankments or managed retreat (Pethick 1993, 2002). Retreat through land acquisition is now viewed as not only possible but also desirable along ocean shores (Godschalk et al. 2000). However, retreat is restricted in highly populated coastal areas, such as urban estuarine shorelines, leaving the construction of flood embankments as the most common mitigation strategy (Jackson 1996). Implementing managed retreat over the construction of flood embankments requires a trade-off between the horizontal displacement of development inland and the vertical displacement of the shoreline while maintaining the location of development. This dissertation addresses the trade-off between horizontal and vertical space along the shoreline by quantifying and evaluating water level elevations and the height and position of flood embankments and other strategies that are used to mitigate inundation from coastal storms.

Data and Geographic Information Systems (GIS)

The role of Geographic Information Systems (GIS) and the production and dissemination of data in digital format are expanding in applied and hazards geography (Pacione 1999; Thomas et al. 1999) and marine and coastal studies (Gornitz et al. 1994; Daniels 1996; Thumerer, Jones, and Brown 2000; Wright and Bartlett 2000). GIS is suggested as a tool that is essential to modern coastal hazards research (Heinz Center 2000) and as a means to achieve better coastal monitoring (Smith and Piggott 1987; Langren, Larsen, and Baybrook 1993; Hickey, Bush, and Bouley 1997). GIS can spatially combine existing flood zone information with new data collected at a scale better suited to portray spatial variability in coastal storm flood hazard along shores. Nevertheless, only a few states in the United States have actively engaged in creating comprehensive digital databases that can be realistically used by planners. Alabama has worked with various federal agencies to produce a coastal hazards assessment CD-ROM in 1997 (http://www.csc.noaa.gov/products/alabama/startup.htm) (Figure 1.3). Texas has developed a two volume Coastal Hazards Atlas with shoreline types plotted as points at ≈ 1 km intervals (http://inet1.beg.utexas.edu/website/coastal_hazards1) (Figure 1.3). Few research studies exist (Gornitz et al. 1994; Daniels 1996) that actively incorporate GIS and coastal hazards but there is a national initiative (USGS 1998) to develop a GIS-based inventory of the physical and social variables that cause coastal change. South Carolina has a digital atlas of environmental hazards (Thomas et al. 1999) and is the pilot study area for the U.S. national coastal assessment. Coastal data can be obtained directly via field surveys, or indirectly as a by-product of other published materials (Wright 2000). There is a need to develop data using GIS for coastal hazard mitigation that makes use of information from various sources and can be widely disseminated and used at federal, state, county and municipal levels (Heinz Center 2000, NOAA 2003).

Studies that have formulated vulnerability indices and digital coastal maps or quantify geomorphic variables (Gornitz 1991a; Gornitz and White 1992; Jensen et al. 1993; Gornitz et al. 1994; Daniels 1996; Solomon, Kruger, and Forbes 1997) do not evaluate the indices using post storm water levels or other post storm impacts, such as erosion. A coastal vulnerability index developed for sustainable coastal management reveals that within a large-scale landform, such as an estuary, many "nested" landforms



http://inet1.beg.utexas.edu/website/coastal_hazards1/viewer.htm

☑ ○ 1987) ft
☑ ○ 1970s Shoreline
☑ ○ 1950s Shoreline
☑ ○ 1930s Shoreline
☑ ○ 1996 Shoreline
☑ ○ 2006_projected
☑ ○ 2026_projected
☑ ○ Net shoreline change (1996-2056)
☑ ○ Urban
☑ ○ Bay Erosion(linear ft/yr)
☑ ○ Shoreline Types
☑ ○ County lines
☑ ○ Base

Map: 316748.41 , 3241961.31 -- Image: 247 , 257 -- ScaleFactor: 225.5057000906616

http://www3.csc.noaa.gov/scripts/esrimap.dll?name=gisprojf&Left=360678.781258 Top=3874594.25&Righ

e=Interstate&Census+Community=Census+Community&County+Boundary=County+Boundary

Visit the Alabama Hazards homepage

Navigate Current Map: (Click map to submit request)
● Zoom In ○ Zoom Out Scale Factor 2 ○ Pan
○ Identify Feature Shoreline (1978-86)

Read the help file

South Alabama Shoreline

☐ Shoreline Change (1970-95)
☑ Shoreline (1978-86)
☐ Historic Shoreline
☑ Scanned T-sheet Map

Figure 1.3 – Internet map servers for GIS-based coastal analysis for Texas (top) and Alabama (bottom).

exist, for example beaches and marshes, that have multiple and varied vulnerabilities to the same process, such as sea level rise (Pethick and Crooks 2000). Only one study evaluates post storm flood data using quantitative techniques (Fletcher et al. 1995) but GIS is not used. No studies use GIS to incorporate post storm water level data collected at local scale (less than a kilometer) with shoreline characteristics and storm conditions. There is a need to use data including post-storm water levels, historical qualitative and quantitative observations of coastal storm impacts to evaluate risk and vulnerability indices and the location of modern flood zone boundaries used by planners. GIS should be used to analyze new ways of evaluating risk and vulnerability, such as quantifying storm-caused water levels to determine spatial variability in susceptibility to inundation at local scales.

Storm Conditions and Shoreline Characteristics

The storm conditions that are used to empirically model storm surge in developed estuaries include storm intensity, which is a function of pressure gradients, and track, which is a function of upper atmospheric dynamics (Zabawa and Ostrom 1982). Pressure gradient and track are useful in predicting large-scale variations in storm surge along relatively homogenous coasts but are not useful for evaluating actual water levels at local scales. Wind characteristics are used as a surrogate for pressure gradients and track. Sustained hourly wind speeds and peak wind gusts are commonly used for evaluating waves and the propagation of storm surge along estuarine shores (Armbruster, Stone, and Xu 1995; Jackson 1995). Wind direction is critical for creating elevated water levels within estuaries (Miller 1988). Wind duration is an indicator of the intensity of coastal storms (Davis, Dolan, and Demme 1993).

Flooding in estuaries is related to large-scale storm conditions and the modification of storm surge within the estuary by shoreline planform and cross-shore profile characteristics (onshore and offshore). Offshore variables include bathymetry, fetch and nearshore factors, such as slope of the low tide terrace, that modify waves (Stive and Wind 1982; Miller and Wei 1987; Kobayashi and Wurjanto 1989; Westerink et al. 1992; Titov and Synolakis 1995). Onshore variables include shoreline orientation, foreshore and backshore geomorphology and topography, and the location of structures within the inter-tidal profile (Everts 1985; Miller and Wei 1987; Swift 1993; Kobayashi and Karjardi 1994; Kobayashi and Raichle 1994; Morton and Speed 1998). Digital nautical charts are used to quantify offshore variables and field surveys are used to quantify onshore variables.

Many studies relate storm conditions to coastal flooding (Dolan and Hayden 1981; Dolan, Hayden, and Heywood 1978b, Dolan, Fenster, and Holme 1992; Dolan and Hayden 1993; Young, Thieler, and Pilkey 1993; Dolan and Davis 1994) but few studies in coastal flooding research incorporate post-storm water elevations tied into a standardized datum plane, such as NGVD 1929, to allow for comparisons between different sites or to predicted flood elevations. A study of overwash in Hawaii caused by Hurricane Iniki determined that coastal flooding is a function of shoreline orientation, offshore slope, friction, and wave set-up (Fletcher et al. 1995). There is a need to determine the onshore and offshore factors that mitigate and exacerbate flooding along developed estuarine shorelines. The factors identified in the study of Hurricane Iniki mitigate and exacerbate flooding along ocean shores, but the factors that that mitigate and exacerbate flooding along estuarine shores have not been verified with post storm water level observations referenced to an elevation standard.

Waves and Wave Run-up

The study of wave run-up is of great importance for coastal researchers because wave run-up represents the zone of interaction for erosion and flooding between the sea and the shore (Komar 1998). The variables that influence wave run-up affect the height of elevated water levels along developed estuarine shorelines. Wave run-up during storm-caused elevated water levels along the shore is a function of wave set up, controlled by nearshore and foreshore variables, and swash, controlled by foreshore and backshore variables (Holman and Guza 1984). Wave run-up can similarly be described as a function of the nearshore, foreshore and backshore variables of surf conditions, slope and nonlinear effects (Ahrens and Titus 1985). The effects of slope, permeability and surface roughness on wave run-up have been modeled in the laboratory (Ahrens and Titus 1985; Ward, Wibner, and Zhang 1998; Mase 1989; Walton and Ahrens 1989; Wurjanto and Kobayashi 1993; Liu and Cho 1994). Wave run-up has been evaluated in the laboratory on specific coastal structures such as revetments (Ahrens and Heimbaugh 1988; Kobayashi and Raichle 1994; Ward, Wibner, and Zhang 1998), and in the laboratory and field for natural beaches (Holman and Guza 1984, Briand and Kamphius 1993; Walton 1994) and dunes (Kobayashi, Tega, and Hancock 1996). Wave run-up is evaluated in this dissertation as a visual water level elevation on the cross-shore profile rather than using process data because sophisticated instruments are not available to municipal managers.

Elevated Water Level Indicators

Aerial photography is frequently used to survey damage after major storms. Aerial photography is useful where sand is abundant and overwash deposits and dune blowouts are conspicuous (Dolan, Hayden, and Heywood 1978a, 1978b; Dolan, Hayden, and Felder 1979a, 1979b; Pilkey and Neal 1993; Dolan, Fenster, and Holme 1992). Estuarine beaches are naturally small and compartmentalized with relatively coarse sands and gravels and low dunes (Nordstrom 1992) and may only be broad and composed of finer sands in areas of beach nourishment. The lack of wide sandy environments in estuaries limits the usefulness of aerial photography for identifying spatial variability in elevated water levels from storm overwash deposits. High water lines can be determined photogrammetrically from the "wetted" bound, the marking delineating wet and dry sand or from wrack (storm debris) lines. Pajak and Leatherman (2002) have demonstrated that Global Positioning Systems (GPS) can be used to map water levels from markings and lines in the field. However, while highly accurate coordinate points may be obtained from GPS (Morton et al. 1993), it is extremely expensive and yields no better vertical accuracy than determining water levels from the elevation of a wrack line from a local benchmark and field surveying techniques.

Monitoring wave energies along sheltered shorelines is common (Bauer 1990; Jackson 1995) but these studies generally do not monitor the resulting water level on the shoreline profile in different parts of the basin. The methodology in this dissertation is not designed to explicitly discern the cause of variability in inundation elevations from coastal storms, (e.g., subharmonic energies) but rather to examine how the flooding signature varies throughout an estuary in response to different shoreline characteristics (ie: shoreline orientation, beach slope). In situ monitoring of wave conditions at a number of field sites necessary for adequate spatial and temporal coverage of spatial variability would require extensive equipment and funding. The use of wrack lines and surveying techniques is not as technologically or fiscally constraining as in situ deployment of pressure transducers.

Most post storm evaluations are reconnaissance level qualitative evaluations especially of property damage and loss (Nordstrom and Jackson 1995). The physical imprints of coastal storms are overwash sands, wrack lines, or vertical flood levels (Nordstrom and Jackson 1995). Wrack lines along estuarine shores are composed of sea grass (*Zostera Marina*), sea lettuce (*Lactuca Una*) marsh grass (*Spartina*) and reed grass (*Phragmites Australis*) (Nordstrom 1992). Wrack lines that are identified at different sites for the same storm can be used to assess spatial variability in elevated water levels if referenced to a geodetically standardized datum. The use of wrack lines in this study can be replicated easily at local scales following storms and addresses the general coastal research need to monitor shorelines following storms by quantifying water levels.

Models

Storm surge models that project elevated waters proliferate in coastal engineering research. One limitation of these models is that the computer grid sizes and subsequent water level calculations are too broad for site-specific application (Oey, Mellor, and Hires

1985; Shaffer, Jelesnianski, and Chen 1986; Miller and Wei 1987). Another limitation is that models only provide vertical water level heights (Oey, Mellor, and Hires 1985; Shaffer, Jelesnianski, and Chen 1986; Briand and Kamphius 1993) while inundation is also a function of waves propagating up foreshore and backshore profiles (Walton 1994). This dissertation addresses the need to collect and analyze nearshore, foreshore and backshore data at scales smaller than those used in current storm surge models. Another limitation is that most models are designed to study circulation and mixing in estuaries or simple tidal propagation, not storm impacts (Oey, Mellor, and Hires 1985; Moses and Blair 1988; Kim, Johnson, and Gebert 1994; Smith 1994). The storm inputs necessary for site-specific analysis have not been adequately quantified in current storm surge models (Lipa and Barrick 1986).

Hurricane models such as SLOSH (Sea-Land Overwash and Surge Height) only incorporate the timing of storms relative to tides and waves, forward speed, landfall point and a wind direction variable (Jarvinen and Lawrence 1985; Shaffer, Jelesnianski, and Chen 1986). Extra-tropical cyclone storm surge models are designed for the entire East Coast and only provide single values for entire bays or continuous ocean shorelines (www.nws.gov). Models are limited because storm surge and resulting flooding is more complicated than a unique set of broad scale physical parameters (Miller 1988). This dissertation does not provide information that current models can incorporate to predict storm surge but provides information that future models might consider in evaluating local scale variability in water levels.

Relationship to the Coastal Hazards Research Paradigm

The modern hazards research paradigm and associated funding is described by some geographers as technocratic; a combination of science, technology and institutions (Hewitt 1997). The technocratic approach is grounded in the belief that hazards are not normal events and are external rather than internal societal occurrences. Therefore, the role of the scientist, engineer or agency in evaluating when and where a hazardous event may occur and the impacts of the hazard are more important than local knowledge. Local knowledge includes experience (Palm 1990), public education (Pulwarty 1999) and economic, social and environmental issues (Heinz Center 2000).

The mitigation of coastal flooding hazards by implementing hard fixed engineered structures, common in the United States (Psuty 1988; Finkl 2002) illustrates the modern technocratic hazards research paradigm. Wooden bulkheads and sloping revetments (some not professionally engineered) are commonly used in developed estuaries because the materials are less expensive than concrete seawalls (Zabawa and Ostrom 1981; Nordstrom 1992). The use of a hard, fixed structure in estuaries to combat coastal storm impacts varies on local scales and competes with other factors such as access to the shoreline. Access and view are critical to the bayshore's appeal (Nordstrom et al. 1986). The construction of a steel sea wall in the Highlands community in Raritan Bay, New Jersey was viewed with skepticism in a local newspaper article titled "Scenic views of the bay are just out of sight" (Larini 1998). The residents were concerned that the seawall, constructed at a height of 11.9 feet above sea level and a cost of 1.2 million dollars, negated the beauty of the natural shoreline. Structures must be built to the elevation of the 100-year flood in Raritan Bay (11.9 feet above sea level) as required by the Federal Emergency Management Agency to acquire governmental funding.

Detailed and site-specific flood data are needed to advance the emerging growth of digital databases in hazards research and in doing so show how local knowledge and data partnerships can be applied in the technocratic analysis of coastal flood hazards (Miglarese et al 1998; Hale et al. 2003). For mitigation to succeed, an improved understanding of the physical environment must be obtained (Heinz Center 2000) and applied in policy (Bush and Young 2000). The conversion of site-specific water level data to digital format and use of GIS addresses a fundamental issue of the current hazards research paradigm. Some researchers postulate that a full federal mandate forcing states to implement a specific policy is needed for coastal hazard mitigation to succeed (Pulwarty 1999). The strength of a GIS-based analysis is the ability to integrate different types of data and to generate answers in a spatial context that can be implemented as policy at federal, state and local levels (Langren, Larsen, and Baybrook 1993; Monmonier 1997). Arcview GIS and its extensions provide all the tools necessary to combine different pre-existing flood data sets, add new data, analyze information and create maps to portray the physical environment at multiple scales (Johnson and Nelson 2000).

Goal and Objectives

The goal of this dissertation is to correlate shoreline characteristics and relate storm conditions with post-storm water level observations to spatial variability in elevated water levels following coastal storms in a developed estuary. This goal reflects various objectives or needs in the fields of coastal hazard assessment and coastal zone management and serves to advance these fields by providing site-specific data and a storm inundation index in a GIS framework.

Research Needs

- Determine the spatial variability in water levels at local scales in developed estuaries.
- Monitor the shoreline following storms by documenting and quantifying the onshore and offshore factors that contribute to coastal inundation over time and space.
- Correlate data from field sites to storm-caused water levels in an estuary at 200 m intervals rather than random post-storm reconnaissance observations.
- Evaluate and quantify the height and position of shoreline environments and protection strategies to determine their effect on wave run-up and inundation.
- Use post-storm water level observations, historical qualitative and quantitative observations of coastal storm impacts to validate the potential inundation of local sites due to shoreline characteristics and the actual inundation due to onshore factors and storm conditions.
- Collect and utilize detailed flood data in a GIS to advance the emerging growth of digital databases in coastal hazard research that create data partnerships and improve the current ways in which mitigation is enacted.

Scope of Field Research

The field study is designed to determine storm-caused water levels in a developed estuary at a local scale and over a one-year time period (March 1997 to March 1998).

The spatial variability of water level observations is determined using descriptive statistics. This research advances the field of coastal hazard research because significant variability in the elevation of water levels is observed between sites, despite observations from only five moderate storms. Water levels vary at sites within and between municipalities in the study area. Other research has connected small storms to geomorphic change along estuarine shorelines (Jackson 1995) and to geomorphic change and increased vulnerability along oceanic shorelines (Fucella and Dolan 1996; Walker and Hammack 2000).

Onshore and offshore variables and post storm water levels were collected on 48 cross-shore profiles spaced at 200 m apart within a developed estuary across 4 municipalities. An additional site was selected where a unique, natural estuarine beach exists midway between a site with a wooden bulkhead and a site with a seawall that had an elevation benchmark. Regression analysis is used to identify the variables that correlate to water level observations. Values for each correlated variable are mapped and categorized using five susceptible classes in a GIS.

Two storm inundation indices are developed to compare the difference in susceptibility between actual and potential inundation. Susceptibility to actual storm inundation is mathematically derived from all correlated onshore and offshore variables. Susceptibility to potential inundation is mathematically derived from only the correlated offshore variables. The comparison is designed to elicit the impact of human alterations on susceptibility to inundation. Coastal storm conditions are determined from meteorological data obtained from a local weather station. Wind speed and duration are graphed and compared to water level observations at sites where each storm produced a distinct wrack line on the profile. Shoreline characteristics and the storm inundation indices are mapped using GIS to provide visual relationships to storm conditions.

GIS provides an immediate spatial portrayal of the variability in water levels between sites and between storm events that can assist in setting up post-storm reconnaissance efforts. The impact of catastrophic coastal storms along the estuarine shoreline could not be assessed because a high magnitude storm did not occur during the research effort. However, using post-storm water level observations to determine spatial variability and to develop potential and actual inundation indices based on shoreline characteristics advances flood hazard mapping in general. GIS, data integration, and indices create maps that compare new site-specific data with the broader scale flood zone delineations that are the present state of the art. Data integration, facilitated through using GIS, is needed to better quantify coastal and riverine flood zones in the United States (Jones et al. 1998). Quantifying water levels and shoreline characteristics that influence storm surge inundation is also critical for developing countries, like Bangladesh, where sea level rise is exacerbating coastal hazards (Murty and Flather 1994).

Data Sources

The research methodology consists of gathering data from multiple sources, converting the data to digital format and querying the data using a GIS. Sources of data include:

- Geodetically referenced profiles of cross-shore transects with post-storm water level observations and an inventory of shoreline protection strategies and structures from a geomorphic field study conducted along 10 kilometers of the Raritan Bay shoreline.
- Offshore characteristics for each transect from digital nautical charts using Maptech software.
- Meteorologic components, (wind speed, duration and direction) of coastal storms between March 1997-1998 from a National Oceanic and Atmospheric Administration (NOAA) weather station along the Raritan Bay shoreline.
- Water level observations from a tide gage employed by NOAA at Sandy Hook, N.J. in Raritan Bay during five coastal storms between 1997-1998.
- Qualitative post-storm water levels and flood impacts throughout the bay from a U.S. Army Corps of Engineers reconnaissance report following a December 1992 storm.
- Digital flood zone and coastal hazard information published by the New Jersey Department of Environmental Protection, Oak Ridge National Laboratory (United States Coastal Hazards Database) and the Federal Emergency Management Agency.

Structure of the Dissertation

Coastal storm conditions and shoreline characteristics that cause elevated water levels in developed estuaries are described in Chapter 2. Differences between ocean and estuarine shorelines are evaluated to provide a rationale for the estuarine focus. Raritan Bay, New Jersey is a highly populated estuary that has been extensively developed, making it a suitable location for conducting an assessment of variability in susceptibility to inundation. The characteristics of this estuary are described in Chapter 3. The methodology for collecting the field data and descriptions of the study area, reaches within the study area and study sites are detailed in Chapter 4. Reach comparisons of the spatial variability in water levels provide perspective on differences throughout the study area. Site characteristics and the spatial variability of elevated water levels between sites are identified in Chapter 5. Regression analysis is used in Chapter 6 to determine if correlations exist between shoreline characteristics and water levels. The impact of physical processes and human modifications on the spatial variability of coastal storm impacts is evaluated from offshore, nearshore, foreshore and backshore variables that correlate to water levels. GIS is used in Chapter 6 to classify each correlated variable based on susceptibility to storm inundation. Two storm inundation indices are derived from the classified variables and discussed in Chapter 7. The use of digital data with the formulation of indices and incorporation into GIS represents a growing trend in coastal zone management and hazard mitigation. The relationship between storm conditions and spatial variability of elevated water levels at selected study sites is graphically illustrated in Chapter 8. The study sites analyzed in Chapter 8 have variability in water levels for different storms. A critique of water levels at specific sites provides a rationale for relating different storm conditions to the storm inundation indices and specific shoreline characteristics. Conclusions and implications of the field data and storm inundation indices to modern hazards research are discussed in the final chapter.

II– COASTAL STORM FLOOD EVALUATION IN DEVELOPED ESTUARIES

Introduction

This research is designed to address two shortcomings in the study of flooding from coastal storms in developed estuaries. First, estuaries are perceived as low risk in broad scale vulnerability assessments of coastal hazards because those assessments use the same physical variables for determining susceptibility to inundation along both ocean and estuarine shores. Few studies adequately consider the physical basis for interaction between variables and a risk and vulnerability assessment works best when the nature of the risk and associated managerial issues are clearly defined (Cooper and McLaughlin 1998). The physical variables that contribute to coastal storm-related risks in developed estuaries have not been adequately defined; instead one set of variables is used to describe both ocean and estuarine shorelines. Second, the spatial variability in elevated water levels along estuarine shores has not been determined or related to the physical variables that create susceptibility to inundation from coastal storms. Current flood mitigation strategies for developed estuaries do not recognize risk variables in the context of elevated water levels and spatial variability. This dissertation evaluates susceptibility to inundation from elevated water level observations determined at a local scale along a developed estuarine shoreline.

Research on Coastal Hazards and Estuaries

The focus of research projects about coastal hazards in the United States has been on storm overwash on ocean shores because more catastrophic scenarios are predicted there than on estuarine shores (Figure 2.1) (Dolan, Hayden, and Heywood 1978a, 1978b; Dolan, Hayden, and Felder 1979a, 1979b; Pilkey and Neal 1993; Dolan, Lins, and Hayden 1988; Dolan, Fenster, and Holme 1992). Estuarine shores are classified as low risk in the digital coastal hazards database for the East Coast of the United States, because the classification uses the same criteria used for exposed oceanic shores (Gornitz et al. 1994). The economic losses and damage to coastal structures incurred by residents along developed estuarine shores in the United States from major coastal storms are comparable to or exceed those incurred by residents along ocean shores (USACE, New York District 1960; USACE, Philadelphia District 1979).

Hazards are exacerbated in developed estuaries because the apparent low wave energy makes people comfortable building homes at the water's edge and often shore protection strategies are ephemeral or ad-hoc (Nordstrom et al. 1986). The mitigation strategies used along estuarine shores to reduce flooding from coastal storms are not identical from estuary to estuary or even within an estuary, and often only low cost temporary strategies are used (USACE, Philadelphia District 1979; Nordstrom 1992). Shore protection structures in developed estuaries are often poorly designed, lack engineering principles and are often funded and built by local residents (Wang et al. 1982). Where large-scale efforts have been made to protect estuarine shores, high

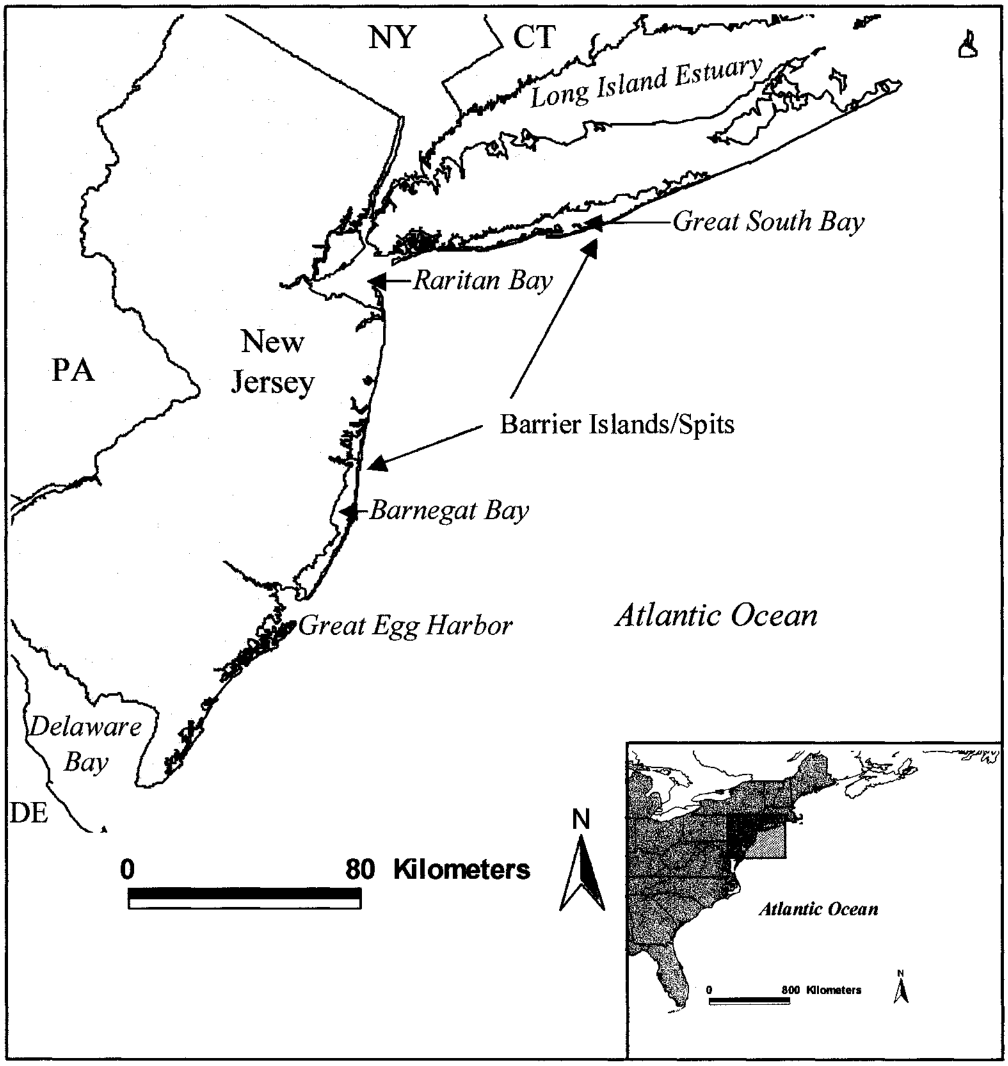


Figure 2.1 - Estuaries and barrier islands along the New Jersey and New York shoreline.

seawalls, bulkheads and beach nourishment are often used (USACE, New York District 1960, 1993). The typical seawall or bulkhead in the United States is built to withstand the flood level from a 100-year storm (a storm with a 1% probability of occurrence) (USACE, New York District 1993) and this single flood level across kilometers of estuarine shoreline, and for barrier islands without regard for local scale cross-shore and alongshore spatial variability.

Seawalls, beach nourishment and artificial dunes are used to mitigate coastal storm flooding on ocean shores but these types of shore protection projects may not be appropriate in estuaries. The purpose of a seawall is to reflect wave energies and prevent erosion (Zabawa and Ostrom 1981). However, wave energies are weak along estuarine shorelines and typically masked by tides and alongshore currents (Jackson 1995). The changes seawalls make in foreshore and backshore geomorphology would not necessarily mitigate elevated water levels because steeper profiles do not reduce encroaching storm surge. Seawalls should be evaluated in the context of reducing or exacerbating water levels as well as for shore stabilization. Wide, sandy beaches and high dunes are not features found on natural estuarine shores. The ability of these soft shoreline protection practices should also be evaluated in the context of reducing or exacerbating water levels.

Relevance of the Coastal Hazard Database and Atlas for the United States

A key to assessing coastal hazards is a better understanding of the physical processes that impact the shoreline (Dolan and Davis 1992). Site-specific determination and analysis of the variables that comprise a coastal hazard, especially meteorological variables, are generally lacking in coastal hazard research (Wood 1990). Large-scale maps use the same variables to determine coastal hazards in estuaries as those used along ocean shores. (Anders, Kimball, and Dolan 1985). The classification of an estuary as low risk to coastal storm flood hazards is subject to conjecture, because physical processes along estuarine shorelines are significantly different from physical processes along ocean shorelines (Nordstrom 1980). One of the key variables assessed in coastal hazard databases is wave height, yet waves are significantly smaller along estuarine shorelines than along exposed ocean shorelines. Data in the digital coastal hazard database and paper atlas allows for the discrimination between hazards on similar shores but are not suited for comparing ocean shores to estuarine shores or between shoreline reaches in an estuary.

The digital coastal hazards database is the seminal work in the creation of coastal hazard data in digital format (Gornitz et al. 1994) but it is limited in application to local coastal storm hazard mitigation because it is based on grids that are kilometers in size. The digital database is divided into grids of 0.25 degrees latitude therefore classifying entire estuaries with one grid (Raritan Bay) or multiple grids (Delaware Bay) (Figure 2.2). The data in the grids used to determine vulnerability consists of 7 variables that are determined from a larger set of 22 variables. The variables are erosion and accretion, wave height, geology, subsidence, elevation, tide range, and geomorphology. The scale of the digital database is too large to evaluate spatial variability in vulnerability within an estuary. The digital database is constructed using grids delineated by latitude and longitude coordinates to create an orderly pattern. This orderly pattern is limited in application because distinctly different coastal environments are sometimes represented

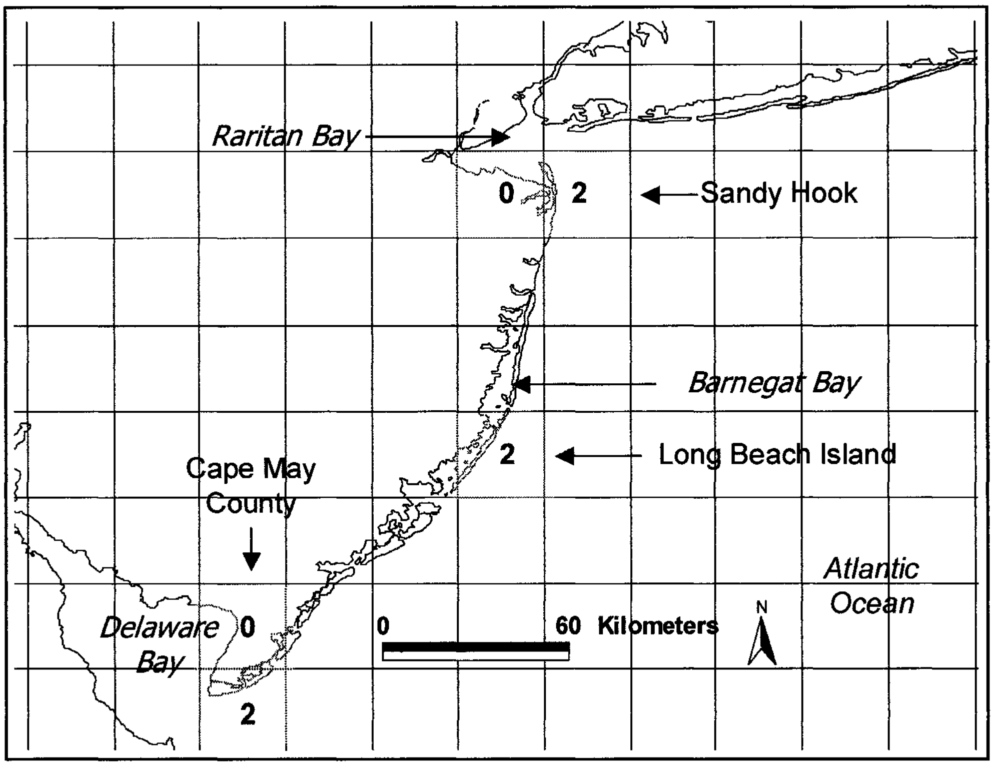


Figure 2.2 – Comparison of wave heights in grid representing ocean and estuarine shorelines in New Jersey from the United States Digital Coastal Hazards Database for the East Coast U.S., Oak Ridge, Tennessee: Oak Ridge National Laboratory (*ORNL & CDIAC-45, NDP-43A).*

in the same grid. For example, one grid contains Long Beach Island and Barnegat Bay, while another grid contains both the ocean side and bay side of Sandy Hook. The vulnerability assessment for these grids is apparently based on the exposed ocean side environments because a value of 2 (with 5 representing highest risk) is given to the wave height variable (Figure 2.2). The value for wave height in grids that contain only estuarine shorelines is zero. Two grids in Cape May County contain both ocean and estuarine shorelines but the southern grid has a value of 2 for the wave height variable and the more northerly grid a value of 0 for the wave height variable. The digital coastal hazard database incorporates important meteorological, oceanographic and geomorphic variables for assessing flooding from coastal storms but the scale is not appropriate for site- specific analysis of vulnerability in estuaries and is further limited because the same classification system is used for oceans and estuaries.

Data in the digital coastal hazard database can be used to differentiate hazard between similar shorelines (between estuaries, between barrier islands, between cliffs) and for comparing Raritan Bay to Delaware Bay at large scales. For example, Raritan Bay is more susceptible to erosion than Delaware Bay (Figure 2.3). There are two major shortcomings in the digital coastal hazard database addressed in this dissertation. First, the variables used in the digital coastal hazard database are best suited for open ocean shorelines with no accommodation for estuarine or sheltered shorelines. Variables are identified and quantified in this dissertation specifically for assessing coastal hazards along sheltered shorelines. Second, the scale used in the digital coastal hazard database is suited for a state or federal level recognition of hazard. Field data is collected in this dissertation at the local scales, where hazard mitigation often takes place.

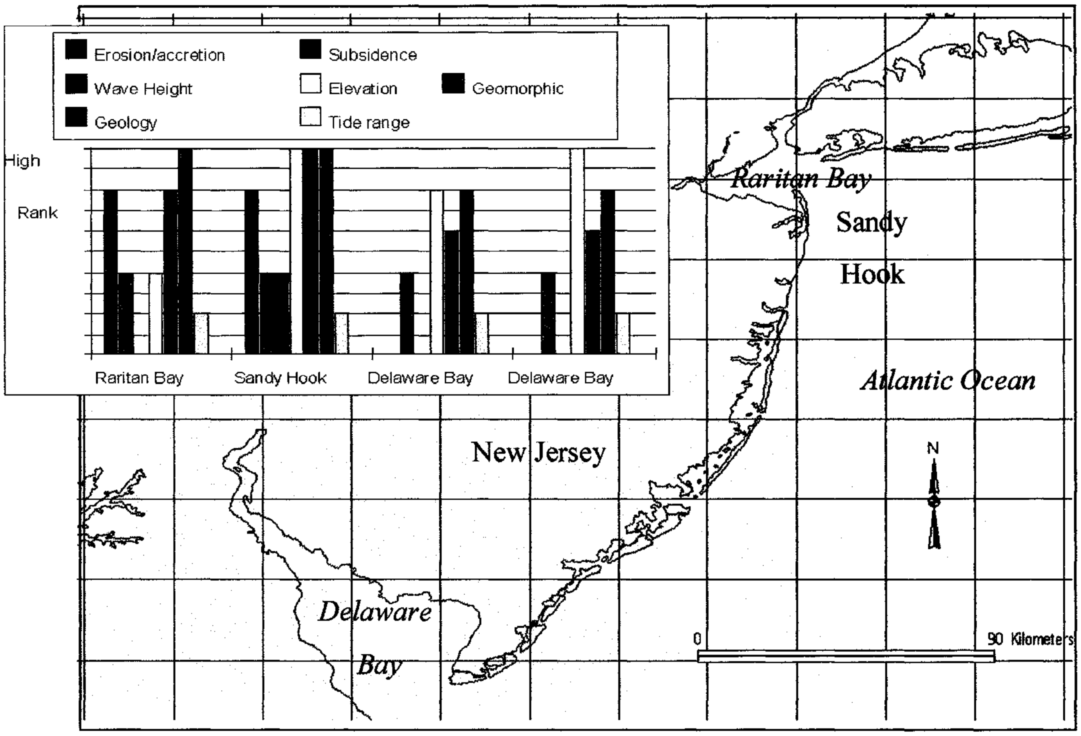


Figure 2.3 – Comparison of all variables used to assess coastal hazards for ocean and estuarine shorelines in New Jersey from the United States Digital Coastal Hazards Database for the East Coast U.S., Oak Ridge, Tennessee: Oak Ridge National Laboratory (*ORNL & CDIAC-45, NDP-43A*).

The United States Coastal Hazards Atlas does not discern differences in hazard between exposed barrier islands, bays, lagoons, barrier islands, some mainland areas and large funnel shaped estuaries such as Chesapeake Bay, Delaware Bay and Raritan Bay. The map scale of the entire atlas is 1:7, 500,000, but even an inset for New York to Cape Cod (1:5,000,000) is too broad to enable differentiation of the complexity that exists along the U.S. coast (eg., estuaries, barrier islands and back bays) or site-specific evaluations between estuarine and oceanic shorelines. It is not clear where Raritan Bay is included on this atlas. The area of New Jersey that would include Raritan Bay on the main atlas is classified as moderate to low risk (green color) (Figure 2.4). The inset labeled New York to Cape Cod may include Raritan Bay and the hazard classification is moderate (pink color) (Figure 2.4). The risk classification is based on four coastal factor variables; shoreline change, overwash distance, storm and wave damage and earth movements, although eight variables are distinguished on the atlas. The other two coastal factors are storm surge and stabilization, and there are two onshore variables; relief and population density. Overall, the United States Coastal Hazards Atlas and its risk assessment technique are considered too complicated for application to coastal hazard mitigation (Monmonier 1997).

The shape and orientation of an estuary along the northeast coastline of the United States are important factors in the development of elevated water levels from coastal storms. Although it is generally accepted that onshore winds produce the highest water levels (Inman and Bagnold 1963), this relationship is complicated along estuarine shorelines where the highest water levels may be influenced more by the orientation of the shoreline and the direction of maximum fetch (Nordstrom 1977). The orientation of

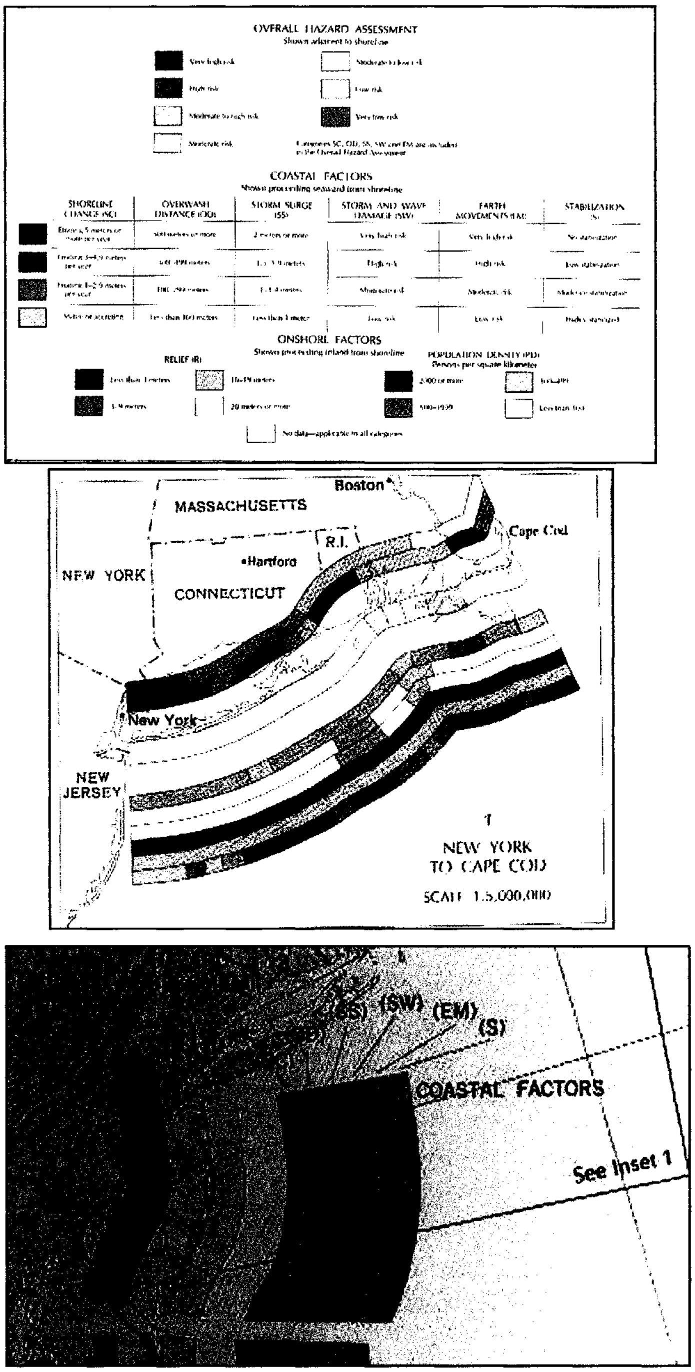


Figure 2.4 – Coastal hazard classification of Raritan Bay, New Jersey in the United States Coastal Hazards Atlas (Anders, Kimball, and Dolan 1985). The top figure is the legend. The middle figure is the inset for New York to Cape Cod and the bottom figure is scanned from the main atlas.

the shoreline relative to northeasterly winds caused by coastal storms allows for the propagation of storm surge in New Jersey. The counterclockwise circulation around coastal storms along the East Coast of the U.S. creates onshore winds from the east that produce storm surge and waves capable of either overtopping or destroying existing shore protection structures. Orientation is not evaluated in either the Coastal Hazards Atlas or the digital coastal hazard database, but is a critical variable in estuarine studies (Nordstrom 1992; Jackson 1995). Coastal flooding from storms along developed estuarine shorelines is controlled by a unique set of parameters that have yet to be clearly identified in coastal hazard research.

Coastal Processes in Estuaries Related to Storms and Elevated Water Levels

Geomorphic studies along estuarine shores have focused on beach formation, winds and waves and alongshore currents and not on storm caused overwash, flooding and hazard (Nordstrom 1977; Nordstrom 1980; Jackson and Nordstrom 1992; Jackson 1995). Research in coastal processes in estuaries has not evaluated spatial variability in elevated water levels caused by coastal storms. Storm impacts on estuarine beaches have been evaluated relative to ocean-side beaches for the same storm (Nordstrom 1980), but not in terms of spatial variability along different estuarine sites for the same storm. Storm surge can cause significant damage along estuarine shorelines but alongshore linkages (e.g., variability) and connections to storm conditions are not documented (Roman and Nordstrom 1996).

Coastal storms on ocean shores generate large waves and storm surge, defined as exceptionally high water caused by wind stress and/or low pressure resulting from the passage of a coastal storm (Godschalk, Brower, and Beatley 1989; Coch 1994; Dolan and Davis 1994). Storm surges along ocean shores due to hurricanes can exceed 5 meters, while in a northeaster the storm surge is usually less than 2 meters (Dolan and Davis 1994). Much of the research that has quantified storm surge using models focuses on oceanic barrier islands and therefore it is not clear how applicable storm surge values from models would be along estuarine shorelines. Storm surge in an estuary is affected by the basin morphology (Jarvinen and Lawrence 1985; Miller and Wei 1987; Moses and Blair 1988; Bode and Hardy 1997) and water made available on the open coast and redistributed within the estuary by local winds (Figure 2-5) (Miller 1988).

This dissertation is designed to quantify water levels that result in part from wave run-up and therefore the variables that influence waves are an important consideration in the analysis. Wave attack is the dominant erosive process in estuaries (Phillips 1985) but the connections between waves and the spatial variability in elevated water levels has not been documented in developed estuaries. The relationship between winds and waves in estuaries depends on wind speed and direction and land-sea interface stresses (eg., friction, flow) that transfer energy (Jackson and Nordstrom 1992). High winds produce incident wave energies in estuaries with high frequency peaks, 0.2-0.4 Hertz (Jackson 1995). While no single or set of variables is the control on winds, waves and geomorphology at all sites there are relationships between fetch and orientation and incident waves (Jackson and Nordstrom 1992). This dissertation uses storm wind conditions and shoreline features as surrogates for wave energy because the magnitude of

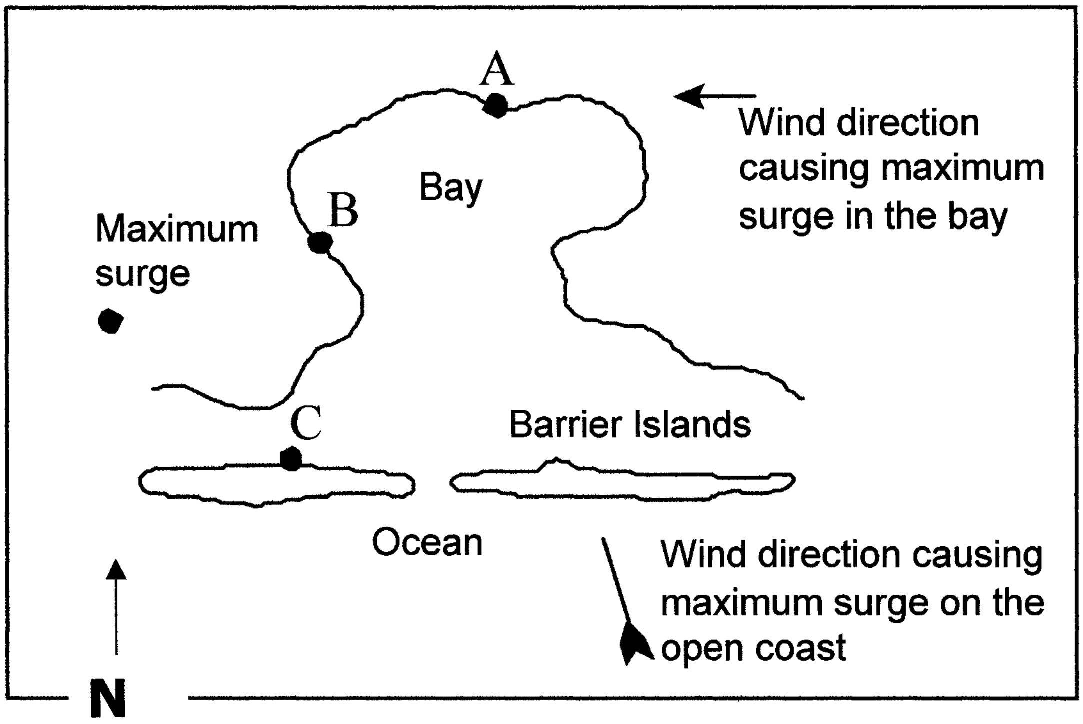


Figure 2.5 - Variability of storm surge in an estuary from changes in local wind direction and shoreline orientation. Location A would have a maximum surge from southerly winds. Location B would have a maximum surge from easterly winds. Location C would have a maximum surge from northerly winds (after Miller 1988).

waves and run-up is directly related to the speed and duration of wind operating over water surfaces.

Specific studies of changes in beach morphology and offshore wave energies are tangential to coastal flooding but provide variables for flood analysis. Quantitative post-storm field observations aid in assessing the susceptibility of a shoreline to flooding by identifying where water levels and waves propagate up the foreshore profile. Post-frontal high frequency storm waves can propagate shoreward and strike high on the foreshore on shorelines exposed to sustained wind directions (Armbruster, Stone, and Xu 1995), where most sediment movement occurs (Jackson 1995). On low tidal range (micro-tidal) estuarine beaches, waves and storm surge cause significant geomorphic change because high water levels are sustained by the slope of the nearshore and foreshore profile (Nordstrom 1987; 1989). Most estuarine studies monitor low energy conditions and cross-shore linkages (Nordstrom et al. 1996; Roman and Nordstrom 1996). This dissertation advances current estuarine research by revealing both cross-shore and alongshore linkages (e.g., spatial variability) and storm conditions.

Spatial Variability, 100-Year Flood Zones, and Mapping

The distribution of damages and inundation caused by coastal flooding tends to be systematically or periodically distributed along sandy ocean shoreline barrier islands (Dolan and Davis 1992). The processes causing the spatial morphologic patterns along oceanic shorelines are not completely understood but are believed to be sub-harmonic wave energies caused by offshore bar-trough morphologies (Dolan, Hayden, and

Heywood 1978a; Dolan, Hayden, and Felder 1979a, 1979b; Dolan and Davis 1981; Dolan and Hayden 1993; Aagard 1990; Bauer 1990). Oceanic bar-trough morphology and alongshore periodicities have not been observed along discrete, isolated reaches in Raritan Bay, a meso-tidal estuary (Nordstrom 1989; Jackson and Nordstrom 1992). Qualitative post storm reconnaissance reports of coastal flooding in estuaries indicate that flooding from coastal storms varies but elevated water levels have not been quantified and spatial patterns have not been determined. While the track of a storm is important, other site-specific near and offshore variables are critical in flooding estuarine shores (Jackson 1995).

The natural response of an estuary to flooding varies according to local topography, sediments, tidal range, erosion susceptibility and the conversion of marshes (ASCE 1992; Pethick 1993). Orientation and fetch have been identified as critical variables in understanding the geomorphic response of estuarine shorelines to offshore variables such as waves (Jackson and Nordstrom 1992). Infra-gravity spectral peaks have been observed during storms in fetch restricted, storm-dominated environments indicating that spatial periodicities may exist (Aagard 1990). It is understood that waves serve as a mechanism for creating elevated water levels but wave heights and periodicities do not have to be analyzed to determine spatial variability and the nearshore, foreshore and backshore variables that influence susceptibility to inundation. The focus of this dissertation is on the elevation of water levels across the estuarine shoreline rather than the geomorphic response of the shoreline (eg., erosion, accretion) to storms that is evaluated elsewhere (Nordstrom 1980; Jackson and Nordstrom 1992).

A study of storm overwash periodicities and patterns along barrier islands indicates that a scale of kilometers is sufficient when evaluating coastal storm overwash and flooding along sandy ocean beaches on barrier islands (Dolan, Lins, and Hayden 1988). Research along estuarine shorelines directed at the spatial variability of elevated water levels is lacking but research on the spatial variability of erosion indicates that a scale of 100 meters is appropriate (Phillips 1985; 1986). A preliminary evaluation of storm surge during large storms calculated from tide gages hundreds of meters apart in Raritan Bay indicates spatial variability of 0.5 m (Dobosiewicz 1997). Studies in coastal storm hazards that have included estuaries use a scale of kilometers (Anders, Kimball, and Dolan 1985; Gornitz et al. 1994), but the geomorphic processes in estuaries exhibit as much variability between sites 100 m apart as between reaches kilometers apart (Phillips 1985; 1986). Estuarine shorelines are compartmentalized at a scale of meters, not kilometers (Jackson and Nordstrom 1992). This research uses a scale of 200 meters, further explained in the methodology, a scale less than what would be appropriate for a flood study of exposed ocean barrier but larger than what has been demonstrated as appropriate for erosion studies along estuarine beaches by Phillips (1986). No research has been designed to collect geomorphic data from field transects and relate it to storm caused water levels in an estuary at any scale other than random post-storm reconnaissance observations.

Spatial Scale and Flood Zone Mapping

The spatial variability of elevated water levels along estuarine shorelines may be significantly different from either ocean or inland flooding, yet the same broad flood zone policy is applied. The primary flood mitigation strategy in the United States, including coastal flooding, is the National Flood Insurance Program (NFIP) implemented by the Federal Emergency Management Agency (FEMA). The mitigation, in the form of flood insurance, comes from premiums paid by residents in municipalities based on flood insurance rate maps (FIRMs). FIRMs are available for municipalities participating in the NFIP and vary in spatial scale. FIRMs rely on the application of random elevations within a municipality to determine flood zones.

FEMA flood insurance rate maps designate risk zones based primarily on elevations and probability curves for 100-year and 500-year storm events. The 100-year flood zone is called the A zone and is divided into areas that have base flood elevations determined and areas that do not have base flood elevations determined. A special rate is applied for locations with potential erosion problems and is designated as a "flooding with velocity" zone, called the V zone.

The 100-year flood level is applied ubiquitously and without much question to mitigating flood hazards throughout the United States (Monmonier 1997). Applying a single 100-year flood level in an entire estuary derived from water level observations recorded at one location does not deal with spatial variability. Questions exist about the statistical derivation of 100-year flood levels and the errors in the 100-year flood level can exceed 20% (Monmonier 1997). Sea level rise and erosion are other concerns that further the uncertainty in flood zones delineated on paper copy FIRMs (Davison 1993). The application of FIRMs is limited because insurance agents may use outdated or wrong maps and FIRMs do not show property lines and have limited detailed information (Monmonier 1997). Current flood mapping tends to address overtopping and overflow but not the potential failure of shore protection strategies or shoreline changes (Davison 1993; Platt 1994; Monmonier 1997). Better flood zone management can be achieved by creating more detailed maps that can be manipulated and updated digitally. This dissertation compares the present 100-year flood levels and coastal flood mitigation to site-specific water levels collected in the field following storms.

FEMA is currently digitizing flood zone data but 40 years would be needed to completely update all flood zone maps in the United States (Monmonier 1997). Flood zone evaluation and mapping using a Geographic Information System (GIS) addresses two problems that exist with current FIRMs and the NFIP. First, paper flood zone maps are cumbersome and readily become obsolete. A GIS provides the ability to combine new data, such as post-storm water levels collected at field study sites, with existing data to formulate a new evaluation of flooding. Second, poorly constructed maps lead some communities to believe that a hazard is non-existent or trivial and as a consequence those communities do not participate (Monmonier 1997). More conspicuous and detailed maps in digital format will aid agencies in presenting information to the public and are also easily transferred using electronic media and the internet.

Storm evacuation maps published by the National Atmospheric and Oceanic Administration (NOAA) provide the most detailed flood information for coastal areas (Monmonier 1997). However, NOAA storm evacuation maps are based primarily on elevation and do not account for variables such as wind direction and shoreline orientation. Storm surge models exist that use meteorological and oceanographic variables for tropical cyclones but they can be somewhat inaccurate with errors up to 20% (Monmonier 1997) and the models do not consider nearshore or onshore geomorphic variables. The 1985 United States Coastal Hazards Atlas is generally considered too complicated for realistic application for coastal hazard mitigation because of its large spatial scale (Dolan in Monmonier 1997 p.75). The book series "Living with US shorelines" is highly recommended for understanding the risks of various coasts (Monmonier 1997), but these books do not explicitly delineate flood zone hazards and they pre-date modern GIS technology. Works that focus on estuarine shorelines have included estuarine beaches (Nordstrom 1992) and human alterations along estuarine shorelines (Nordstrom 1994; Roman and Nordstrom 1996) but have not explicitly defined flood variables and appropriate mitigation strategies.

Geographic Information Systems (GIS) and Mitigation Strategies

GIS can assist in coastal management and has been used in the study of many hazards (Monmonier 1997). Applications of GIS in coastal hazard research have been of various scales and purposes, none of which explicitly address coastal flood hazards in estuaries. Three-dimensional models of the migration and erosion of barrier islands along the southeast United States coast integrated with GIS describe ocean processes and shoreline response (Daniels 1996) but not sheltered estuarine processes and shoreline response.

The use of GIS for evaluation and education pertaining to coastal hazards has been suggested by researchers but has not been sufficiently evaluated (Langren, Larsen, and Baybrook 1993). More detailed quantitative studies of specific coastal environments are needed. Few works have used GIS for post storm flood analysis (Fletcher et al. 1995; McDermott and Hatheway 1997). FEMA publishes flood zone data in digital format that can be used in a GIS, but paper FIRMs are used exclusively for flood zone determination in municipalities. GIS provides a means for evaluating existing digital flood zone data from sources (e.g., FEMA, NJDEP) and overlying new data that may be more appropriate for a municipality to plan a mitigation strategy for its estuarine shorelines. This dissertation will provide a strategy for coastal counties and municipalities to become more involved in understanding spatial variability in flooding from coastal storms, evaluate and monitor existing shoreline structures and strategies, and use GIS for planning and mitigation. Raritan Bay, New Jersey is an ideal site because it is a developed estuary with a number of municipalities with shoreline interests, a variety of human alterations exist, flooding from coastal storms has been documented, and ample digital flood-related data exists to provide reference maps for the site-specific analysis proposed in this dissertation.

III - Study Area: Raritan Bay

Introduction

Raritan Bay, New Jersey is used as for this dissertation because: 1) the shoreline is developed (Figure 3.1); 2) the shoreline is accessible before and after storms; 3) the shoreline is susceptible to periodic flooding by coastal storms; 4) qualitative observations of water levels are available for a few severe storm events (USACE, New York District 1960, 1993); 5) a variety of flood mitigation strategies are in place (Jackson 1996); and 6) coastal hazard and flood zone information are available from a variety of sources (eg., NJDEP, FEMA). This chapter evaluates these components in the context of the spatial variability in elevated water levels in Raritan Bay and the susceptibility of the shoreline to inundation from coastal storms.

Raritan Bay is located within the Coastal Plain Province of New Jersey and the shore consists of Upper Cretaceous/Tertiary Period sediments overlying bedrock of crystalline rock with Triassic Period sediments (USACE, New York District 1993). The funnel-shaped estuary is approximately 20 km in length and trends east with a width of 2 km at South Amboy to 10 km at the Atlantic Highlands. Sandy Hook is a sandy spit at the ocean terminus of the bay that is approximately 10 km in length, making the opening of the bay to the ocean to be 7 km wide. A navigation channel is maintained around Sandy Hook with depths up to 9 m (30 feet), but depths of over 5.5 m (18 foot contour) are common. Numerous federal and local scale shore protection measures exist including bulkheads, seawalls, revetments, jetties, groins, levees and approximately 10 km of beach fill. These measures are identified in the methodology (Chapter 4).

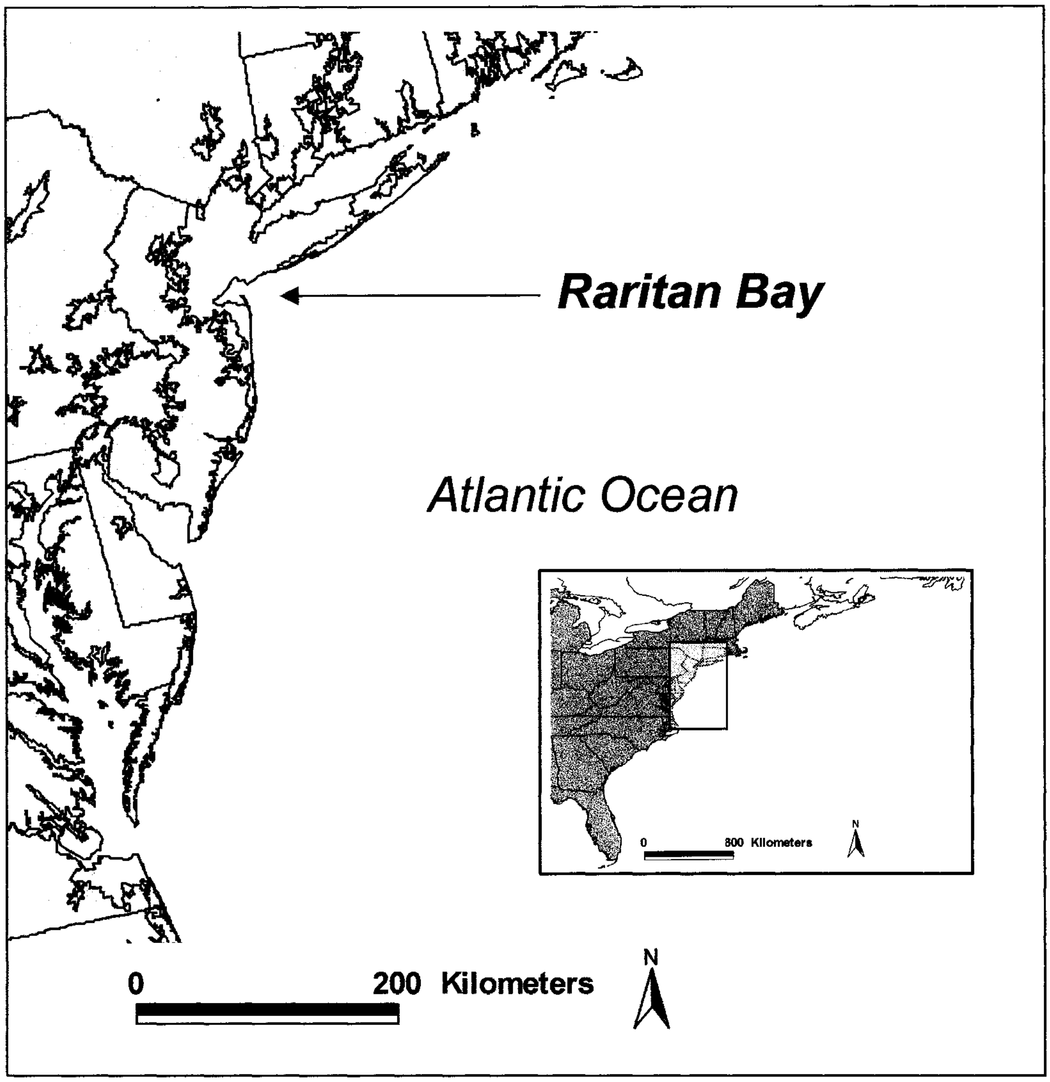


Figure 3.1 – Urbanized (developed) areas (highlighted in yellow) along the Mid-Atlantic Bight (GIS data from Environmental Systems Research Institute (ESRI), Redlands, CA).

The area selected for conducting topographic field surveys and quantifying water levels consists of a variety of natural and developed shorelines that are readily accessible and where elevated water level indicators are visible. Potential study areas were first identified using topographic maps of the area and a post storm reconnaissance report consisting of flood observations (USACE, New York District 1993), with the final study area determined following site visits. Access within 1 or 2 days following a storm event is critical for evaluating water levels because the evidence of water levels, such as lines of un-weathered vegetation or sediment movement in the form of escarpments of beach fills or dunes, are quickly altered or removed by people along developed shorelines. Access is facilitated in developed estuaries because roads are built close to the bay waters, the beaches tend to be maintained by local municipalities for recreational purposes and the marshes have been filled.

Population

Paradoxically, estuaries support diverse natural ecosystems and highly populated urban areas. Many of the world's major cities coincide with natural estuarine ecosystems, resulting in most hazards research focusing on environmental quality of bays, especially those identified in the United States National Estuary Program (Imperial, Robadue, and Hennessey 1992). Raritan Bay illustrates this paradox. The result has been extensive research in Raritan Bay on water and sediment pollution (Jeffries 1962; Stokes, Lutzic, and Forndran 1986; Kennish 1994; Wolfe, Long, and Thursby 1996), biota (Stainken 1984; Zdanowicz, Gadbois, and Newman 1986, Ropes 1987; Mackenzie and Pikanowski1999; Cai et al. 1994; Kennish and Ruppel 1996; May and Burger 1996), and circulation and dispersion (Oey, Mellor, and Hires 1985; Ahsan et al. 1994) but not the spatial variability of coastal storm flood impacts and its physical controls.

Major cities of New Jersey and New York lie in close proximity to Raritan Bay. According to the 1990 Census, over 1 million people live in the counties that border Raritan Bay, Middlesex and Monmouth, and growth rates for those counties are rising. The number of people living along the Raritan Bay shoreline in Monmouth County is comparable to the number of people living along the Atlantic Ocean shoreline of Monmouth County. Twelve of the thirty-eight 1990 census tracts in Monmouth County that intersect FEMA digital 100-year flood zones bordering open water bodies (V Zones) are located along the Raritan Bay shoreline (Figure 3.2). The twelve census tracts account for 54,557 people, 39% of the total population of Monmouth County.

Damage and Losses from Coastal Storms

Major storms have caused significant damage and severe monetary losses in the past 50 years along the Raritan Bay shoreline. The Hurricane of September 14 in 1944 caused storm surge to penetrate 150-600 m inland and resulted in $2.5 million in damages. Two deaths were reported from a northeaster on November 25, 1950. The northeaster on November 6-7, 1953 resulted in the organization of the "Legislative Commission to Study Sea Storm Damage" in New Jersey (USACE, New York District 1993). Two storms in the early 1960's, Hurricane Donna and the Ash Wednesday Northeaster, produced the highest monetary losses in the history of the Raritan Bay

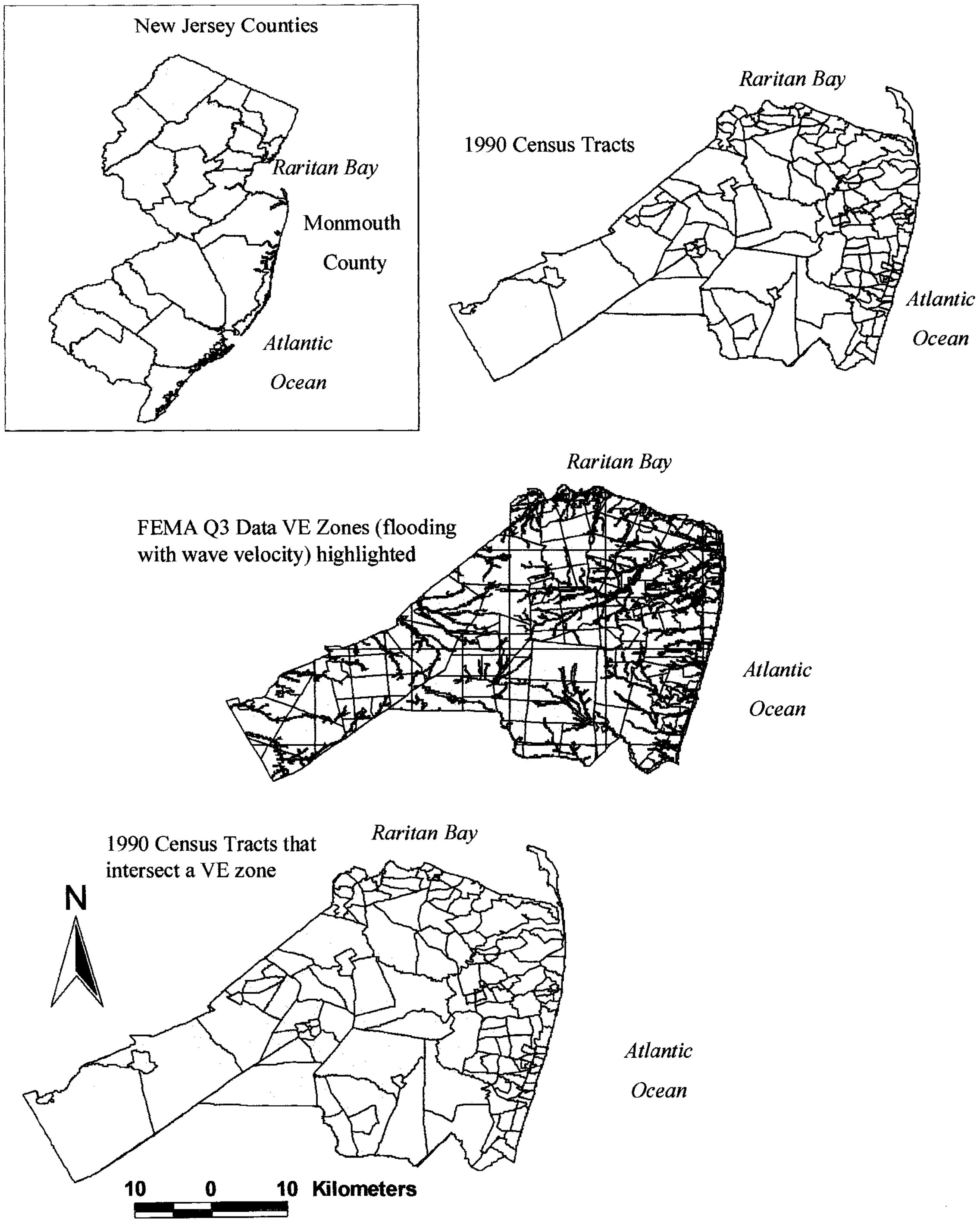


Figure 3.2 - Census Tracts within the VE Zone in Monmouth County, N.J.

shoreline, 6 and 6.4 million dollars, respectively. The losses incurred by residents along the Raritan Bay, New Jersey shoreline following the Ash Wednesday Storm exceeded those incurred on the ocean shoreline from Sandy Hook to the Manasquan inlet (USACE, New York District 1960). However, the extensive research on coastal storm impacts along eastern shoreline of the United States shoreline that followed the Ash Wednesday Northeaster and subsequent storms (Breitschneider 1964; Mather, Adams, and Yoshioka 1964; Mather, Field, and Yoshioka 1967; Hayden 1975; Dolan, Hayden, and Heywood 1978a, 1978b; Dolan, Hayden, and Felder 1979a, 1979b; Pilkey and Neal 1993; Dolan and Hayden 1993; Dolan, Fenster, and Holme 1992; Dolan and Davis 1992; 1994) has not documented the impacts to developed estuaries.

The most recent major coastal storm event occurred in December 1992, a storm similar in magnitude and meteorological parameters to the Ash Wednesday storm; however, only $ 2.5 million in damages were reported (1992 Dollars) (USACE, New York District 1993). Research has identified a need to quantify post storm flood impacts to determine which mitigation strategies work best (Jackson 1996) and if spatial variability is critical for evaluating flooding from coastal storms.

Coastal Storm Dynamics

Residents living along the Raritan Bay shore are vulnerable to coastal flooding caused by two types of storms, distinguished by severity as tropical cyclones, also called hurricanes and extra-tropical cyclones, also called northeasters. Raritan Bay has been severely affected by two major tropical cyclones since 1960, Hurricane Donna in 1960 and Hurricane Belle in 1976. Extra-tropical cyclones occur more frequently with hazardous storm events occurring in 1962, 1984, 1991 and 1992 (Psuty et al. 1996).

Tropical cyclones, low-pressure disturbances that originate in the equatorial regions of the Atlantic Ocean, do not occur frequently along the New Jersey coast, but their extreme wind speeds are especially dangerous. Peak season for these storms is between August and September, when equatorial ocean waters are at their highest temperatures. The Saffir-Simpson scale categorizes the strength of a tropical cyclone using wind speeds ranging from 74 to over 155 mph (123-250 km/h). The low probability of tropical cyclones occurring along the New Jersey shoreline and a lack of quantifiable historical storm-caused coastal flooding data prohibit these storms from being central to this dissertation. The storms directly evaluated in this dissertation are as not as severe as tropical cyclones but the data collected and techniques used, specifically water level observations, digitized data and GIS, are directly applicable to assessing vulnerability to storms at local scales.

Extra-tropical cyclones, low-pressure disturbances that develop along cold fronts, occur frequently along the New Jersey coast. The most intense of these storms occur between October and March. The path of a northeaster is critical to the direction, duration and sustenance of high winds and is driven by upper atmospheric circulation (Davis and Benkovic 1992; Jones and Davis 1995). The seminal works in categorizing northeasters use eight classes based on synoptic meteorology (Mather, Adams, and Yoshioka 1964; Mather, Field, and Yoshioka 1967; Davis, Dolan and Demme 1993). Other classification systems, similar to the traditional Saffir-Simpson Hurricane scale, combine meteorologic, oceanographic and geomorphic parameters with the duration of the storm (Halsey 1986; Dolan and Davis 1992). The amount of damage caused by a northeaster is related to the number of tidal cycles over which a storm lasts (Halsey 1986). Storms lasting only one tidal cycle, less than 24 hours, produce minimal beach and dune erosion and little if any flooding. In meso-tidal estuaries, storm surge can persist well above the low tide terrace even during low tides (Nordstrom 1992), potentially increasing storm impacts to the foreshore and backshore. The speed, direction and duration of storm winds are compared with shoreline characteristics and water levels to determine spatial variability in coastal storm flooding impacts. The storms used in this dissertation correspond to category 1 in the Halsey (1986) classification.

Another classification system for northeasters is based on a statistic called "wave power", a function of significant wave height and storm duration (Dolan and Davis 1992). More intense extra-tropical cyclones may be generated in the future because of the cyclic nature of these storms (Davis and Benkovic 1992; Dolan and Hayden 1993) and classifying these storms quantitatively would better support coastal zone management. The Dolan/Davis classification system is based on analysis of over 1000 coastal storm occurring in the Atlantic Ocean using 50 years of data, but it has not demonstrated that the wave power statistic is applicable to estuarine environments because the studies have applied their results to barrier islands. Estuarine and sheltered shorelines have lower significant wave heights than the open ocean (Nordstrom 1977; Jackson 1995), so using a classification system based on wave power may not be appropriate for Raritan Bay. The storms used in this dissertation correspond to category 2 in the Dolan/Davis classification.

This dissertation utilizes the storm parameters in the Halsey and Dolan/Davis classifications in concept but the methodology is based on detailed shoreline characteristics at a small spatial scale, including orientation and fetch and cross-shore geomorphology. Developing a classification system for coastal storms or northeasters is not a goal of this dissertation, but rather to substantiate the connections between meteorological and geomorphic variables on developed estuarine shores.

Flooding from Coastal Storms in Raritan Bay

Raritan Bay is particularly vulnerable to tropical and extra-tropical cyclones because the bay axis is perpendicular to the Atlantic Ocean, thus maximizing potential water levels due to easterly storm winds. A comparison of the conceptual diagram of storm surge (Figure 2.5; Miller 1988) to Raritan Bay (Figure 3.3) suggests that maximum surge is produced by strong easterly winds providing water from the Atlantic Ocean, with north and northeast winds redistributing that water in the bay and at the shoreline. However, many locations along the Raritan Bay shoreline are sheltered from northeast and east winds or have restricted fetch distances in these directions, potentially mitigating water levels. As storms move north, the counterclockwise circulation would produce winds from the north and increase storm surge at locations in Raritan Bay that are sheltered to the east. The highest historical water levels have occurred at Keyport (USACE, New York District 1993) where the shoreline is sheltered to the east. Wind speed, direction and duration are used to evaluate how storm surge water is distributed along the Raritan Bay shoreline and which locations are most susceptible to inundation and under what storm conditions.

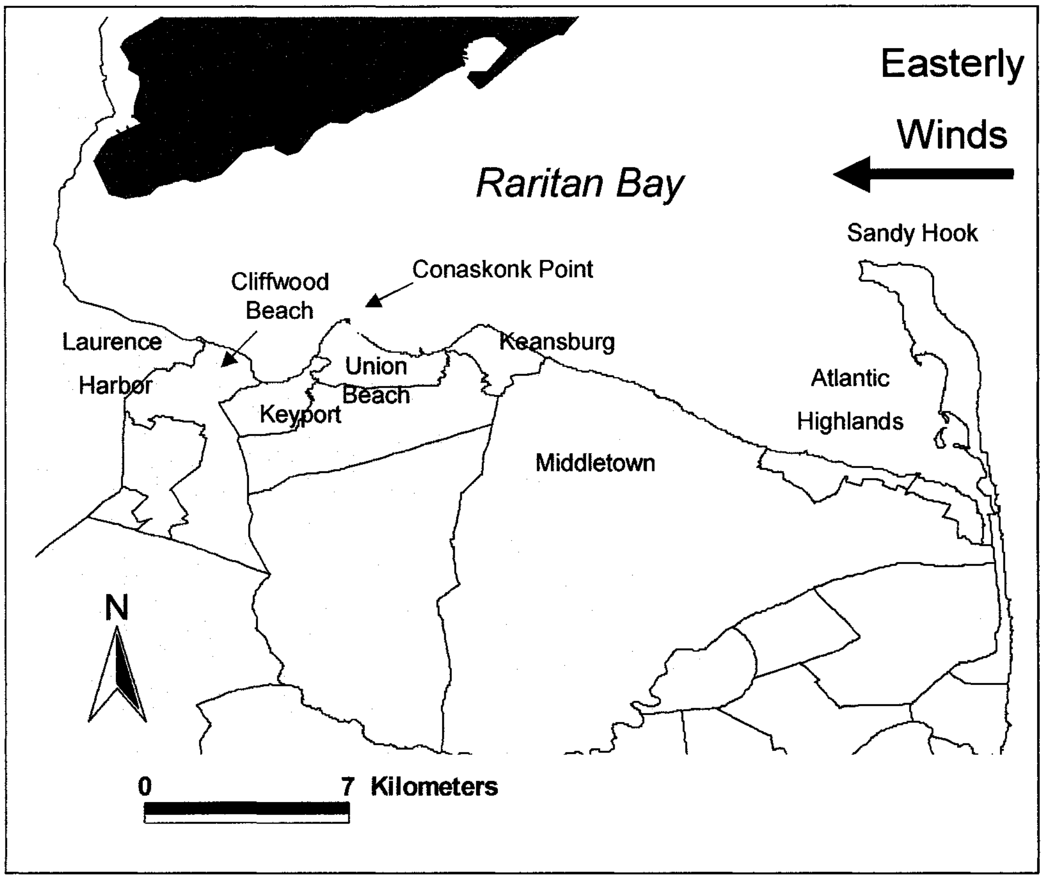


Figure 3.3 - Relationship of the New Jersey shoreline of Raritan Bay to easterly winds (Conaskonk Point is highlighted between Keyport and Union Beach.

Current Flood Zone Assessment in Raritan Bay

The National Flood Insurance Program (NFIP) established in 1973 provides the primary source of flood mitigation and legislation to reduce future losses in the event of a flood in the United States. The Federal Emergency Management Agency (FEMA) conducts on-site elevation surveys to determine the 100-year flood level in a municipality. Development in A and V zones requires flood insurance. A zones are areas that would be inundated by 100-year still water flood levels. V zones are areas that would be inundated by 100-year still water flood levels and would sustain significant damage from wave activity (breaker heights greater than 3 feet). V zones are the key coastal component of the NFIP with premiums typically twice as much as those assessed for A zones. The field sites evaluated in this dissertation are within FEMA V zones. B zones are areas that would be inundated by 500-year flood water levels and C zones are areas designated as minimal flooding. The 100-year flood zone along the Raritan Bay shoreline in Monmouth County, New Jersey extends up to 1 kilometer from the shoreline in most areas and as far as 8 kilometers inland, peripheral to tidal creeks (Figure 3.4). This dissertation is significant for current flood zone mitigation because the data collected far exceeds that used by FEMA to evaluate flood zones and apportion flood insurance rates.

There is no adjustment for variability in water levels in FEMA V zones other than land elevation. All of the study sites in this dissertation are in FEMA V zones. Human alterations in the form of soft and hard structures are built along the Raritan Bay shoreline to heights based on the 100-year flood height derived from water level observations at a tide gage at Sandy Hook, N.J. however, there is no evidence to

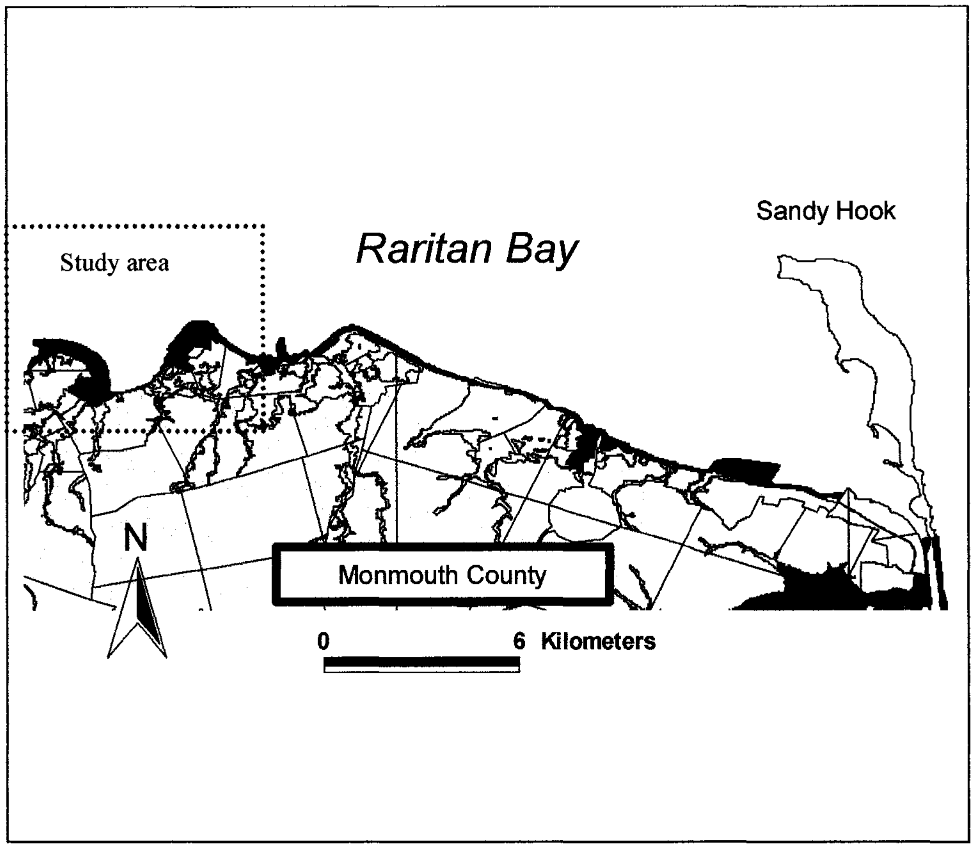


Figure 3.4 – FEMA V zones (red) and A zones (yellow) along the Raritan Bay shoreline in Monmouth County, N.J.

suggest that these structures would contain 100-year flood water levels. Water level observations at sites with hard, vertical structures are higher than observations at nearby sites with beach nourishment. Some municipalities in New Jersey add 25% to the 100-year flood level as a flood hazard precaution (Rodburg, Dore, and Stewart 1989) but no quantitative rationale is given or alternative considered. Flood zone and GIS data from state and federal agencies contain land use features but are lacking in detailed onshore and offshore data and the ability to assess variability in flood vulnerability at local scales.

Flood hazard management in the United States and New Jersey is regulated under the Flood Hazards Area Control Act of 1979, prohibiting building or altering any structure within the 100-year floodplain of any stream or water body without a permit from the New Jersey Department of Environmental Protection (NJDEP). The 100-year still water flooding level has been ubiquitously adopted as the basis for flood mitigation and regulation in the United States (Davison 1993; Platt 1994; Monmonier 1997). If no 100-year flood line exists from NJDEP or Federal Emergency Management Agency (FEMA) studies, the 10-foot topographic contour elevation is used (NJDEP 1986). No research has identified how to quantify local scale variability in flood lines and while this dissertation is not equipped to speculate as to 100-year flood water levels, the results do suggest that local scale variability is significant and that offshore and onshore variables, including human alterations are important. 100-year flood zones defined by digital FEMA A zones and NJDEP flood zones can be approximated from digital elevation models (Jones et al. 1998; Dobosiewicz 2001). The 100-year storm flood water level at Sandy Hook is applied universally throughout the bay because many water level records do not exist to quantify spatial variability.

The New Jersey shoreline of Raritan Bay is irregularly shaped, creating a diversity of orientations and different fetch distances to the mouth of the bay (Figure 3.3). Orientation relative to the mouth of an estuary is critical to the effect of ocean waves along individual reaches (Jackson 1995) and therefore to flooding from coastal storms. Visual observations of water levels at Conaskonk Point and Keansburg (Figure 3.3) following the passage offshore of Hurricane Eduard in the summer of 1996 indicate a significant contrast between wave heights at sheltered and unsheltered sites of approximately 0.5 m. Flood zone assessment in Raritan Bay should recognize the onshore and offshore factors that cause variability in susceptibility of sites to water levels at local scales.

The onshore variables assessed in this dissertation are strongly influenced by human alterations and are subject to the constraints of legislation guiding shoreline protection. From 1959 to 1974, $49 million dollars in federal, state, municipal and county funds were spent on shore protection in New Jersey. In 1977, a $20 million dollar Beach and Harbor bond was passed and in 1983 a $50 million dollar Shore Protection bond. The New Jersey Coastal Storm Hazard Mitigation Planbook emphasizes mitigation through land use controls. Recommendations for municipalities starting plans are to:

1. Analyze vulnerability and potential loss based on the 100-year storm,
2. Map and assess status of shore protection structures, and
3. Estimate populations and value of structure.

The problem of the guideline put forth in the New Jersey Coastal Storm Hazard Planbook is that while post-storm recommendations are to control land use through acquisition, the more common practice is to fortify existing shore protection and to control construction standards. Approximately one in three sites (36%) in the study area consist of hard shoreline protection either as seawalls, bulkheads or revetments. A general problem of using hard shoreline protection is that coasts and coastal landforms are dynamic, while seawalls, bulkheads and the homes behind are static. Dunes are dynamic coastal geomorphic features that serve as flood control but hard structures are considered better for the sole purpose of flood control. Some of the problems associated with hard structures are aesthetics, hazardousness to swimmers and loss of beach (Jackson and Nordstrom 1994; Komar 2000). Many coastal municipalities in New Jersey have dune ordinances in addition to participating in the National Flood Insurance Program. Flood-proofing by law requires that the lowest possible structural member of a building, except pilings, be at or above the base 100-year still water flood (NJDEP 1985a, 1985b).

The New Jersey Shore Protection Master Plan (SPMP) emphasizes the use of non-structural approaches to shore management, such as building and maintaining dunes and beaches. Good dune practices, such as maintaining large, hummocky dunes with vegetation can lower property damages (NJDEP 1986). Storm damages along ocean shorelines in New Jersey from a storm in 1984 were mitigated in municipalities with large, vegetated dunes. Dunes must have significant accumulation above the 100-year still water flood level to be effective in flood control (NJDEP 1986). Large dunes and wide sandy beaches are not natural features of estuarine shorelines yet they are commonly built as shore protection structures along the Raritan Bay shoreline (Nordstrom 1992). Artificial dunes have been built to a height of approximately 4 meters above mean sea level at locations along the Raritan Bay shoreline exceeding the 100-year flood levels (3.54 meters above mean sea level based on observations at Sandy Hook). Artificial dunes built in Port Monmouth were eroded and breached in some locations by a severe winter storm in 1992. (USACE, New York District 1993). The water levels produced from the December 1992 storm have a return interval of only 15-20 years. No research has evaluated how effective large artificial dunes would be in mitigating storm-caused water levels from moderate or large storms. Beach nourishment projects, some with developed dunes, some with only dune fencing, exist along the Raritan Bay shoreline at elevations of heights of 3- 3.5 meters above mean sea level. These beach nourishment projects are eroded by frequent seasonal winter storms and would be severely impacted by erosion and inundation from larger storms (Figure 3.5).

The New Jersey Shore Protection Master Plan also recognizes the threat of rising sea levels to buildings near the shore. The New Jersey coastline is divided into relatively homogenous reaches in the plan and the entire New Jersey shoreline of Raritan Bay is considered a single reach. The reach plan for Raritan Bay is to maintain structures and recreational beaches, especially in Keansburg, and to regulate a setback zone 30 – 70 meters from beaches and 6 meters from seawalls. However, since the bay shoreline is highly irregular, individual plans of different scales (single lot, municipality) are conditionally acceptable on a case-by-case level. For example, rip-rap, loosely placed large pieces of rock, is commonly used as a contingency plan to protect small stretches of the shoreline of Raritan Bay (NJDEP 1985a). Seven sites in the study area are buffered by rip-rap revetments as a means of shoreline stabilization. The rip-rap revetment in Laurence Harbor consists of large boulders of steel reinforced concrete creating an unattractive and poorly connected means of shoreline protection (Figure 3.6)

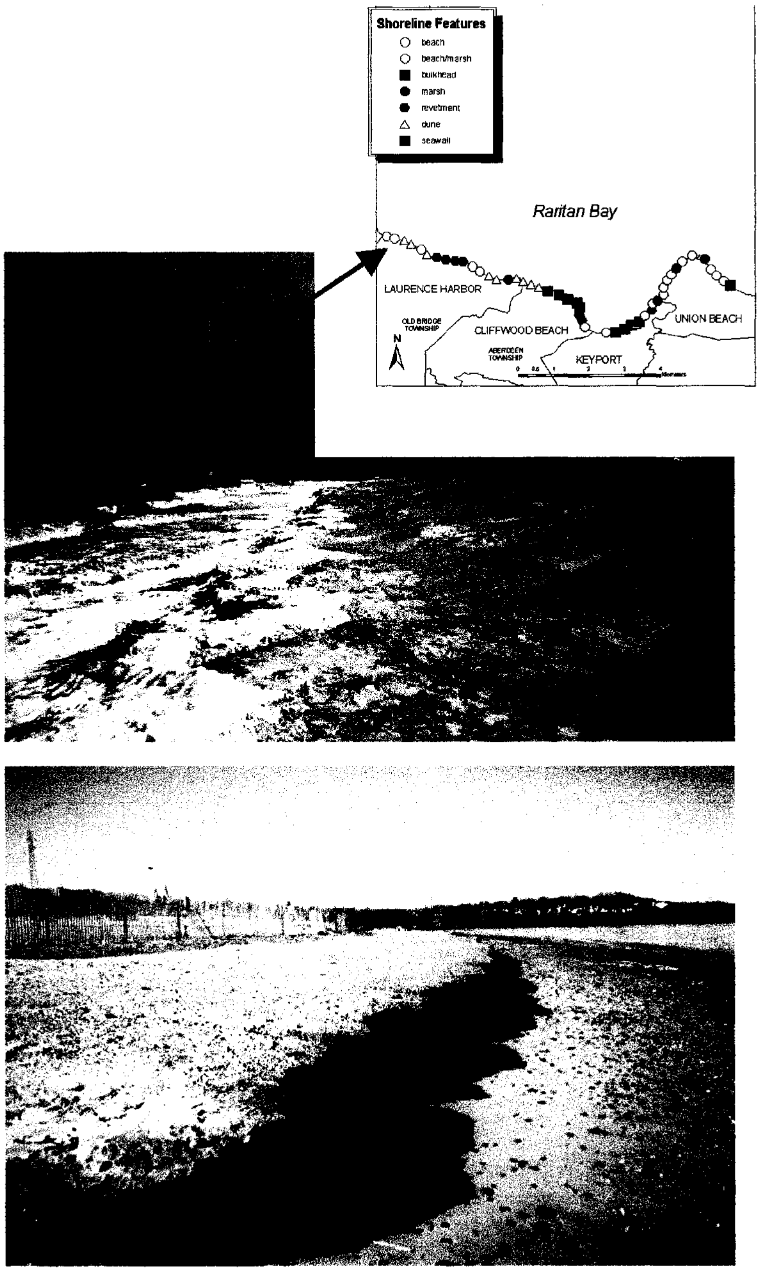


Figure 3.5 - Erosion of a beach nourishment project from winter storms in 1998 at site (Site 3) in Laurence Harbor, N.J. Classification of study sites in the inset .

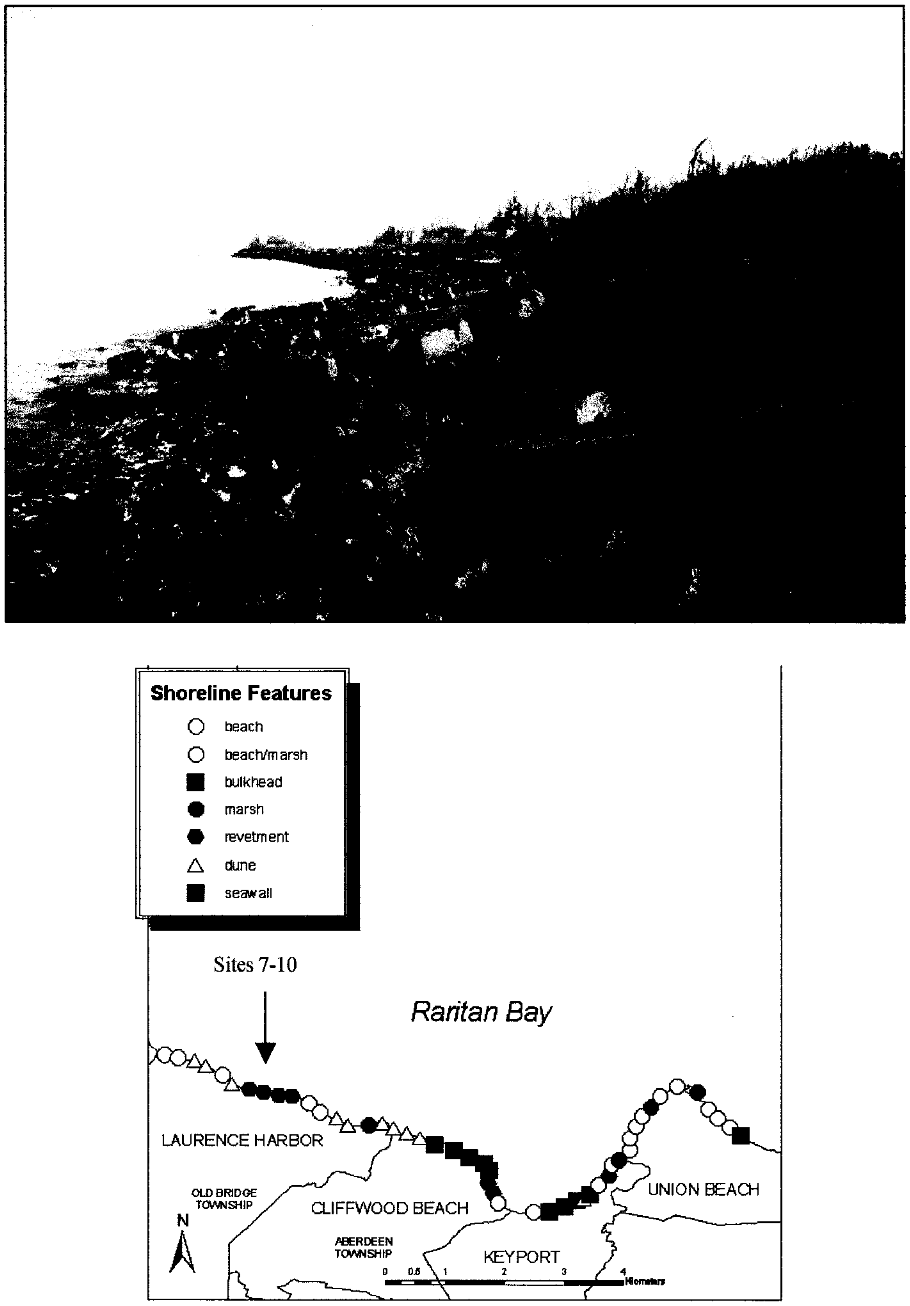


Figure 3.6 – Study sites (Sites 7-10) in Laurence Harbor with rip-rap revetment (top) with other sites in the study area with rip-rap revetments (hexagon-shaped) (bottom).

Some recommendations of the New Jersey Hazard Mitigation Plan Section 406 (1986) are to practice dune building and maintenance, inspect bulkheads and attempt to institute setbacks, zoning and land reclamation and acquisition. A critical component of assessing susceptibility to water levels is the structural integrity of the shore protection structures in addition to elevation. Table 3.1 outlines the vulnerability perceived in the 1980's and the damages to the Raritan Bay shoreline during the December 1992 storm. Significant damage occurred where bulkheads and beach fill that seemed adequate failed or eroded.

Wetlands or marshes provide a natural buffer to coastal storm impacts and while marshes are expansive in some places along the Raritan Bay shoreline, major development has occurred with little or no natural buffer from the water (Figure 3.7). Wetlands need to be preserved because their geomorphology and vegetation reduce flood vulnerability and need to be further evaluated as a means of shoreline protection and to determine between-storm variability in water levels.

The legislation and policies in the United States that focus on coastal zone management and flood hazard mitigation have been developed at broad scales (federal and state) and then applied at local scales (municipality); however, variability has not been identified in current policies at local scales such as within a singular landform (e.g., beaches, marsh) or at broad scales (e.g., barrier islands, estuary). Current flood zone delineation or mitigation strategies in Raritan Bay are based on a broad scale application of a single, statistically derived 100-year flood elevation and therefore do not account for spatial variability.

Table 3.1- Perceived vulnerability of Raritan Bay in the 1980's compared to actual damages from the December 1992 storm.

Location	Vulnerability (Nordstrom et al.1986)	Actual Damages (USACE, New York District 1993)
Highlands	Sheltered, bulkheads tilting flimsy but adequate.	Bulkheads failed producing widespread flooding.
Atlantic Highlands-Port Monmouth	Low energy, bulkheads and fill not beyond means of local residents.	Dunes scarped, flooding from tidal inundation.
Port Monmouth – Keansburg	Substantial beach fill.	Dunes scarped.
Keansburg – Union Beach	Marsh.	Tidal inundation.
Union Beach	Bulkheads seem adequate.	Bulkheads damaged, severe flooding from bay and tidal creeks.
Conaskonk Point-Keyport	Seawalls and bulkheads, only pocket beaches.	Bulkheads and walkways damaged, tidal inundation.
Keyport – South Amboy	Beaches wide where nourished. Many hard structures not maintained.	Tidal inundation, homes and buildings flooded.

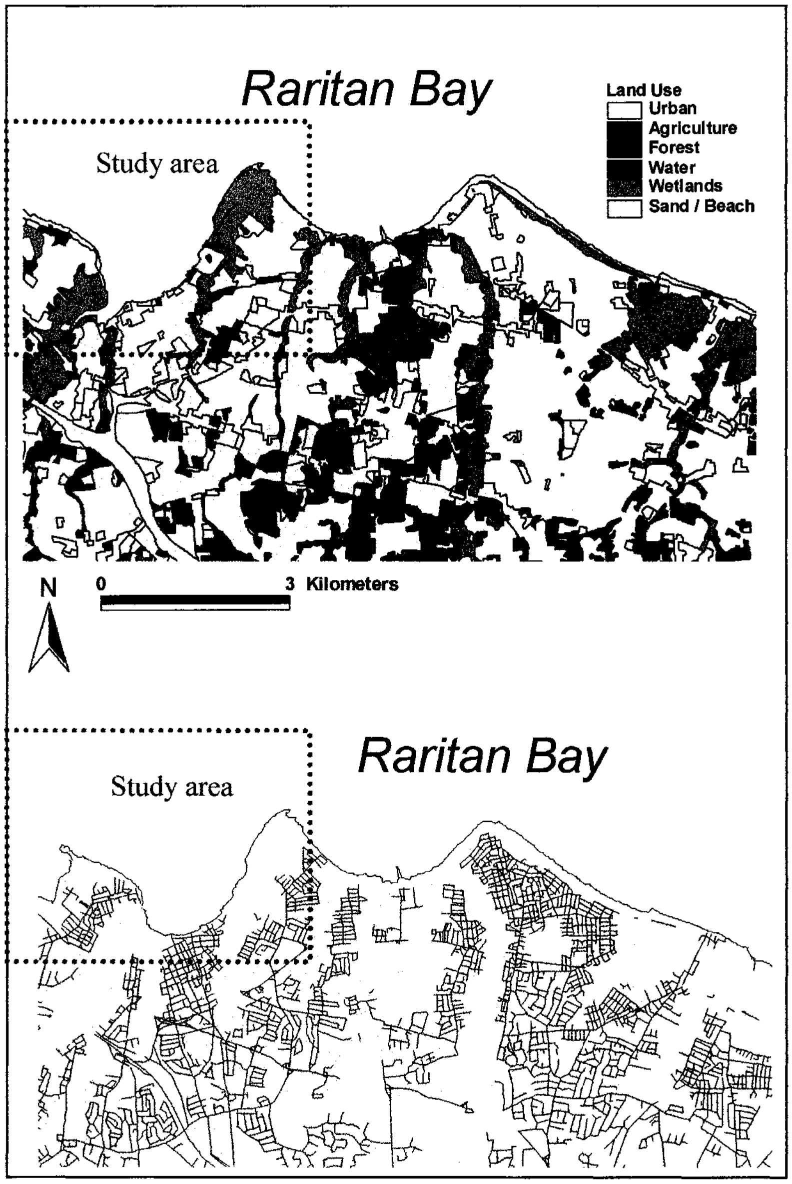


Figure 3.7 - Land use in the Keyport Quadrangle in Raritan Bay (Top) and with roads intersecting wetlands determined using GIS (Bottom).

The Rules on Coastal Resources and Development illustrate and summarize the current status of shoreline flood management along New Jersey shorelines (NJDEP 1986). Ocean setbacks are required, residential development is prohibited and commercial development discouraged in coastal high hazard areas. Setbacks are required on coastal bluffs and within 25 feet of intermittent streams. Non-structural approaches are preferred but with the understanding that their feasibility is a function of geometry, slope, sediment, winds, exposure and boating. Hard structures should have a 50-year design life. If no FEMA or NJDEP flood hazard line exists, the 10-foot contour is used. V zones are identified as areas subject to inundation with wave velocity and a 50-foot setback is mandated on the ocean from bulkheads, seawalls and revetments. Legislation does not explicitly state how implementation of these guidelines should be applied spatially, but it is usually at the local scale where actual mitigation occurs (Godschalk, Brower, and Beatley 1989). The Coastal Blue Acres program in New Jersey provides incentives for municipalities to preserve high hazard areas as open space (NJDEP 1997) but no acquisitions have been made. Setbacks are not financially or socially feasible along the highly developed Raritan Bay shoreline and the approach has been to adopt structural approaches that vary at local scales but do not consider onshore and offshore factors collectively. This dissertation provides evidence that water levels vary during moderate storms in Raritan Bay and shoreline characteristics influence the spatial variability in susceptibility to inundation at local scales.

IV – METHODOLOGY

Introduction

Storm inundation indices were developed from onshore and offshore variables that are correlated to elevated water levels. The indices evaluated the susceptibility of sites to actual and potential inundation from coastal storms. This requires the collection of water level observations at a local scale for multiple storm events using a standard datum and detailed onshore geomorphic and topographic data collected from transect lines at field sites with corresponding offshore bathymetric data from nautical charts. GIS is used as a tool for mapping the spatial variability of water levels from storms, classifying the susceptibility of the shoreline from onshore and offshore variables, comparing each storm inundation vulnerability index and evaluating the relationship of site-specific data in current flood zone assessment for the study area in Raritan Bay.

Study Area and Site Selection

Variability in elevated water levels and the susceptibility of developed estuarine shorelines to inundation from coastal storms is related to nearshore, foreshore and backshore characteristics, including onshore topography and offshore distances. The field study is conducted over 10 kilometers of Raritan Bay shoreline, almost ½ of the New Jersey side of the bay, resulting in 48 field surveys determined at an interval of 200 m (Figure 4.1). The entire bay is not used because of the difficulty in identifying and surveying the elevations of post storm water level markers over a large area, such as debris lines, before removal by wind, waves or people and because access to the shoreline

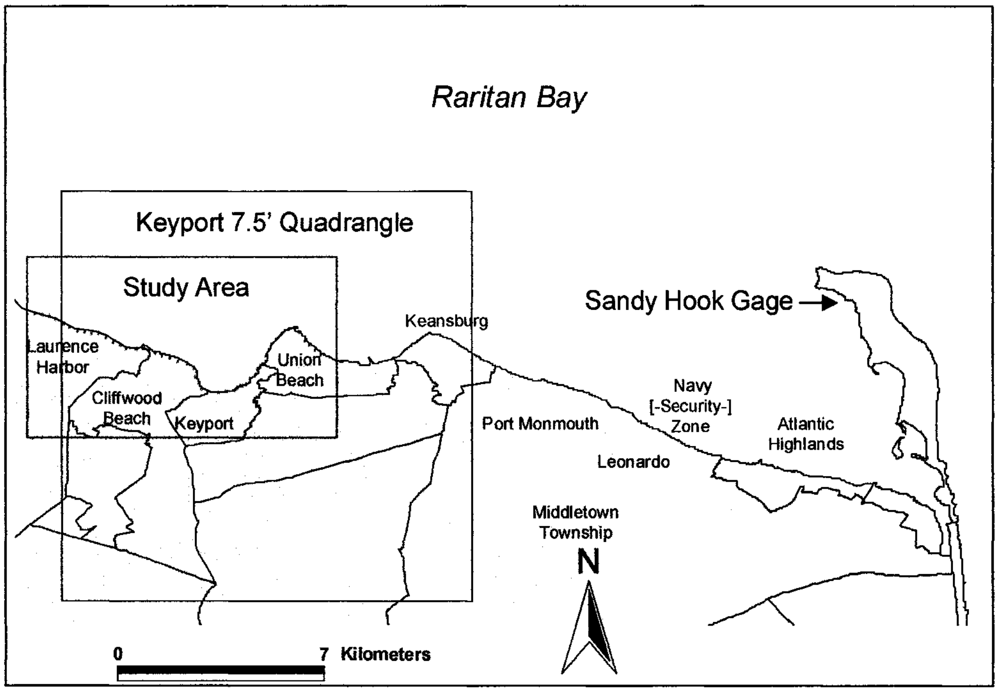


Figure 4.1 – Location of the study area and transects along the Raritan Bay shoreline.

from Leonardo to the Atlantic Highlands is restricted because of a naval station. A nested or hierarchical sampling strategy for the entire bay is not used because the research is designed to evaluate variability between local sites and between storm events and not to determine the impact of variables at different scales (e.g., orientation is broad scale, sediment is local scale, see Phillips 1986). Use of the entire bay is not required because the study area is representative of different offshore and onshore geomorphic characteristics, including shoreline protection strategies (Figures 4.2 and 4.3). The orientation of the shoreline in the study area varies, with limited exposures to northeasterly winds produced by coastal storms at Keyport and unlimited exposures at Laurence Harbor, most of Cliffwood Beach and Union Beach. The shoreline characteristics of these sites are comparable to sites around Point Comfort from Union Beach to Keansburg.

Large artificial dunes in the study area near Cliffwood Beach are similar in elevation, width and orientation to the dunes outside the study area from Keansburg to Port Monmouth (Figure 4.3). Bulkheads at Union Beach are similar to the bulkheads outside the study area located at the Atlantic Highlands. The study area also encompasses some unique features not found elsewhere along the Raritan Bay shoreline, specifically a 2 km seawall in Cliffwood Beach and a large, sheltered funnel shaped creek, Matawan Creek, located near Keyport. Water levels are historically the highest at Keyport from coastal storms, and a gage was placed there in the 1970's to evaluate tidal range. The area from Keyport to Union Beach is classified as a high hazard area in the NJDEP digital database (Figure 4.3). An extensive natural marsh between Union Beach and Keansburg has limited access to the shoreline from nearby roads. The extensive

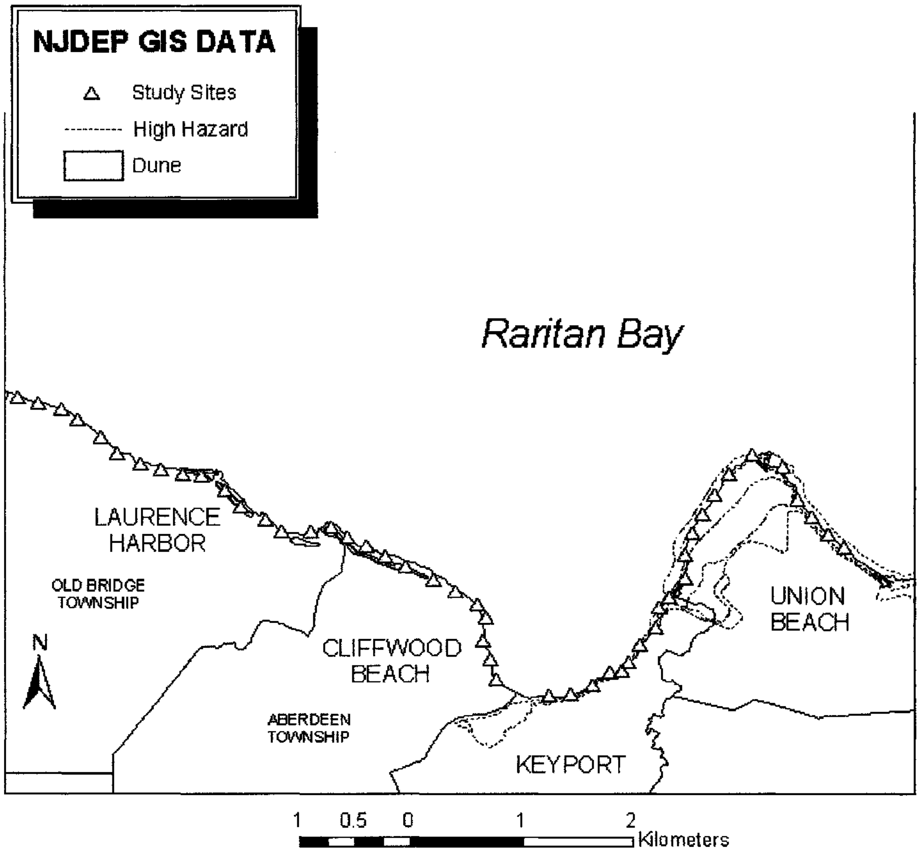


Figure 4.2 - Study sites with high hazard line and dunes (GIS data from NJDEP).

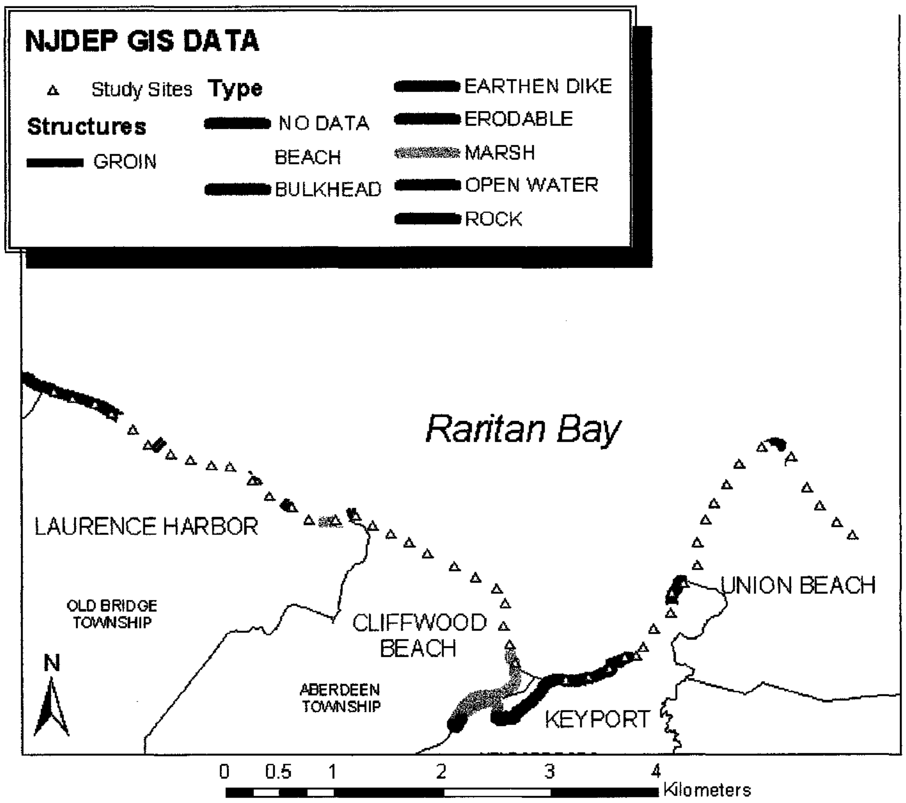


Figure 4.3 – NJDEP digital shoreline types in the study area.

marsh between Union Beach and Keansburg limits access via roads but its offshore and onshore characteristics are similar to the sites detailed between Keyport and Union Beach making it redundant. The study area boundaries are established by hard shoreline structures, a jetty at Cheesequake Creek to the west and a bulkhead at Union Beach to the east. The study area includes a variety in foreshore and backshore characteristics that are predominantly the result of human alterations (Figure 4.4). Approximately 35 % of the study sites are protected by hard shore parallel structures, where usually only a low-tide beach is present. Of the sites protected by hard shore parallel structures, seven are protected by poorly constructed rip-rap revetments, seven by concrete seawalls and three by bulkheads. Approximately 65% of the study sites are natural or protected by soft shoreline protection structures. Twelve sites are protected by beaches fronting marsh, ten sites by beaches fronting dunes, six sites by beach and four sites by marsh. Beaches at most sites outside marsh areas are artificially nourished.

Sampling Interval

The 200 m interval starts at the eastern bank of Cheesequake Creek and ends at a bulkhead in Union Beach. The intervals are continuous with the exception of a 0.5 km gap where Matawan Creek separates Cliffwood Beach from Keyport. Determining a sampling interval is complicated by the tendency for shoreline processes and response to be auto-correlated and over-sampling may occur or spurious relationships examined. A spatial analysis of shoreline recession and accretion using geostatistics for barrier islands (Dolan, Fenster, and Holme 1992) indicates that a 50 m sampling interval is highly redundant and can be expanded to hundreds of meters with high levels of confidence and

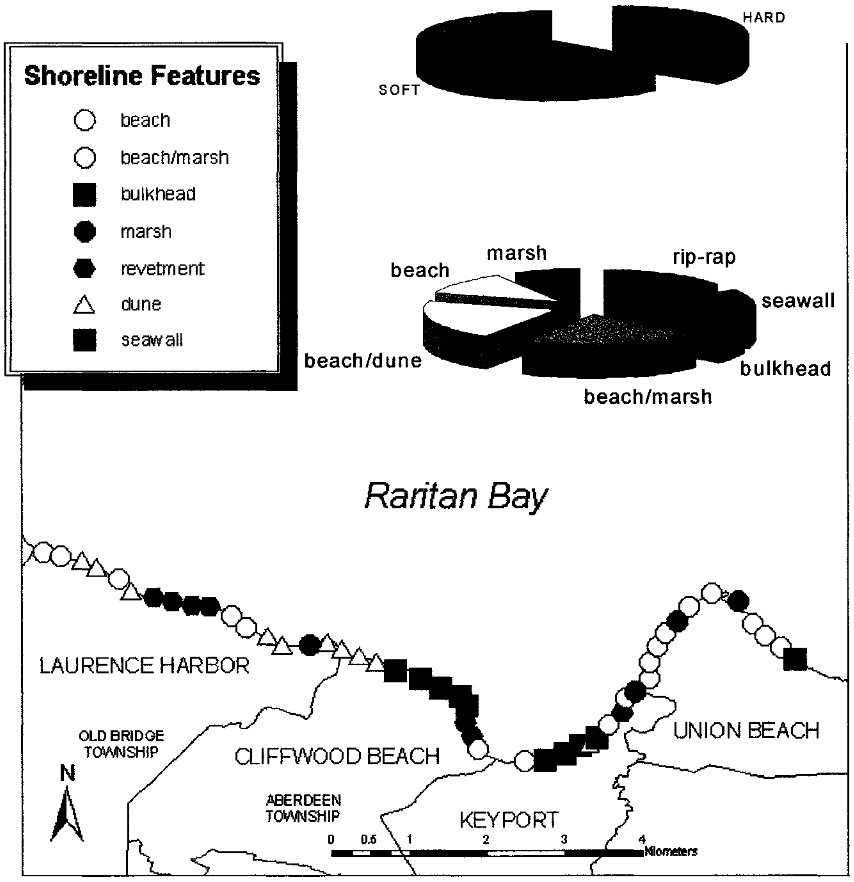


Figure 4.4 – Shoreline types identified in the field for the study area at 200 m intervals.

acceptable margins of error for specific locations. A 100 m sampling interval has been used to determine spatial variability in shoreline change along oceanic barrier island shorelines (Dolan, Hayden, and Heywood 1978a; 1978b) but another study (Dolan, Fenster, and Holme 1992) of coastal storm periodicities along barrier islands suggests that a scale of 1 km is effective.

A 200 m sampling interval is larger than the 100 m strategies commonly employed for erosion studies (Phillips 1986) along estuarine shorelines but less than kilometers which would be appropriate along ocean shorelines (Dolan, Fenster, and Holme 1992). The 200 m sampling interval allows for multiple sites within shoreline types and reaches. The use of a 200 m sampling interval is substantiated by a histogram of water levels that indicates spatial patterns on the order of hundred of meters for Raritan Bay (Figure 4.5). Upon conducting the field survey, an additional site was identified between site 31, a bulkhead, and site 32, a small seawall, located in Keyport and is noted here as site 31.5. Site 31.5 was selected because wrack lines were evident here between storm events while nearby sites with vertical shoreline protection structures or marsh did not produce wrack lines at different elevations for different storms. Site 31.5 is one of the few unaltered estuarine beaches throughout the study area and is rare along the highly developed shoreline at Keyport. Site 31.5 is included in the histogram and used for between site analyses of spatial variability but more importantly the data from Site 31.5 is used to determine between-storm variability for Reach 4.

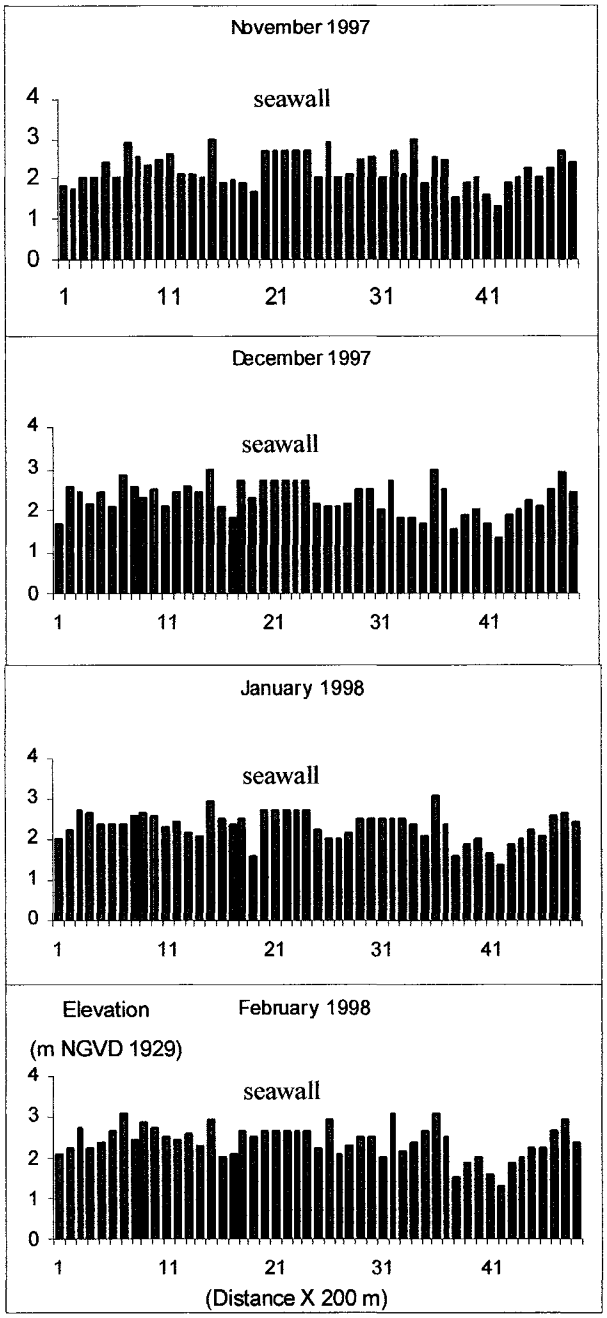


Figure 4.5 - Histograms for post-storm water levels collected in the study area.

Explanation of Onshore Variables

Forty-eight variables are quantified in this dissertation including 14 onshore and 34 offshore variables. The 14 onshore variables are determined in the field using a compass, rod and auto-level and a 50 m tape (Table 4-1). The alongshore and cross-shore azimuth establish the transect line for the field profile and these variables represent the orientation of the shoreline and subsequent exposure to winds and waves from storms. Orientation is the most cited variable in studies of erosion and storm surge penetration, both along ocean and estuarine shorelines (Dolan, Hayden, and Heywood 1978a, 1978b; Dolan and Hayden 1981; Baumer and Hardaway 1982; Anders, Kimball, and Dolan 1985; Phillips 1986; Balsille 1986; Gornitz 1991a; Fletcher et al.1995; Jackson 1995; Bode and Hardy 1997). The twelve other onshore variables are related to topography and geomorphology and determined along a transect profile line established perpendicular to the alongshore azimuth with elevations determined using an auto-level and rod. Each site is profiled using a 5 m interval plus elevations taken at conspicuous changes in slope or environment, such as a dune scarp or change in substrate (e.g., sand to marsh transition). The landward extent for profiling a site is the end of the shore protection structure. Distance to the nearest cultural feature is determined from topographic maps.

Five benchmarks recovered in the field are used to reference the onshore topographic data. Two benchmarks were identified from 7.5-minute topographic maps and three benchmarks were provided from projects conducted by the US Army Corps of Engineers. A permanent sub-datum is established at each site from the benchmarks using rod and transit leveling with errors relative to benchmarks ranging from 1-10 cm.

Table 4.1 – Onshore variables from field sites correlated to water level observations.

1. Profile Orientation
    - Along-shore azimuth (degrees from True North)
    - Cross-shore azimuth (degrees from True North)
2. Elevation (relative to NGVD 1929)
    - Maximum elevation on the profile (m)
    - Low tide terrace (m)
    - High tide line (m)
    - Storm berm (m)
    - Dune Crest
3. Width
    - Shore zone[1]
    - Foreshore[2]
    - Dune
    - Sand
    - Peat
4. Slope
    - Mean shore zone
    - Foreshore
5. Description of nearest land-ward cultural feature (not quantified)

[1] distance from maximum elevation to low tide elevation
[2] distance from high tide elevation to low tide elevation

Elevation data for the field profiles and water level observations are referenced to each local sub-datum to allow for between-site comparisons throughout the study area.

Onshore Topographic Variables

Maximum elevation on the profile represents the height of shoreline protection from elevated water levels. The spatial distribution of topographic highs and lows allows for water levels to either be absorbed by or inundate the shoreline and their distribution is a function of the storm processes (Fisher, Dolan, and Hayden 1984). The low tide elevation is used as a baseline for water levels but this elevation also corresponds to the break in slope between the low tide terrace in the near-shore and active foreshore. Low tide terraces along estuarine shorelines are broad and gently sloping, potentially dampening wave energies (Jackson and Nordstrom 1992). Shore zone width and mean shore zone slope are variables that would buffer storm impacts (Bode and Hardy 1997). Shore zone width is the distance on the profile between the maximum elevation on the profile and the low tide elevation. Mean shore zone slope is calculated from the shore zone width and the change in elevation from the maximum elevation to the low tide elevation. Mean shore zone only reflects the average slope of the entire profile and it excludes any break in slope between the maximum elevation and the low tide elevation. Foreshores and shore zones along natural estuarine beaches tend to be narrow and steep (Nordstrom 1992). Sites of beach nourishment have longer and more gently sloping shore zones than natural sites found along estuarine shorelines and would attenuate elevated water levels. High tide elevation is determined from wrack lines produced during non-storm conditions and it establishes a baseline for the active foreshore and daily water levels. Foreshore slope differs from shore zone slope because it is calculated from the change in elevation from the high tide to low tide distance, not the maximum elevation on the profile. Foreshore slope affects the propagation of waves and water levels up the profile (Dolan, Hayden, and Heywood 1978b; Fletcher et al. 1995).

Onshore Geomorphic Variables

Marsh and peat outcrops attenuate storm surge and wave energies because of the gentle slope, resistance of the substrate, and wave dampening affects of vegetation (Pethick 1992). Marsh and peat outcrops in the study area range alongshore from tens of meters between Cheesequake Creek and Matawan Creek to kilometers between Keyport and Union Beach. Beach nourishment extends alongshore for hundreds of meters of the shoreline from Cheesequake Creek to Whale Creek, west of the seawall in Cliffwod Beach and between the marsh and bulkhead at Union Beach. Beach width, berm elevation, dune elevation and dune width are determined at the sandy sites in the study area. Wide beaches with high berm elevations impede water levels from propagating inland (Dolan, Hayden, and Heywood 1978b).

Dunes are the primary flood mitigation strategy along the coastlines of the United States (FEMA 1997). Natural dunes on estuarine beaches are low, narrow and compartmentalized (Nordstrom 1992), but artificial dunes are over 3 m above the high tide water level in Laurence Harbor and Cliffwood Beach and extend hundreds of meters alongshore. The nearest landward cultural features are noted for each site and used to qualitatively assess vulnerability but not for quantitative analysis with water levels. Field profiles and sub-datum elevations for sites are illustrated in the Appendix.

Explanation of Offshore Variables

Offshore variables are determined from digital NOAA nautical charts number 12327S0 and 12331S0 using the software Maptech Chart Navigator 3.0 (Table 4.2). Chart number 12327S0 is a 1:40,000 scale chart of New York Harbor, including all of Raritan Bay and is used for determining fetch distances. Chart number 12331S0 is a 1:15,000 scale chart of Raritan Bay and the southern part of Arthur Kill but does not include the entire bay. The 12331S0 chart provides more detail of the offshore characteristics of the study site and is used to determine distances to the 6 and 12 foot (1.83 m and 3.66 m) depth contour lines with more accuracy than using the 1:40,000 chart.

Offshore variables are evaluated using four categories: fetch; distance from the shoreline to the 6 foot bathymetric contour; distance from the shoreline to the 12 foot depth contour; and distance between the 6 foot and 12 foot depth contour. Each variable is measured in multiple directions from the cross-shore transect, producing 29 variables. Mean values are calculated for the four categories using three directions relative to shore normal and within a 90^0 window, to bring the number of offshore variables to 33. The azimuth of the maximum fetch within a 90^0 window is determined, bringing the final number of offshore variables to 34. The four offshore categories are measured in the shore normal direction, perpendicular to the alongshore azimuth and in line with the

Table 4.2 – Offshore variables from field sites correlated to water level observations. (measured in km)

Variable	Direction
1. Fetch Distance	
	Shore normal
	45^0 East of shore normal
	45^0 W of shore normal
	Maximum within 90^0 window of shore normal[1]
	North
	Northeast
	East
	Northwest
2. Distance to 6 foot depth	
	Shore normal
	45^0 East of shore normal
	45^0 W of shore normal
	North
	Northeast
	East
	Northwest
3. Distance to 12 foot depth	
	Shore normal
	45^0 East of shore normal
	45^0 W of shore normal
	North
	Northeast
	East
	Northwest
4. Distance from 6-12 foot depths	
	Shore normal
	45^0 East of shore normal
	45^0 W of shore normal
	North
	Northeast
	East
	Northwest
5. Mean Fetch[2]	
6. Mean Distance to 6 foot depth[2]	
7. Mean Distance to 12 foot depth[2]	
8. Mean Distance from 6-12 foot depth[2]	

[1] azimuth also recorded for maximum fetch in degrees from True North

[2] calculated using 3 values (shore normal and 45^0 E and 45^0 W of shore normal)

cross-shore transect. Variables are measured shore normal to represent the direction from which storm winds would produce waves and storm surge with the least modification by refraction. The four offshore categories are also measured in the direction of winds caused by coastal storms; north, northeast and east and the predominant wind direction, northwest.

Fetch is an offshore variable critical to waves, storm surge and elevated water levels (Phillips 1985; Balsille 1986; Ekwerzel 1990; Jackson and Nordstrom 1992; Baumer and Hardaway 1993). Distances to offshore contours represent nearshore and offshore bathymetry that modify storm surge, waves and elevated water levels approaching the shoreline (Dendrou, Moore, and Myers 1985; Phillips 1985; Baumer and Hardaway 1993; Fletcher et al.1995).

Maximum fetch distance is determined within a 90^0 window (45^0 east and 45^0 west of the shore normal direction) because the fetch distance shore is not necessarily the maximum fetch distance. Maximum fetch would provide the most open water for wind to work and produce elevated water levels at the shoreline (Phillips 1985; Ekwerzel 1990). Azimuth of the maximum fetch within a 90^0 window is determined and represents exposure to storm wind directions. While it may seems obvious that orientation of the shoreline and long fetch distances in the direction of storm winds are critical for producing elevated water levels, the relationship between the variables and spatial variability in actual water levels has not been documented. The flow of water through ocean entrances to estuaries complicates simple relationships between winds and water levels (Ward 1978; Miller 1988).

Water Level Observations

The elevation of water levels along study site transects are determined using wrack lines deposited by five storms occurring between March 1997 and March 1998. An autolevel is used to determine elevation relative to a subdatum established along each transect that was referenced to NGVD 1927, providing an absolute measuring technique for the study area. Water level observations were not made from Chingora Creek to Union Beach for the first storm in March 1997 because the sites were not accurately profiled until June 1997. Wrack lines of debris and vegetation are the primary marker but in some location scarps are used. A post-storm profile was conducted for a few sites with conspicuous beach deposits and where geomorphic changes were obvious. Regression analysis is used to determine the relationship between the onshore and offshore variables and storm-caused water levels. Variables that are significant at the 95% level using a t-test are selected for further analysis and the creation of storm inundation indices that evaluate susceptibility to inundation from coastal storms using Arcview GIS.

Meteorologic Components of Coastal Storms

Previous studies identify the need to better quantify storm conditions in the assessment of coastal hazards (Smith and Piggot 1987; Platt, Beatley, and Miller 1991). The storm conditions that have been related to waves and elevated water levels are wind speed and duration (Dendrou, Moore, and Myers 1985; Miller 1988; Murty 1993; Murty and Flather 1994; Dolan and Davis 1994; Gornitz et al. 1994) and track (Shaffer, Jelesnianski, and Chen 1986; Gornitz et al. 1994).

Hourly wind speed and direction at Bergen Point, West Reach, Kill Van Kull, New York station number 8519483, located at the north entrance of Raritan Bay, are obtained from the internet (http:\\www.opsd.nos.noaa). A 72-hour graphic profile of wind speeds and directions for five storms occurring between 1997 and 1998 is created to quantify sustained and peak wind speeds, directions and duration that can be compared for different storms. 72-hours covers the duration of moderate coastal storms. Wind speeds are in meters per second and directions in degrees with 0 = true north. Each storm is evaluated on the duration of sustained and/or peak winds over 10 m/s from the north, northeast or east representing coastal storm conditions that occur yearly in Raritan Bay (USACE, New York District 1993).

Wind speed, direction and duration are qualitatively related to the spatial variability of water levels in the study area to determine between-site variability and then at 10 sites to determine between-storm variability. The 10 sites selected have the most variability in water levels between storms, satisfying a minimum criterion that the site has different water level observations for at least 4 storm events. Regression analysis is used to determine if there is any relationship between storms, by evaluating whether any sites consistently have the highest or lowest water levels. The qualitative relationships are used to explain between-site and between-storm variability in the storm inundation indices.

The relationship between reach characteristics and variability in elevated water levels is discussed in Chapter 5. Onshore and offshore variables are statistically related to between-site variability in elevated water levels in Chapter 6. Storm inundation indices for the study site are determined and mapped using GIS in Chapter 7. Between-storm variability is evaluated in Chapter 8. Implications and major contributions of this dissertation for coastal zone management in New Jersey are in the concluding chapter, Chapter 9.

V – Field Evaluation of Site Characteristics and Water Levels

Introduction

Field data collected along the Raritan Bay shoreline are evaluated in this chapter qualitatively and quantitatively from both reach and individual site perspectives. Comparisons of the field data and storm conditions are evaluated in Chapter 8. While the focus of this dissertation is the quantification of site-specific variables and water levels, the use of reach level observation aids in the comparison of the site-specific data across the entire estuary. Other studies along estuarine shorelines have been conducted using sites to evaluate reaches with results applied broadly (Nordstrom 1977, 1987; NJDEP 1985a, 1985b; Phillips 1985; Nordstrom et al. 1986; Jackson and Nordstrom 1992). The study area is divided into six reaches based primarily on shoreline orientation, natural boundaries, such as creeks, and artificial boundaries, such as revetments and bulkheads (Figure 5.1). Digital topographic maps are used as base maps to show the relationship between the location of the 49 field sites and natural, topographic and cultural features. These characteristics are evaluated for each site and reach and compared to water levels. Spatial variability in elevated water levels from coastal storms is determined from a descriptive statistical analysis of post-storm water level observations. Spatial variability is evaluated as either between sites or between storms. Between-site variability refers to variability in the water levels at all sites for one storm. Between-storm variability refers to variability in water levels at an individual site for different storm events. Historical observations from USACE reports of catastrophic events in Raritan Bay are included to

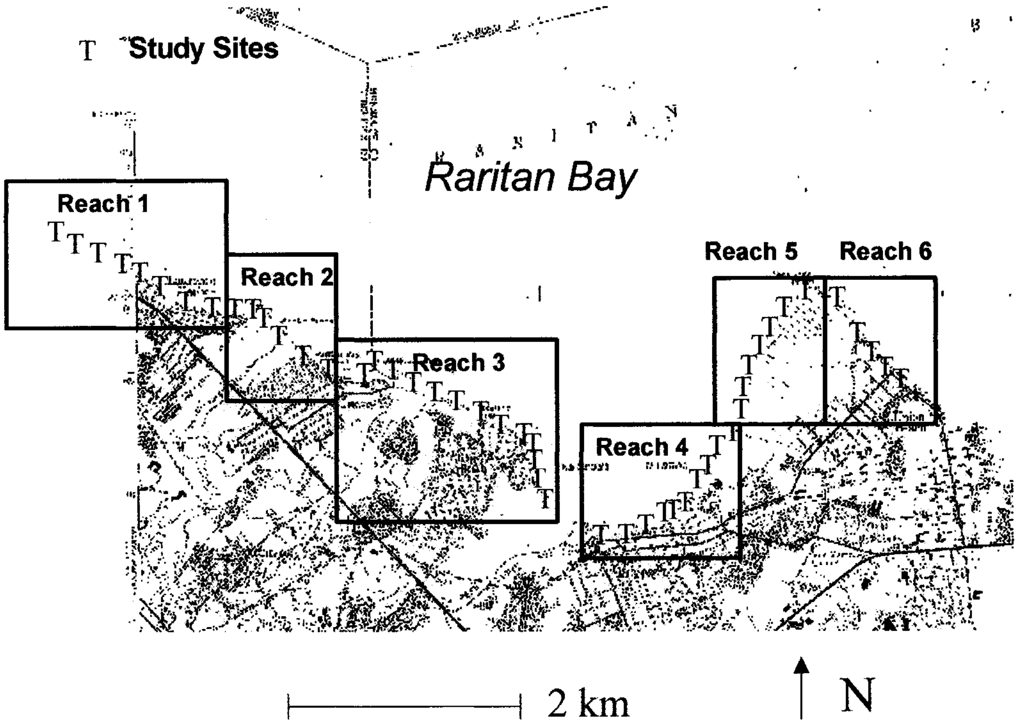


Figure 5.1 – Location of study sites and reach boundaries on the USGS 7.5 minute topographic quadrangle for Keyport. (Sites 1-4 are located on the South Amboy quadrangle which is not shown here).

determine if locations where flooding from coastal storms has been highest are consistently identified in the storm inundation indices.

Spatial Variability in Water Levels

The distribution, central tendency and variability of the water level observations are determined for all sites and then for a reduced set using sites where between-storm variability is observable. Mean water level observations at the 49 study sites for the five storms ranged from 2.28 to 2.55 m (all water level observations and elevations on profiles are referenced to NGVD 1927 in this Chapter) with a standard deviation from 0.38 to 0.43 m and a sample variance of 0.14 to 0.18 m (Figure 5.2 and Table 5.1). The 95% confidence interval on either side of the mean is between 0.11 and 0.14 m. The range of water levels between sites, 1.65 to 1.78 m, indicates that some consistency exists over all the sites independent of the storm event. That is, some sites within the study area consistently have higher water levels than other sites and there is measurable variability throughout the entire study area. This observation is supported by an analysis of tide gage observations for Raritan Bay (Dobosiewicz 1997) that exhibits variability in storm-caused water levels at large scales (kilometers) and statistical correlation coefficients of water levels from different sites between storms (Table 5.2).

Descriptive statistical analysis of the storm-caused water levels for all sites indicates large-scale variability throughout the entire study area, but it may not be the best indicator of local-scale variability. Wrack lines were not observed in different locations for different storms on the profile for sites with marsh, revetments, or vertical

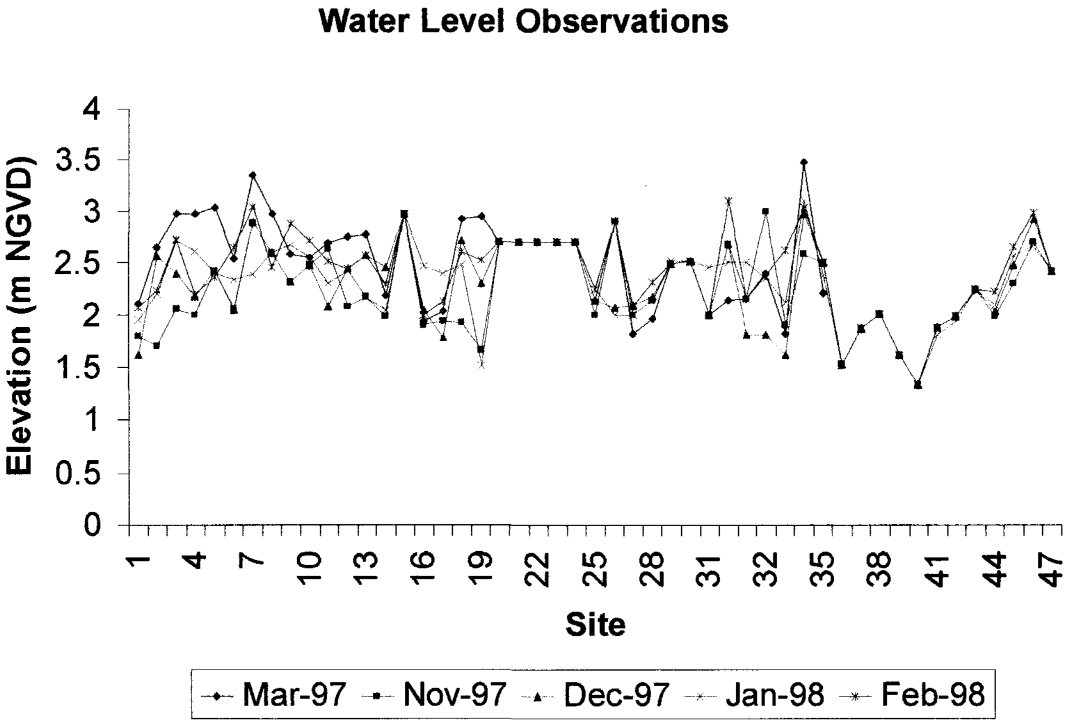


Figure 5.2 – Distribution of water level observations for all sites. The sample size is N= 37 for the storm labeled Mar-97 and N=49 for the other storms.

Descriptive Statistic	*Mar-97*	*Nov-97*	*Dec-97*	*Jan-98*	*Feb-98*
Mean	2.55	2.24	2.27	2.32	2.41
Standard Error	0.070	0.058	0.058	0.054	0.057
Median	2.64	2.15	2.31	2.40	2.46
Mode	2.70	2.70	2.70	2.70	2.70
Standard Deviation	0.425	0.409	0.408	0.376	0.401
Coeff. Of Variation	16.7	18.3	18.0	16.2	16.6
Sample Variance	0.181	0.168	0.166	0.141	0.161
Range	1.67	1.67	1.65	1.78	1.78
Minimum	1.81	1.33	1.33	1.33	1.33
Maximum	3.49	3.00	2.98	3.11	3.11
Count	37	49	49	49	49
Confidence (95.0%)	0.142	0.118	0.117	0.108	0.115

Table 5.1- Descriptive statistical analysis of water level observations.

Table 5.2 – Correlation of water levels from different storms based on water level observations at sites.

R^2	**Range**	**2/98**	**1/98**	**12/97**	**11/97**	**3/97**
Range	1	0.101	0.002	0.002	0.001	0.028
2/98	0.101	1	0.634	0.634	0.597	0.355
1/98	0.002	0.525	1	0.538	0.493	0.146
12/97	0.002	0.634	0.538	1	0.443	0.429
11/97	0.001	0.597	0.493	0.443	1	0.165
3/97	0.028	0.355	0.146	0.429	0.165	1

structures (bulkheads or seawalls). At sites with marsh, wrack and debris are dispersed throughout the marsh and generally collect in depressions or adjacent to tidal creeks. Therefore, the water level observations for marshes are the same as the maximum height on the cross-shore profile and there is no between-storm variability in these observations. Wrack and debris tends to collect in cracks between the rock rubble at revetments and often accumulated in the same spot for different storms. Wrack and debris is deposited at the base of vertical structures in the active foreshore structure at some sites, unless the structure is overtopped by the water level. None of the five storms caused significant overtopping of vertical structures in the study area.

Due to the lack of water level observations between storms at all sites, a second descriptive statistical analysis of water level observations is determined using only sites where moderately sloping sandy beach profiles exist that allow for the accumulation of wrack or debris lines for each storm event. Twenty-two of the 49 sites are used for this analysis, Sites 1-6, 11-14, 16-19, 28, 31.5, 33-35 and 45-47, with all the reaches represented except Reach 5, a marsh environment near Conaskonk Point, where the sandy overwash beaches are too low to provide a profile for collecting multiple wrack lines. The results of the pared down analysis of water level observations using 22 sites are similar to the results from all sites, with a mean between 2.21 and 2.53 m, compared to a mean of 2.28 and 2.55 m for all sites. The standard deviation and sample variance are 0.37 and 0.14 m, respectively, for the pared down analysis, values that are similar to the standard deviation and sample variance for all sites of 0.41 and 0.16 m, respectively. Therefore, although it was not possible to determine differences in water levels at some sites between storms, it does not affect the finding of large-scale variability at all sites.

Reach Descriptions

Reach 1 – Cheesequake Creek to Seidler Beach (Sites 1-10)

The general shoreline trend of Reach 1 from Cheesequake Creek to Seidler Beach (Figure 5.3) is southwest, approximately 160 degrees, creating long fetch exposures to northeast winds, from 7.24 to 12.08 km, but relatively short fetch exposures to more northerly winds, from 3.64 to 4.69 km. Site 1 is a marsh area by a 100 m long rock jetty stabilizing the east bank of Cheesequake Creek. Sites 2-6 are 50-100 m wide artificial sandy beaches, with undeveloped and sparsely vegetated dunes. The wide beaches create a formidable barrier to inundation from moderate coastal storms and result in low water level elevations. Site 2 is a 100 m wide sandy beach but is low in elevation, less than 3 m and without a dune. Site 2 is located in front of a parking lot with a major highway, Route 35, 200 m from the active foreshore. Smaller beaches, 50 to 60 m wide, with poorly developed dunes 3 to 4 m high are located at Sites 3-6, with single-family homes less than 50 m behind these sites in Laurence Harbor. The homes are located on a 5 m high cliff, between the shoreline and the 20' (6.1 m) contour on the digital topographic maps. Storm produced waves actively interact with the artificial sandy shoreline in Reach 1, with obvious erosion occurring at Site 3 (Figure 5.4a).

Two 50 m long groins, not seen on the topographic map, compartmentalize the reach between Sites 4 and 5, potentially modifying encroaching waves from the north and north east, and producing crescent-shaped along-shore profiles (Figure 5.4b). A non-engineered rubble revetment, made of broken slaps of steel-reinforced cement waste ≈ 1 m in size (Figure 5.4b), stabilizes the shoreline of Sites 7 – 10. Homes are located on the opposite side of a road that is 40 to 60 meters from the revetment and beach.

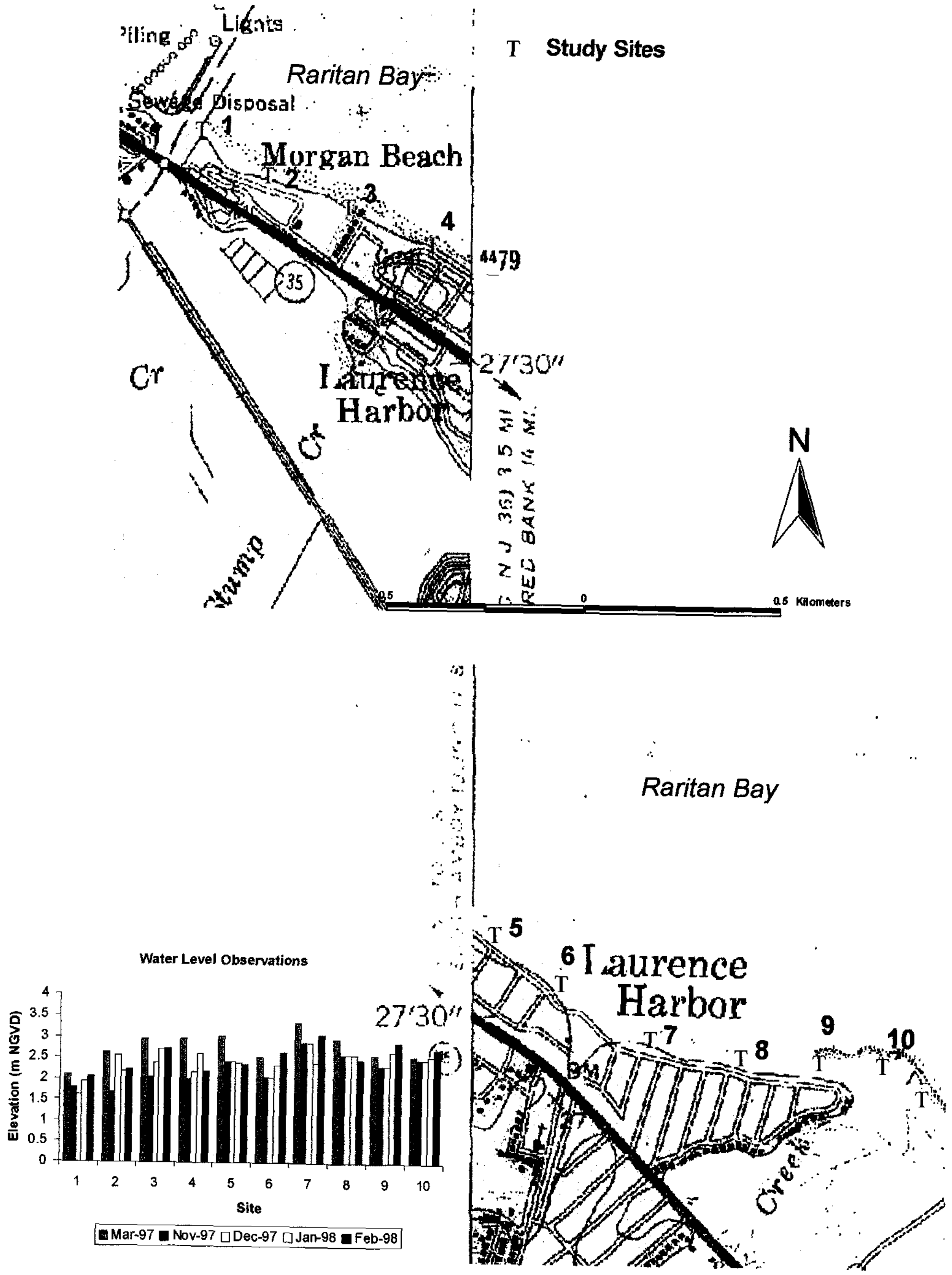


Figure 5.3 - Reach 1 (Sites 1-10).

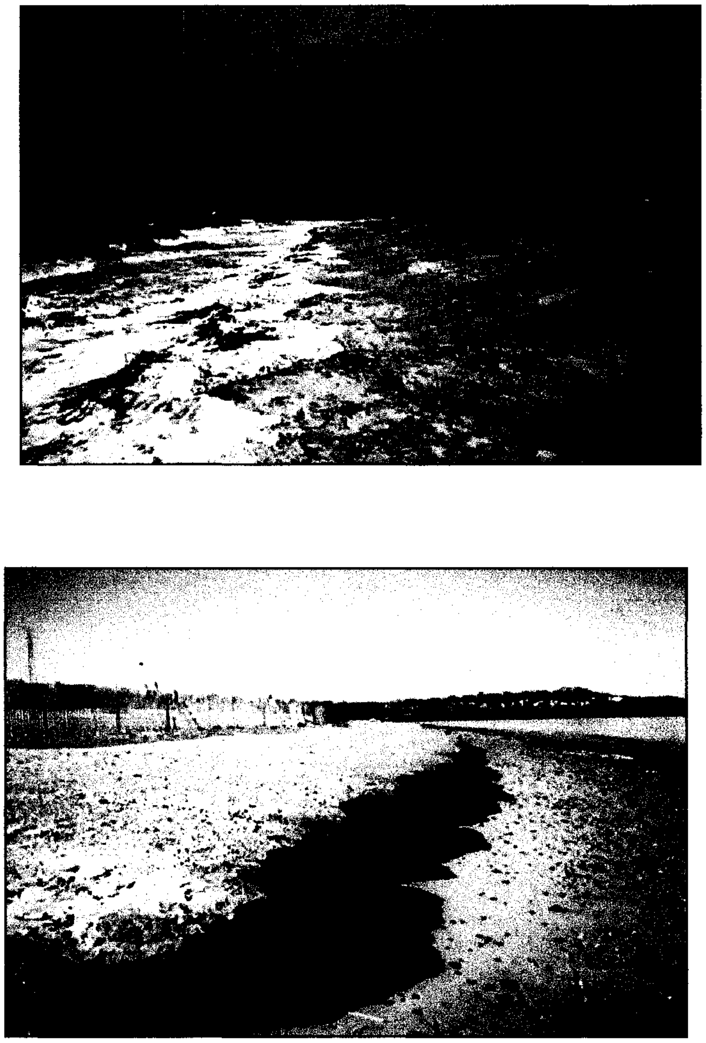


Figure 5.4a - Erosion of a beach nourishment project from coastal storms in 1998 at Site 3 in Laurence Harbor.

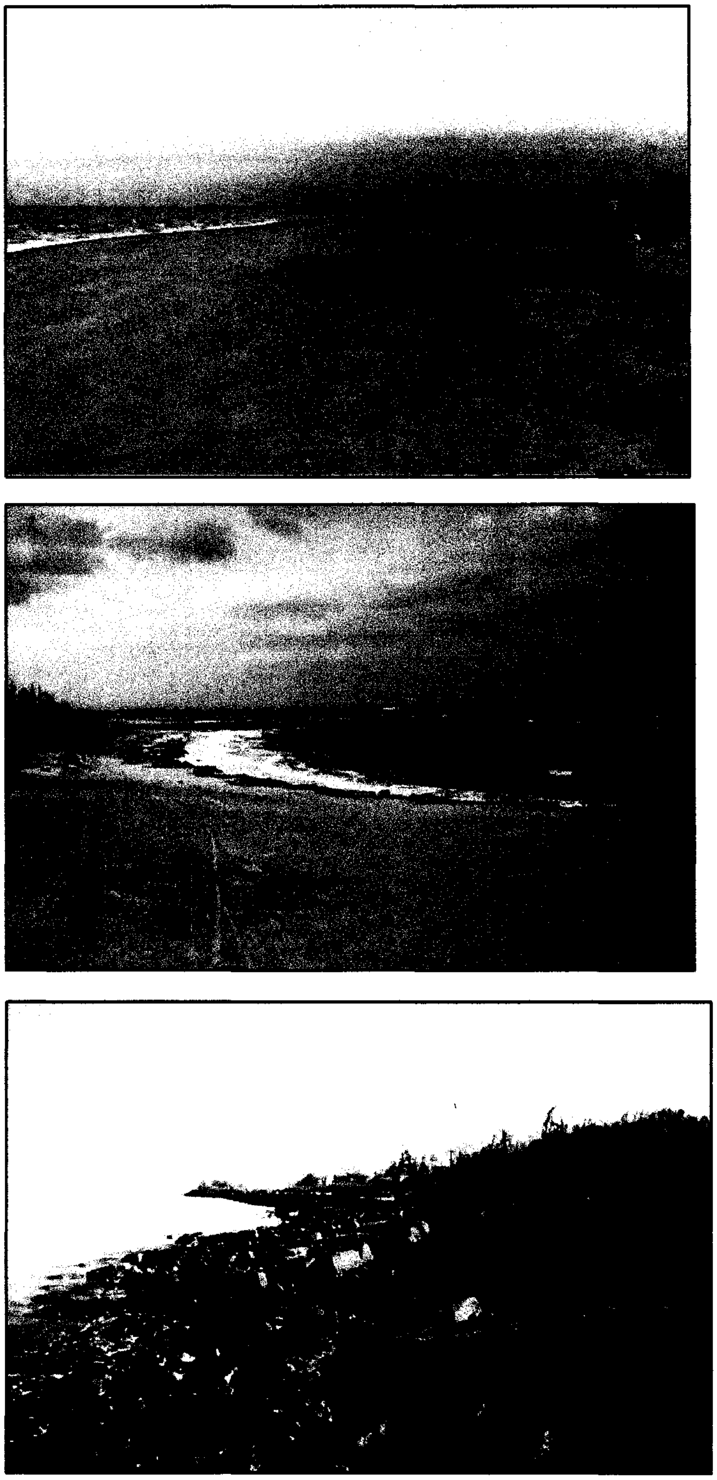


Figure 5.4b – The top 2 pictures show groins between Sites 4-5 in Laurence Harbor. The bottom picture is a rubble revetment (Site 7 located in the foreground) in Laurence Harbor.

Qualitative reconnaissance reports indicate that roads and homes in Reach 1 were frequently flooded by coastal storms prior to beach fill and revetment projects (USACE, New York District 1960). The northeaster in December 1992 flooded a bar and Route 35 situated 50 m behind Site 2 to a still water flood level of approximately 1m (USACE, New York District 1993). The average water level observations at each site in Reach 1 vary from 1.91 to 2.91 m and are lowest by the jetty near Cheesequake Creek and highest at the sites with revetments (Figure 5.3). The spatial variability in water levels between sites in Reach 1 is approximately 1 m. Since all sites in Reach 1 have similar orientation and fetch characteristics, it appears that human alterations of the onshore geomorphology are critical in creating variability in water levels. The lowest water level observation is found at Site 1, a marsh, and the highest at Sites 7-9, a rubble revetment. Intermediate water level observations are found at Sites 2-6, the nourished beach and artificial dune environments.

Reach 2 – Seidler Beach to Whale Creek (Sites 11-15)

The fetch characteristics in Reach 2 are similar to Reach 1 with long northeast fetch distances and limited exposures to the north, but the shoreline trend is more southerly, (Figure 5.5). Relatively natural landforms exist from Seidler Beach to Whale Creek, with small steep sandy beaches, less than 30 m wide and dune crest elevations 2.5 to 3 m high (Figure 5.6). The only human alterations are the decaying remnants of a wooden dock and a sewer out-fall pipe that exist on the low tide terrace. Site 15, near

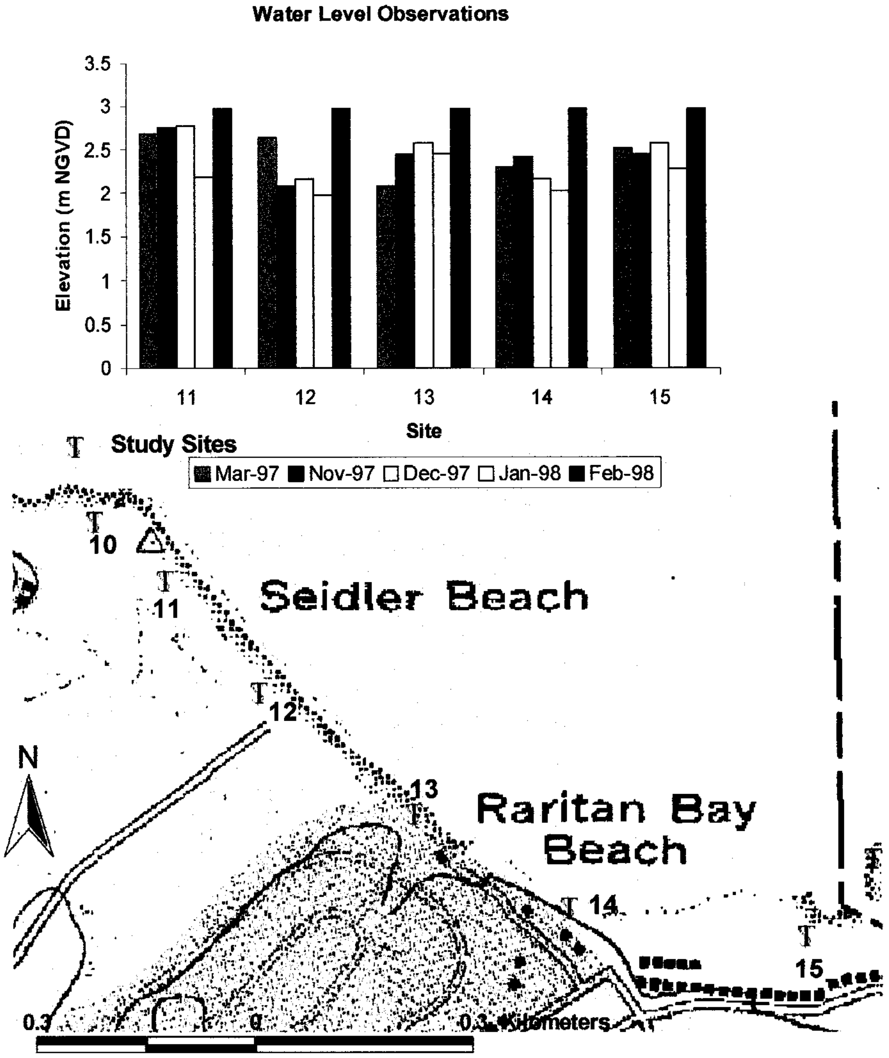


Figure 5.5 - Reach 2 (Sites 11-15).

Figure 5.6 – Natural estuarine beach and dune conditions at Sites 13 & 14 in Seidler Beach.

Whale Creek, is a completely vegetated marsh but some vegetated peat outcrops occur on the low tide terraces of the other sites. Homes are situated 20 to 30 m landward of sites 12-14 and at elevations over 6 m. A playground and overgrown ball-field are located behind Site 15 at an elevation ≈ 5 m . The homes are at elevations near or above the 20' contour, above the threat of elevated water levels from typical coastal storms. Small steep beaches and low dunes are in front of the substrate upon which the homes are built (Figure 5.6). The position of water level observations at the base of the dune on the profile at Sites 13 and 14 indicate that the beaches and dunes protect the cliff from exposure to coastal storm flood impacts. The average water level observations at each site in Reach 2 varied from 2.19 to 2.97 m (Figure 5.5). The variability in the water level observations along Reach 2 is not consistent with the variability found at similar environments in Reach 1, with higher values near the marshes at Sites 11, 12 and 15 for some storms than at the sandy beaches at Sites 13 and 14. This suggests that along estuarine shorelines with minimal human alteration, there is little difference in water levels at marshes, marshes with beaches in front or beaches at local scales, because the topography and geomorphology of these landforms reduce inundation despite similar shoreline exposure to storm conditions. The change in shoreline orientation, while creating a long northeasterly exposure and shore normal fetch distance, shelters the shoreline from more easterly winds. The overall impact of the change in orientation is shorter mean fetch values at sites 12 and 13 than at sites 14 and 15. No historical storm water levels from this reach are found in the USACE reports, but Route 35 is located 600 m inland of marsh near Site 11 and flooding occurs during typical winter storms and spring tides (Personal Observation).

Reach 3 – Whale Creek to Matawan Creek (Sites 16 – 27)

The shoreline orientation of Reach 3 is southeasterly, creating a long unrestricted fetch distance to the northeast (Figure 5.7). Sites 25-27 have limited easterly fetches because of sheltering by Conaskonk Point. Major storms in the 1960s caused severe flooding and shoreline erosion along this reach, spurring massive shoreline protection projects in the 1970's. A beach nourishment project extends approximately 1 km from Whale Creek to a large rock seawall with dunes 4 m high at Sites 17-19. The large rock seawall extends approximately 1.5 km with elevations ranging from 3.3 to 3.5 m. The seawall absorbs wave energies and stabilizes a cliff supporting single-family homes in the municipality of Cliffwood Beach. Artificial beach fill was placed in front of the entire seawall but is now visible for only 200 m at the west end of the seawall when water levels are below high tide. Site 16 is located adjacent to a 50 m jetty that stabilizes the entrance to Whale Creek. Sites 17-19 are west of the seawall and consist of nearly a kilometer of artificial beaches and vegetated dunes (Figure 5.8). Sites 20, 21 and 22 have low tide beaches but high tide does not recede enough in front of Sites 23 and 24 to expose any beach (Figure 5.8). Sites 25 and 26 are located east of the seawall approaching Matawan Creek and have a loosely configured rubble revetment made of steel-reinforced cement slabs ≈1 m wide. Site 27 is near Matawan Creek and is the only natural site within the reach consisting of a well-developed 40 m wide overwash platform on a marsh that extends 1 km inland.

Despite the massive shore protection projects in portions of the shore landward of the beach, inundation occurs in Reach 3 from major coastal storms that are less powerful

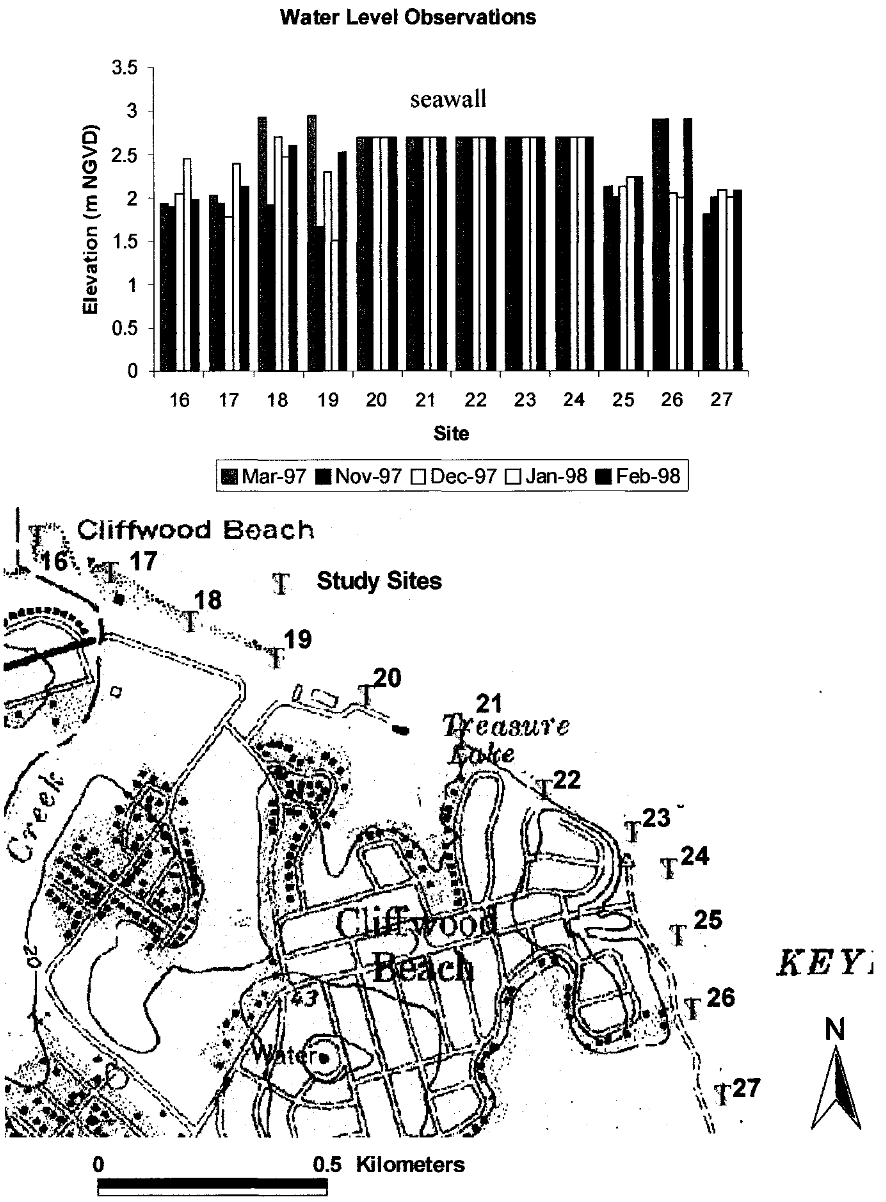


Figure 5.7 - Reach 3 (Sites 16-27). No between-storm variability was detected from Sites 20 – 24, where wrack lines are not observed because a massive seawall exists in the foreshore.

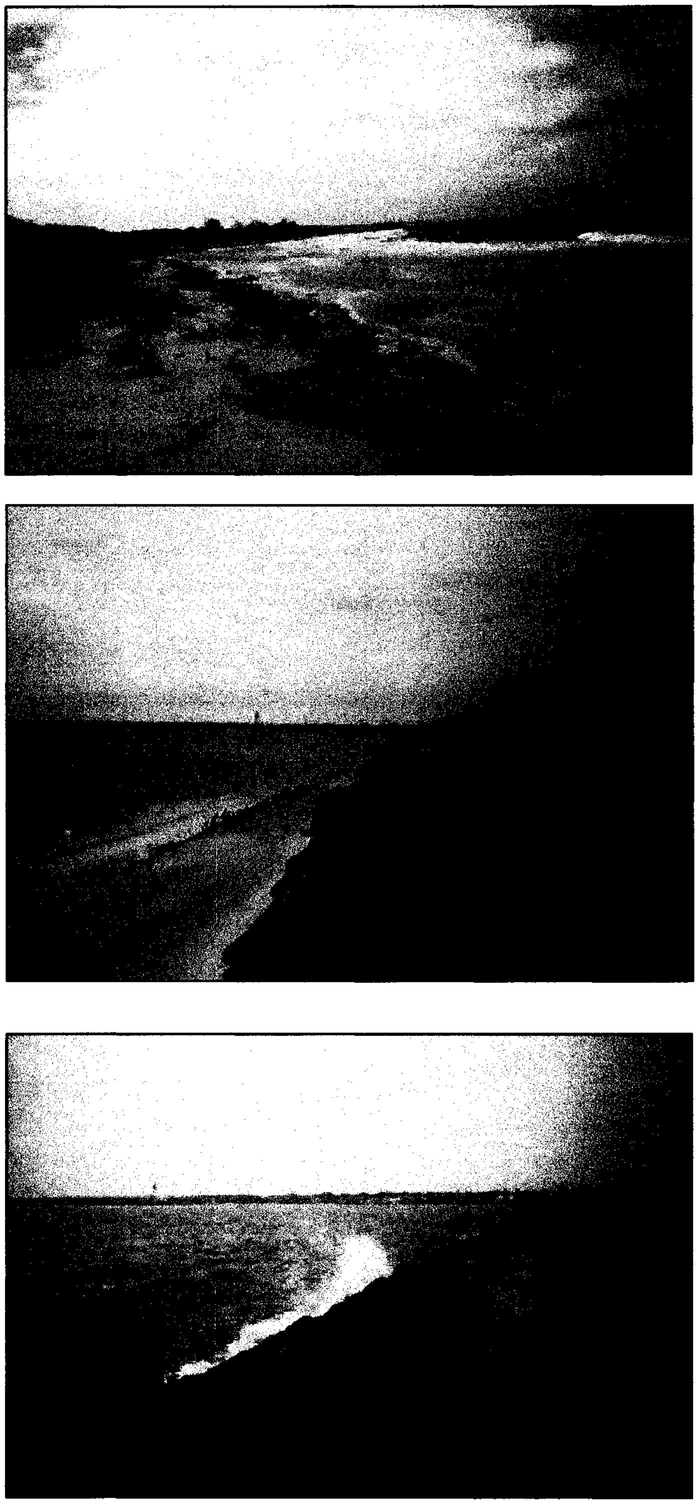


Figure 5.8 – Artificial beach and dunes (top) at Site 19 in the foreground and seawall at Site 20 (middle) and Site 22 (bottom) in Cliffwood Beach. Storm-caused water levels occur at an elevation of 2.7 m in the bottom picture.

than the design life of the projects. Debris found in a fence surrounding a playground behind Sites 18 and 19 indicate water levels of over 1 m and breaching of the artificial dunes during a northeaster in December of 1992 (USACE, New York District 1993). Wrack is consistently deposited at all the sites on the Cliffwood Beach seawall at an elevation of 2.7 m. This elevation is high on the seawall and causes minor overtopping and spray at elevations of over 3 m despite moderate storm conditions. Water levels observed at Sites 16 -19 vary between storms and between sites. For example, water levels can be high at Site 18 and 19, near 3 m, completely overtopping the beach and reaching the base of the dune for some storms (Figure 5.8), but observations following other storms indicate water levels of less than 2 m (Figure 5.7).

The water level observations from Sites 16 - 19 exhibit the same between-storm and between-site variability occurring at Sites 1-5 in Reach 1. Sites 1 and 16 consist of marshes situated near tidal creeks with beach environments located to the east. Higher and more variable water levels are observed at the beach sites than at the marsh sites. The high water level observations at the rubble revetment at Site 26 are consistent with high water level observations at rubble revetments in Reach 1 (Sites 7 - 10). While maximum fetch distance is greater along Reach 1, fetch distance in storm directions, North and Northeast, is greater along Reach 3 and is responsible for creating higher water level observations at sites in Reach 3 than at sites in Reach 1.

Reach 4 – Matawan Creek to Chingora Creek (Sites 28 –36)

The shoreline orientation of Reach 4 is significantly different from the shoreline orientation of Reaches 1 - 3. The cross-shore azimuths change from northerly near the creek, where water levels are the highest, to northwesterly at the marsh between Keyport and Chingora Creek, where flooding is generally lower. The northeasterly trend of the shoreline shelters the foreshore from the east, limiting the effects of waves generated across long northeast fetches (Figure 5.9). Reach 4 encompasses the town of Keyport, where the highest historical flood elevations in Raritan Bay have been recorded (USACE, New York District 1993). The northeaster in December 1992 caused extensive flooding and structural damage at Keyport with still water levels exceeding 1 m in some buildings and along a link fence near a bulkhead stabilizing the entrance to Matawan Creek. Overtopping of the 3.5 m high bulkheads and shore parallel structures built by individual homeowners in Keyport was also reported (USACE, New York District 1993). Unlike the massive broad scale state projects at Cliffwood Beach designed to mitigate coastal storm flood impacts, the shoreline of Keyport is armored with individual small-scale structures, delineated spatially by property lines. Most homes are located within 10 meters of the water, between the high water line and the 20' contour. Many backyards protected by either small cement or wood shore parallel structures abut the water during high tide (Figure 5.10). Wide, sandy beaches, common in Reaches 1 - 3, are not found along Reach 4. Sites 28 and 31.5 have natural coarse sand beaches that are narrow, with minor dune development. Both sites are located in front of playgrounds, not homes (Figure 5.10). Five sites have shore parallel structures: Sites 30 and 31 have wooden

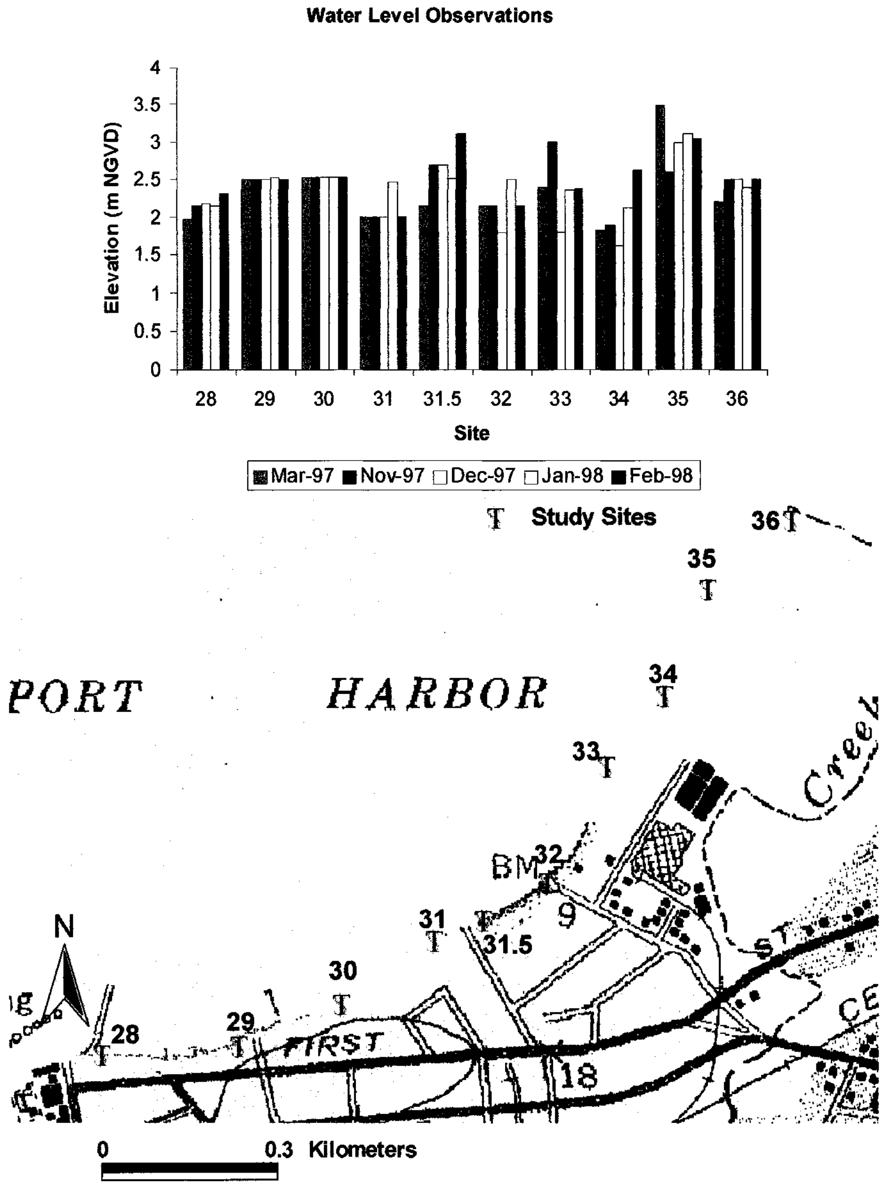


Figure 5.9 - Reach 4 (Sites 28-36).

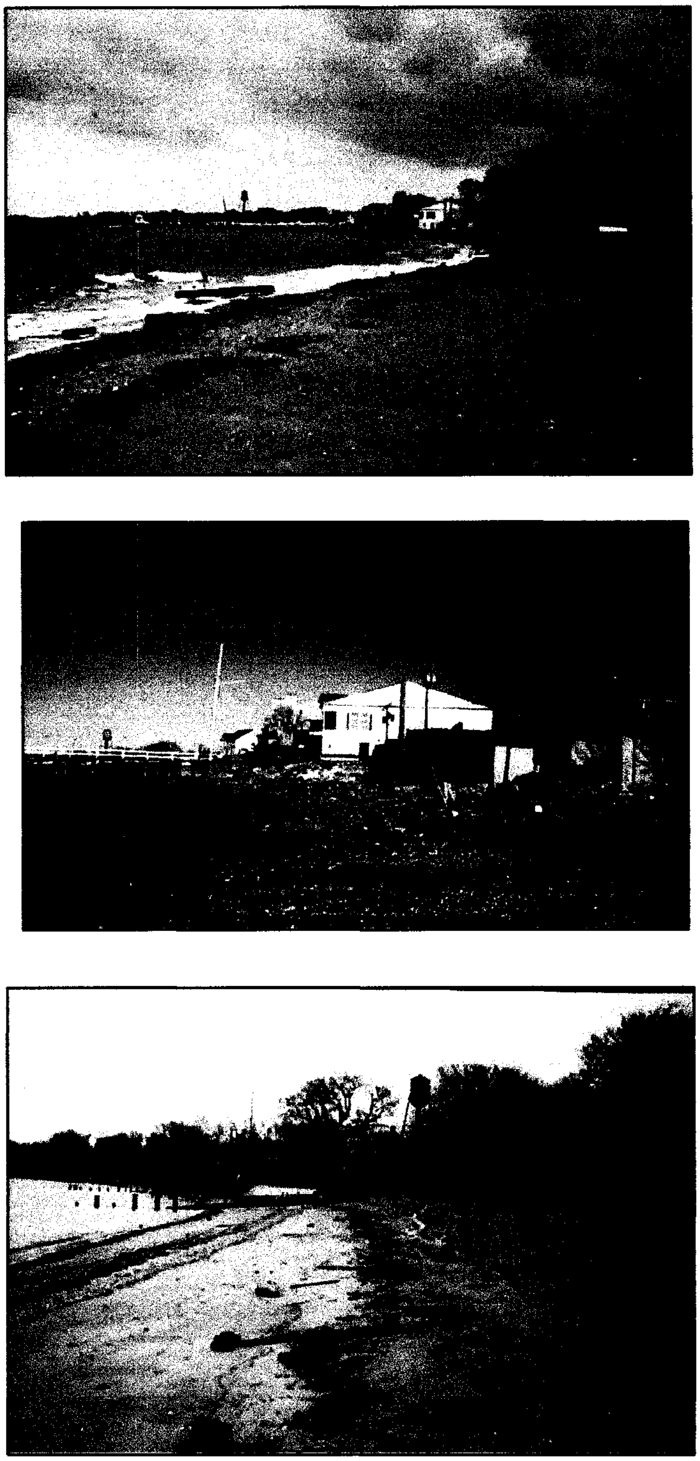


Figure 5.10 – Homes with various shoreline protection structures at Site 28 (top) and Site 29 (middle) and a natural beach and dune at Site 31.5 (bottom) in Keyport.

bulkheads in good condition; Sites 29 and 32 have cement seawalls; and Site 35 has a rock rubble revetment. Sites 33, 34 and 36 are extensive marsh deposits with sandy overwash platforms with no individual property or cultural features nearby.

It is difficult to evaluate between-storm variability in water levels at Sites 29, 30, 31 and 32 because the storm wrack collects at the base of vertical wooden and cement structures. Persistent water levels, such as daily high tides, are evident from the weathering of wooden bulkheads and accumulation of organic matter, such as green algae (_Volvox_), at wooden and cement structures. However, storms do not produce water levels for a sufficient amount of time for chemical or biological evidence to be a useful indicator. Some of these locations are accessible during moderate storms, and water level observations can be made during a storm relative to the top of the structure. None of the observed storms caused water levels to exceed the elevation of the vertical structures. The top of the vertical structure serves as an overtop boundary, and average water level observations at Sites 29, 30, 31 and 32 ranged from 2.09 to 2.46 m (Figure 5.9). The between-storm variability in water level observations at Site 31.5 ranged from 2.13 to 3.12 m. The water level observations for Sites 28, 33 and 34 ranged from 2.01 to 2.38 m and between-storm variability is also evident because the sandy profiles allowed for wrack lines to accumulate in different locations on the profile. Water levels at a rubble revetment at Site 35, in a cove between two marsh sites, ranged from 2.59 to 3.35 m, exceeding the water levels at site 31.5.

Water levels are higher and more variable for the natural estuarine beach at Site 31.5 than at the beach at Site 28, near Matawan Creek. This observation is consistent with water level observations in Reaches 1 – 3. Water levels are higher at sites with sandy beaches than at nearby sites with marsh along similarly oriented shorelines. The shoreline orientation of Sites 28-32 produces long northerly fetch distances, some exceeding 8 km. Generally, water level observations for the five storm events were higher at Reaches 1 and 3 than at Reach 4, because of the limited northeasterly exposures. Storms with persistent northerly winds created higher water levels at Keyport than anyplace else in the study area.

Reach 5 - Chingora Creek to Union Beach (Sites 37 –43)

Reach 5 consists of a large marsh indicative of low energy estuarine environments. Cross-shore azimuths gradually change from westerly at Site 37 to northwesterly on the west side of Conaskonk Point, to northerly at Conaskonk Point, and slightly northeasterly at Site 43. Maximum and mean fetch distances normal to the shore in Reach 5 are some of the lowest for the entire study area, less than 9 km overall with some sites having less than 6 km (Figure 5.11). Overwash platforms, from 60 to 20 m wide, have developed on the marsh at Sites 37, 38, 41, 42 and 43 with marsh deposits exclusively at sites 39 and 40 (Figure 5.12). Sites 42 and 43 are located near Conaskonk Point and have coarse sand overwash beaches from 30 to 60 m wide (Figure 5.12). Numerous creeks dissect the marsh and attenuate wave energy traveling up the creek and subsequently dissipating in the marsh. There is no historical evidence of flooding along this reach in USACE reports to compare to my water level observations.

There is little between-storm variability in water level observations throughout the reach except at Sites 42 and 43 following the January 1998 storm. The lack of variability

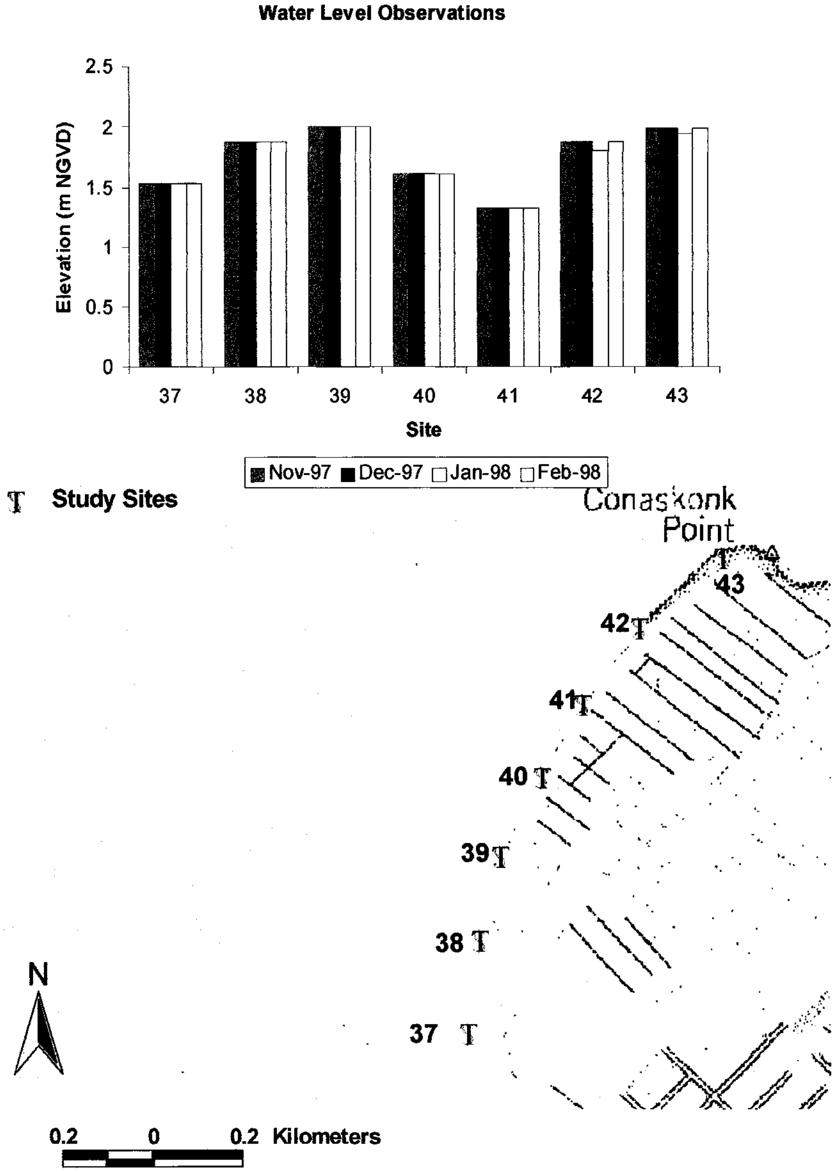


Figure 5.11 - Reach 5 (Sites 37-42). No between-storm variability was detected from Sites 37 – 43, because wrack is observed at the same location on the marsh profile for all storms.

Figure 5.12 – Typical marsh found between Sites 39-43 near Conaskonk Point. Site 39 (top) has no beach deposits while Site 42 (bottom) has a fairly well developed beach of coarse sediments in front of the marsh. The foreshore of sites with and without sediments is flooded by moderate storms.

is caused by the dispersion and deposition of wrack throughout the marsh, indicating that the marsh is flooded by water levels from the observed storms. Water level observations vary by 0.5 m between sites, the least amount of variability for all reaches. The orientation of the sites in Reach 5 minimizes water levels produced by moderate winds from the observed storms. Wrack deposits at Site 39, in the middle of the reach, were the highest for all sites with only marsh, slightly over 2 m high. Water level observations range from 1.33 to 2.01 m, which is consistent with water level observations at marsh sites in Reaches 1-4. Site 42, near Conaskonk Point, has a more easterly shoreline orientation and greater fetch distances than the other sites in the reach and water level observations are the highest (Figures 5.11).

Reach 6 – Union Beach (Sites 44-48)

The shoreline trend along Reach 6 is southeast, resulting in long fetch distances coincident with northeasterly storm winds, similar to Reaches 1, 2 and 3. Reach 6 has longer northerly fetches, from 7 – 8 km than Reaches 1, 2 and 3 (Figure 5.13). Union Beach has a history of severe flooding from coastal storms. The December 1992 northeaster caused still water levels over 1 m in homes up to four blocks (approximately 0.5 km) from the shoreline in Union Beach (USACE, New York District 1993). Reach 6 and the rest of Union Beach outside the study area is currently protected by a 500 m beach nourishment project and a bulkhead ≈ 3 m high and 1 km long. A moderate winter storm in 1996 produced wrack lines across the northern end of Front Street in Union Beach into driveways and near homes and at the time no shoreline protection strategy

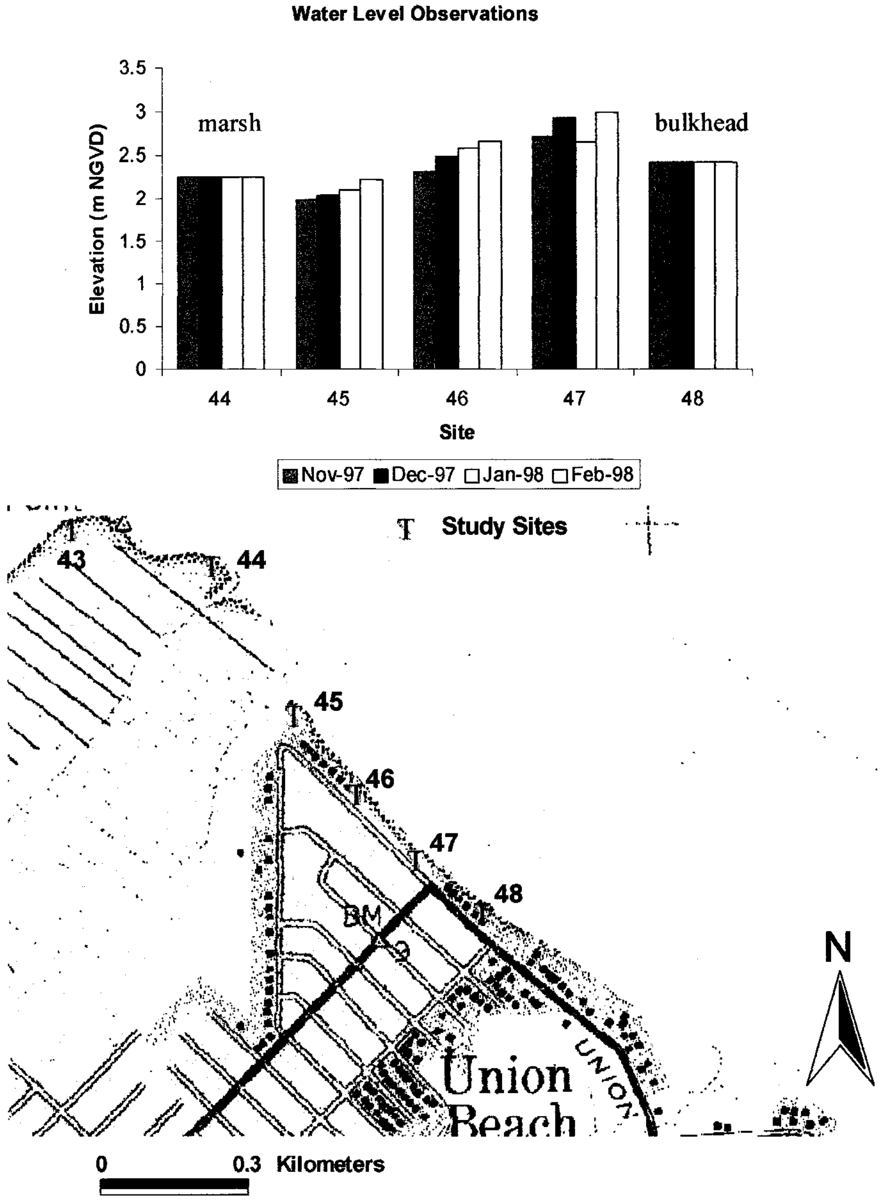


Figure 5.13 - Reach 6 (Sites 43-48). Between-storm variability in water levels was not observed at Site 44 (marsh) and Site 48 (wooden bulkhead).

was in place. The present beach fill and bulkhead project was implemented between my initial observations in 1996 and the establishment of my field sites in 1997.

Water level observations were not made for the March 1997 storm because the sites in Reach 6 were not accurately profiled until June 1997. Site 44 is a marsh site with wrack deposited at an elevation of 2.25 m. Sites 45, 46 and 47 are located along a recent beach fill project. Water level observations are progressively higher at sites east of the marsh, from 2.08 m at site 45 to 2.82 m at site 47 (Figure 5.13). The water at Sites 45 and 46 is within 10 m of homes in Union Beach on the bayside of Front Street. Site 47 is located on a 500 m long beach nourishment project next to a walkway and bulkhead on Front Street. A large townhouse complex is located on the landward side of the street, less than 50 m away (Figure 5.14). The bulkhead and the highest elevation of beach nourishment are both over 3 m high and water level observations ranged from 2.65 to 2.92 m at Site 47. The profile at Site 47 is scarped at the base of the dune indicating that coastal storms are causing erosion. Site 48 is located at a 3.4 m high wooden bulkhead protecting the remainder of Front Street (Figure 5.14). An artificial cobble beach is present at the toe of the bulkhead at Site 48 and moderate storm water levels strike the bulkhead at elevations at approximately 2.4 m with spray occurring over the bulkhead. Water level observations are lowest at Site 45, a marsh, and highest at Site 47, an artificial beach. This observation is consistent with water level observations from the other reaches and study sites where marshes occur near beach deposits along southeasterly trending shorelines. The maximum fetch distances are long, nearly 20 km, and the azimuth of the maximum fetch is northeast making Reach 6 especially susceptible to inundation from water levels produced by strong northeasterly winds.

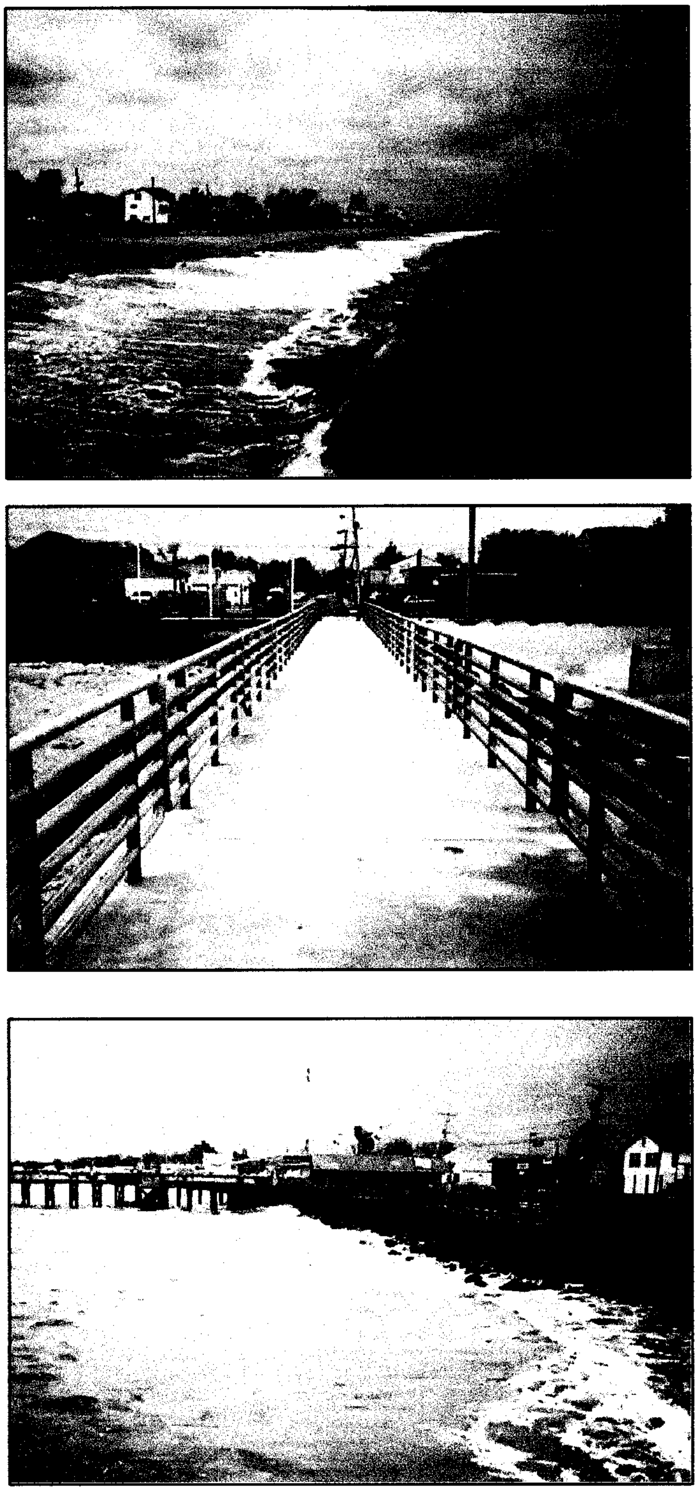


Figure 5.14 – Beach fill with a groin (middle) separating the beach fill project at Site 47 from the bulkhead (bottom) that starts at Site 48 in Union Beach.

Summary of Between-Site Variability

Between-site variability of 1.6 to 1.7 m is evident from the range in water level observations at sites across the study area for the same storm event. Correlation coefficients comparing water levels at individual sites for different storm events range from 0.08 to 0.50, indicating that water levels are consistently high at some sites and low at others. Some general patterns are observed by examining reaches and then by examining individual sites. Water level observations at Reach 5 were consistently the lowest, rarely exceeding 2 m. Water level observations at Reaches 1, 4 and 6 were consistently the highest, rarely lower than 2 m (Figure 5.15).

Water level observations at Sites 7, 27, 34 and 47 within Reach 1, 3, 4 and 6, respectively were consistently the highest for the observed storms. The orientation of these reaches creates long fetch distances to the north and northeast. Rubble revetments exist in the foreshore at sites 7, 27 and 34 and the foreshore slopes of these revetments are twice as steep as nearby sites consisting of beach. Beach nourishment at site 47 does not have a steep foreshore slope nor the largest fetch distances, but the azimuth of the maximum fetch at that site is northeast making it susceptible to water levels caused by northeast winds. Most of the beach and dune deposits in the study area are the result of artificial fill with elevations up to 3 m, below the 100-year flood level, but less than the elevations of the vertical structures. Water level observations at sites with beach are moderate to high, from 2-3 m at Sites 3 and 47 in Reach 3 and 6, respectively. These sites consist of beach nourishment projects approximately 50 m wide with developed berm crests and dunes roughly 3 m in elevation.

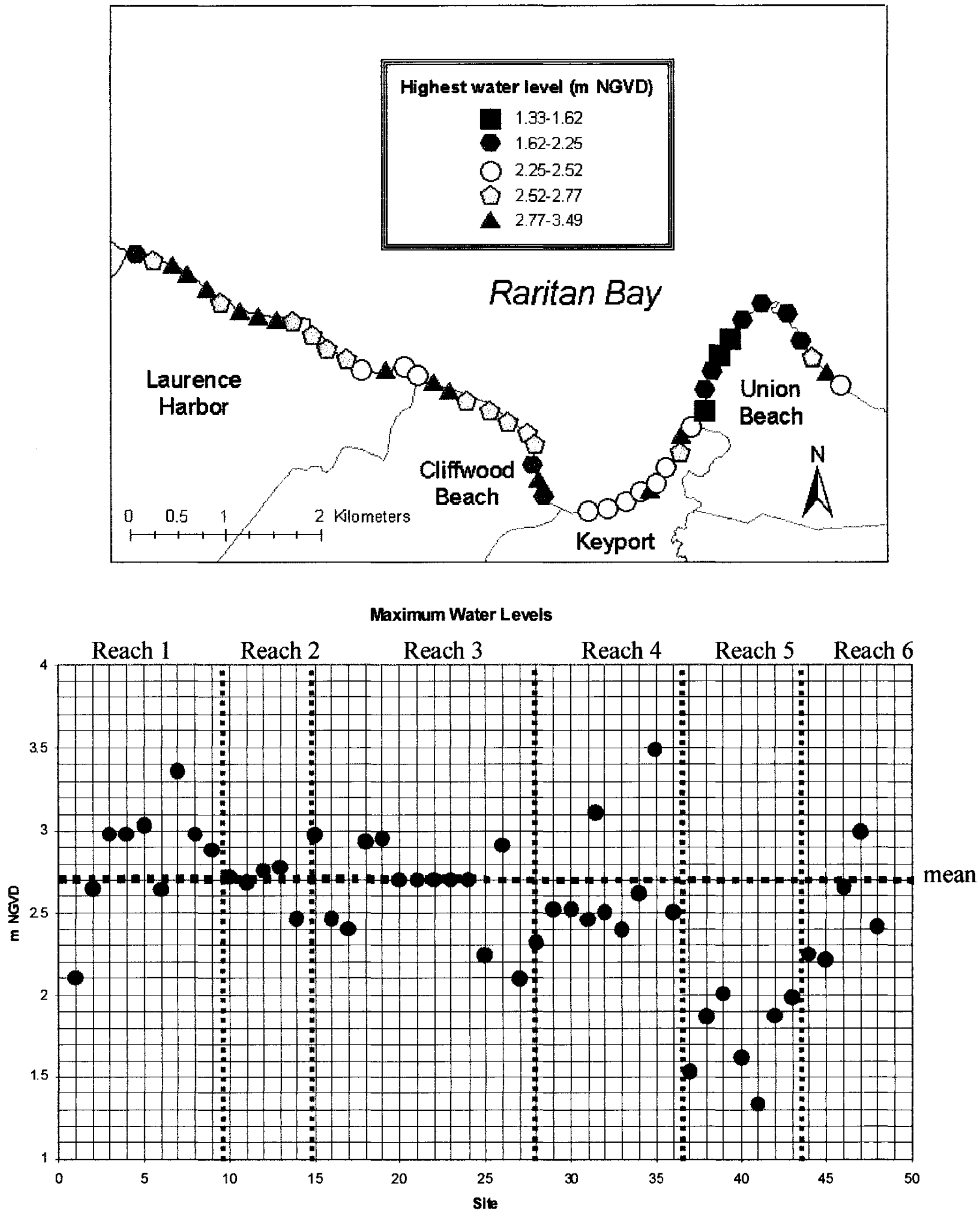


Figure 5.15 - Distribution of highest water level at each study sites (top) and reaches (bottom) relative to the mean = 2.70 m NGVD 1929.

Water level observations are the lowest at sites within or near marsh environments. Reach 5 consists entirely of marsh and water levels are generally lower than 2 m. Individual marsh sites within the other reaches also have low water level observations, rarely exceeding 2 m. Low water level observations exist, despite marsh sites in Reaches 1, 2, 3, 4 and 6 that have offshore characteristics that are similar to beach or human-altered sites within the same reach.

Summary of Between-Storm Variability

Between-storm variability ranged from 0 at 13 sites to a maximum of 1.45 m at a site (Site 19) with values typically from 0.3 to 0.9 m. The inability to distinguish wrack lines from different storms in marshes and at bulkheads and seawalls is not significant for evaluating between-storm variability across the entire study area because there are 22 sites with beaches and dunes spread across all reaches except Reach 5 where between-storm variability is evident. The 22 sites have similar offshore characteristics to nearby sites with marsh or vertical structures. Between-storm variability is conspicuously low at the beach sites in Reach 6, less than 0.4 m, perhaps because wave run-up is dissipated on the foreshore by the nourished beach, not propagating inland. This is similar to the between-storm variability at Site 3 in Reach 1. Water levels at most beach sites in Reach 1 vary by as much as 0.97 m for different storms but only by 0.58 m at the beach located at Site 3, where the beach is also nourished. The beach fill at Site 3 is scarped by water levels produced from typical coastal storms.

The spatial variability of water levels across sites, reaches, and the study area has been identified in this chapter. Onshore and offshore variables at each site are correlated to elevated water levels in Chapter 6. Storm inundation indices are determined from the correlated variables and used to compare susceptibility to actual and potential inundation in Chapter 7. Between-storm variability is further evaluated from an analysis of 10 sites where wrack lines from each storm are evident and related to storm wind conditions in Chapter 8.

VI- Correlation of Onshore and Offshore Shoreline Characteristics to Water Levels

Introduction

Regression analysis is used to correlate the variables that represent onshore and offshore shoreline characteristics and water level observations at field sites for the five coastal storms. Values of each correlated variable are grouped into five classes representing susceptibility to storm inundation. The susceptibility classification of a variable is determined from statistical methods in Arcview GIS, with high to low values assigned on the basis of measures of central tendency of the water level observations. Each class is given a numeric ranking to create two comprehensive storm inundation indices for each field site, discussed in detail in Chapter 7. The classes are high (5), moderate to high (4), moderate (3), low to moderate (2), and low (1). Three statistical methods in Arcview GIS are used for classifying the correlated variables; natural breaks, quantiles, and equal intervals, to determine if the way values are grouped influences the susceptibility classification and the storm inundation indices. Evaluation of the different classification methods is based on a comparison of sites that changed classes based on maps generated in the GIS. Ten sites, sites where between-storm variability in water levels is observed, are selected for further analysis to compare onshore and offshore variables to storm conditions in Chapter 8.

Statistical Analysis

Seven offshore variables are correlated to water levels for at least one storm, or the range of water levels between all five storms, at the 95% confidence level using an F-test distribution; Azimuth of Maximum Fetch, Maximum Fetch Distance within a 90^0 Window from Profile Orientation, Mean Fetch, Mean Distance to the 6' Depth Contour, Mean Distance from the 6' to 12' Depth Contour, North Fetch Distance and Northeast Fetch Distance. Eight onshore variables are correlated to water levels for at least one storm or the range of water levels between storms at the 95% confidence level; Profile Orientation, Maximum Elevation on the Profile, Shorezone Width, Dune Elevation, Dune Width, Berm Elevation, Foreshore Slope and Sand Width (Table 6.1). Fifteen variables are classified and mapped using Arcview GIS. The final classification used for creating the storm inundation indices is based on Jenk's Optimization, a statistical technique embedded in Arcview GIS that uses natural breaks in the data to minimize variability within classes. The determination of high versus low susceptibility is based on the average value for a variable taken from 14 sites where water levels exceeded 2.7 m, the statistical mean and median (Table 6.2). Theoretical analysis of each variable and its basis for flooding from current estuarine studies and historical observations from USACE reports are used to substantiate the relationship between variables, water levels, and susceptibility to storm inundation classification.

Table 6.1 - R^2 values for variables significant at the 95% confidence level to water level observations to at least one storm or the range between storms (* represents values that are significant). The sample size for the storm labeled 3/97 is N= 37 and the sample size for the other storms is N= 49.

	DATE OF STORM					
Variable	3/97	11/97	12/97	1/98	2/98	Range
Profile Orientation	0.15*	0.04	0.18*	0.07	0.17*	0.01
Maximum Fetch within 90^0 window	0.21*	0.07	0.15*	0.08*	0.17*	0.02
Azimuth of Maximum Fetch	0.01	0.07	0.24*	0.13*	0.18*	0.00
Mean Fetch	0.21*	0.01	0.11*	0.04	0.06	0.04
Mean Distance to 6' depth contour	0.07	0.07	0.09*	0.11*	0.01	0.00
Mean distance from 6-12' depth contour	0.02	0.01	0.09*	0.00	0.03	0.04
North Fetch Distance	0.00	0.09*	0.03	0.01	0.01	0.05
Northeast Fetch Distance	0.04	0.03	0.14*	0.03	0.07	0.01
Maximum Elevation of the profile	0.17*	0.20*	0.24*	0.31*	0.50*	0.22*
Shore Zone width	0.02	0.12*	0.00	0.01	0.01	0.21*
Dune Elevation	0.01	0.03	0.02	0.01	0.03	0.25*
Dune Width	0.00	0.02	0.01	0.00	0.02	0.19*
Berm Elevation	0.01	0.03	0.07	0.00	0.11*	0.02
Foreshore slope	0.02	0.09*	0.04	0.04	0.03	0.07
Sand width	0.00	0.18*	0.01	0.03	0.05	0.13*

Table 6.2 – Values of correlated variables at sites with average water levels exceeding 2.7m NGVD, the statistical mean and median, used to evaluate susceptibility classification from high to low. (Actual fetch measurements taken to 2 decimal places and actual elevation measurements to 3 decimal places).

Site	Profile Orientation	Maximum Fetch	Azimuth of Max. Fetch	Mean Fetch	Mean 6' depth	Mean 6-12'depth	Maximum Fetch (N)	Maximum Fetch(NE)
3	16	24.68	61	10.73	1.48	3.13	3.79	8.88
4	43	24.43	60	11.08	0.89	4.78	3.86	9.64
5	40	24.28	60	10.71	0.88	4.53	4.01	10.57
7	15	24.12	59	11.03	0.98	2.42	4.26	11.99
9	2	11.93	45	6.63	1.01	2.33	4.48	11.93
10	27	23.79	58	11.47	0.81	2.51	4.69	11.77
12	43	23.53	57	6.99	1.39	4.95	5.1	19.2
13	44	23.53	56	9.31	1.23	2.19	5.3	18.72
15	3	19.96	48	10.35	0.98	2.91	5.44	18.8
18	25	22.84	55	11.19	0.93	3.33	5.65	19.25
19	21	22.84	54	11.34	0.95	3.33	5.76	19.37
31.5	330	9.63	15	6.12	1.36	3.14	8.1	0.3
35	301	8.43	316	5.58	1.03	2.53	7.63	0.37
47	43	19.6	48	9.59	1.61	1.66	7.85	19.13
Mean	68	20.26	71	9.44	1.11	3.12	5.42	12.85
Median	34	23.19	57	10.53	0.995	3.02	5.2	11.96
Units	(^{0})	km	(^{0})	km	km	km	km	km

Site	Max. Profile Elevation	Shore Zone Width	Dune Elevation	Dune Width	Foreshore Slope	Berm Elevation	Sand Width
3	4.051	55	4.051	10	0.0663	0	45
4	4.627	105	4.627	15	0.0852	3.717	90
5	3.142	68	0	0	2.424	2.424	68
7	4.385	25	0	0	0.1325	0	10
9	4.156	17.5	0	0	0.1304	0	0
10	4.224	18	0	0	0.0677	0	0
12	2.44	30	2.444	10	0.0514	0	30
13	2.661	35	2.661	10	0.0755	0	30
15	3.459	50	0	0	0.0689	0	0
18	4.841	75	4.841	10	0.0381	0	65
19	4.052	65	4.052	15	0.0539	0	40
31.5	3.958	30	3.958	10	0.1061	0	30
35	3.376	35.5	0	0	0.0794	3.376	15
47	3.464	53	3.33	20	1.588	0.845	53
Mean	3.77	47.3	2.14	7.14	0.35	0.69	34.0
Median	4.005	42.8	2.553	10	0.0775	0	30
Units	m	m	m	m	No	m	m

Discussion of Correlation Coefficients

While all variables used in this dissertation are theoretically related to coastal storm flooding, it has not been determined if the variables explain variability on local scales. High correlation coefficients may not occur because storm surge in estuaries is complicated by the variability of the shoreline, bay configuration and storm wind conditions. The correlation coefficients (R^2 values) for variables that did test as significant range from 0.09 (9% explained) to 0.50 (50% explained) but rarely did values exceed 0.20 (20%). Bivariate correlations between process-response variables on beaches can be low (Nordstrom 1977). The relatively low correlation coefficients suggest that these variables should be further explored and coupled with a long-term field evaluation of water levels to include more storm events. For example, while maximum fetch distance within a 90^0 window of the profile orientation and the azimuth of that fetch distance did test as significant, the maximum fetch distance normal to the shoreline orientation did not. This implies that waves and associated water levels approaching perpendicular to the shoreline are not as important as waves and water levels generated along longer fetch distances that are not perpendicular to the shoreline. This hypothesis is not consistent with research suggesting that fetch distance perpendicular to the shoreline orientation is critical in waves and water level development along estuarine shorelines (Jackson 1995). Fetch distance perpendicular to the shoreline orientation may not be as important as a maximum fetch within 45^0 of perpendicular and also in the same direction as sustained storm winds.

Variables that Represent Shoreline Characteristics

Profile Orientation and Azimuth of Maximum Fetch

Profile orientation (of the cross-shore transect) and the azimuth of maximum fetch of the study sites correlated at the 95% confidence level to water levels from three storm events. Degrees are used with 0^0 representing geographic north. The mean value for profile orientation at sites with higher than average water levels (Table 6.2) is 68^0 but is skewed by the high orientation values for sites 31.5 and 35 in Reach 5, 330^0 and 315^0 respectively. The median value from Table 6.2 is northeast (34^0) and is not influenced by outlier data like the mean and therefore used to validate the high storm inundation classes in Figure 6.1. The mean value for azimuth of maximum fetch was 71^0 with a median of 57^0 (Table 6.2), corresponding to the highest susceptibility class using the equal interval method but also for moderate to high susceptibility in other classification methods in Figure 6.2.

Theoretically, profile orientations and maximum fetch directions that are incident to storm wind directions, ranging from 0^0-45^0 to 45^0 –90^0 are more susceptible to inundation because unsheltered exposures to water from the ocean increases storm surge elevations during northeasterly storm events. Reaches 1,2, 3 and 6, which include sites from Laurence Harbor, Cliffwood Beach and Union Beach, have profile orientations and maximum fetch directions favorable to producing high water levels (Figures 6.1 and 6.2). Reach 5 is sheltered from easterly winds but has long fetches to the north. Reach 5 includes Keyport where historical accounts indicate the highest flooding occurs. The use

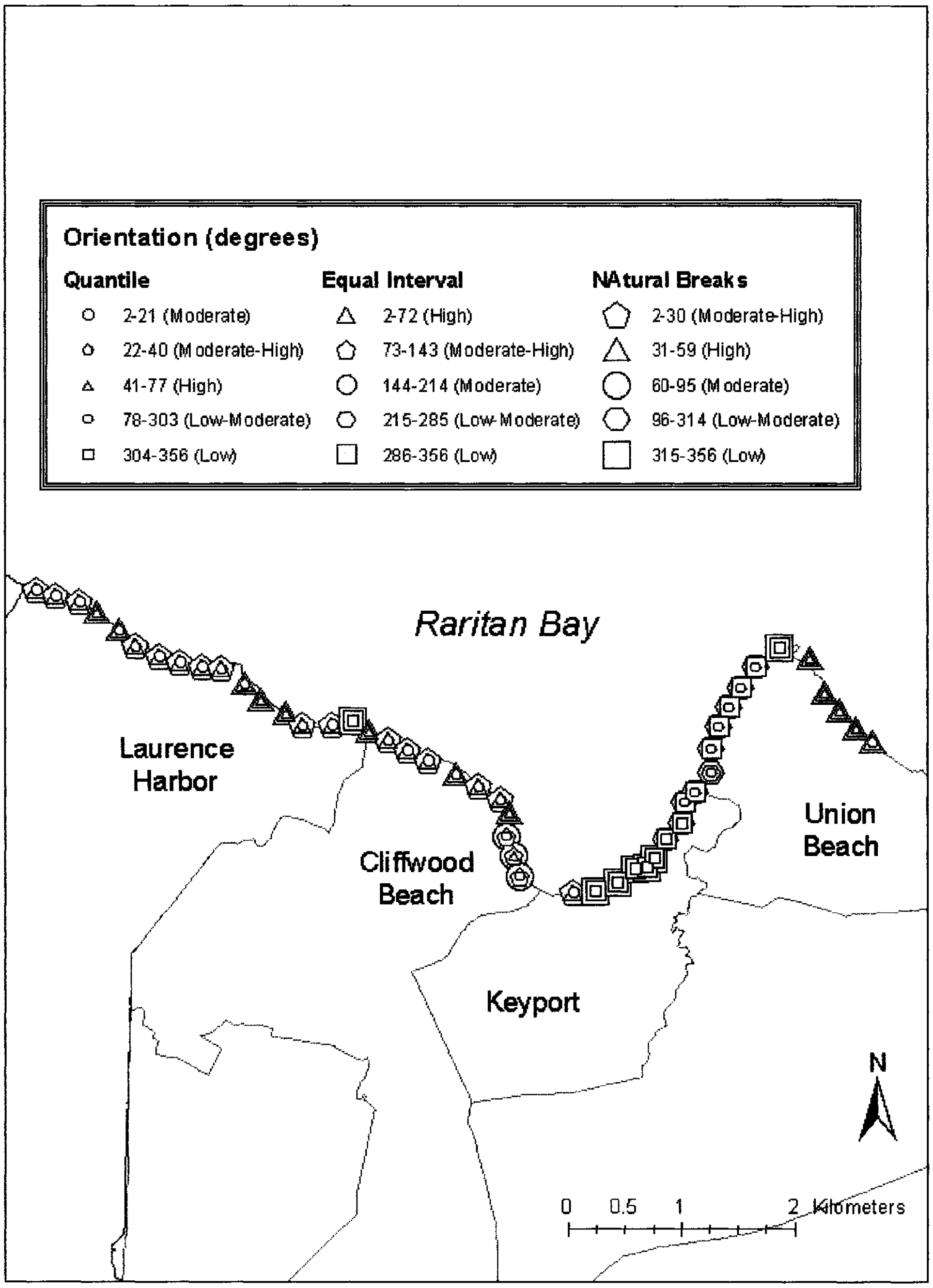


Figure 6.1 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Orientation (In Figures 6.1 through 6.15, different size symbols are used to overlay the 3 classifications at each site).

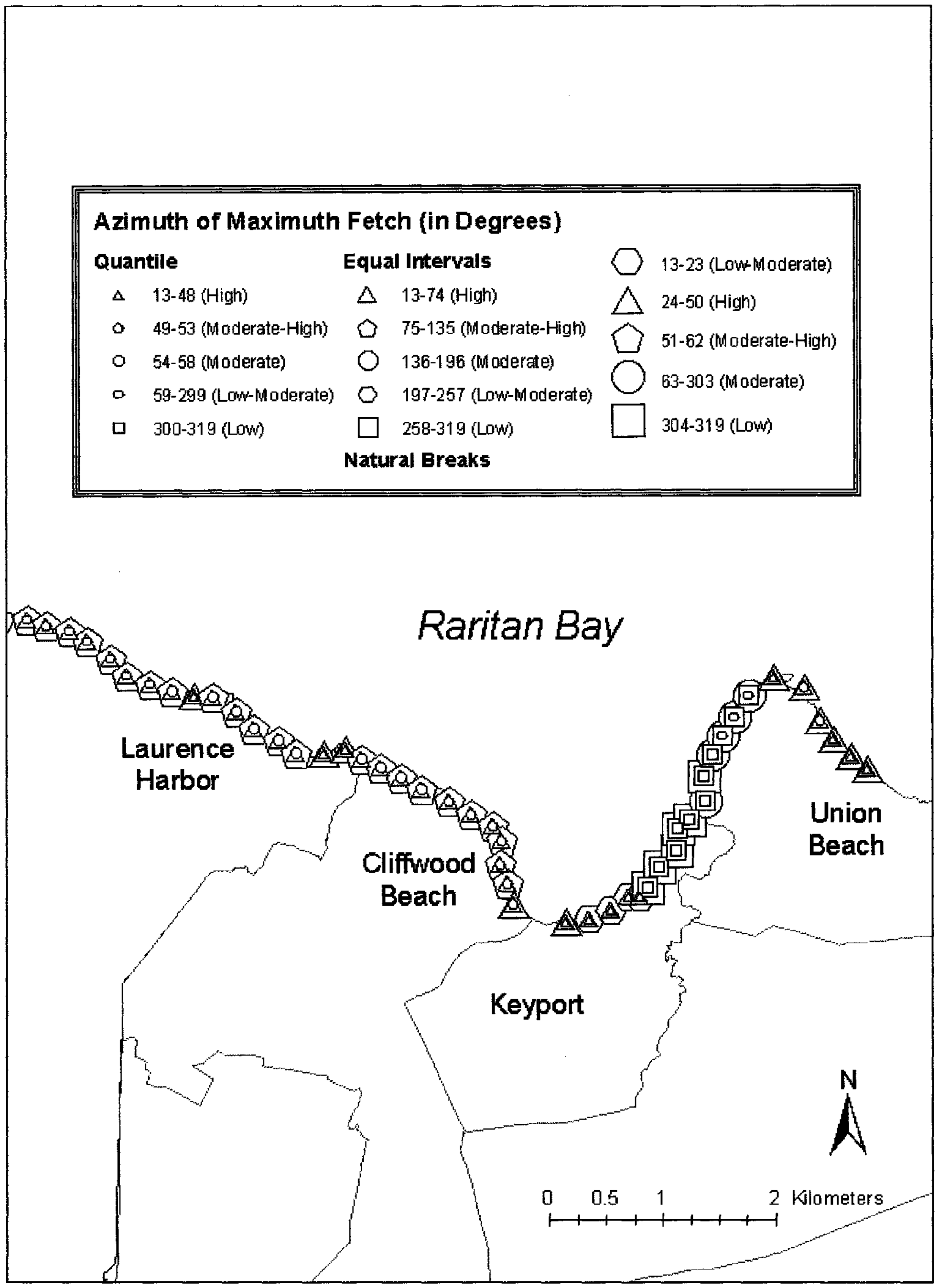


Figure 6.2 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Azimuth of Maximum Fetch.

of different statistical methods in Arcview GIS did not affect the inundation classifications of individual sites. Few sites were classified differently. Fourteen sites remained in the same class and only ten sites changed more than two classes for the Azimuth of Maximum Fetch variable.

Maximum Fetch Distance within a 90^0 Window from Profile Orientation and Mean Fetch

Maximum fetch distance within a 90^0 window from profile orientation correlated to water levels from four storm events, the highest for any offshore variable. The correlation coefficient was not significant for the storm in March 1997, conceivably because of the absence of data from Reach 6 where some of the highest water values and longest maximum fetch distances exist. The mean maximum fetch within a 90^0 window for the 14 sites with the highest water levels (Table 6.2) was 20 km with a median value of 23 km and the highest susceptibility classes exceed these values (Figure 6.3). Long fetch distances perpendicular to the shoreline orientation are critical for building waves (Jackson 1995).

Mean fetch is derived from the average of three fetch distances, one perpendicular to the shoreline orientation and two taken 45^0 from perpendicular. Mean fetch values correlated to high water levels from two storm events and values range from 5.6 km to 11.5 km for the 14 sites in Table 6.2. The mean of mean fetch is 9.4 km and the median, 10.5 km. Sites with values equal to or exceeding the mean and median are placed in high susceptibility classes (Figure 6.4). Mean fetch values are more equally distributed throughout Reaches 1, 2, 3 and 6 than the maximum fetch values and many sites are

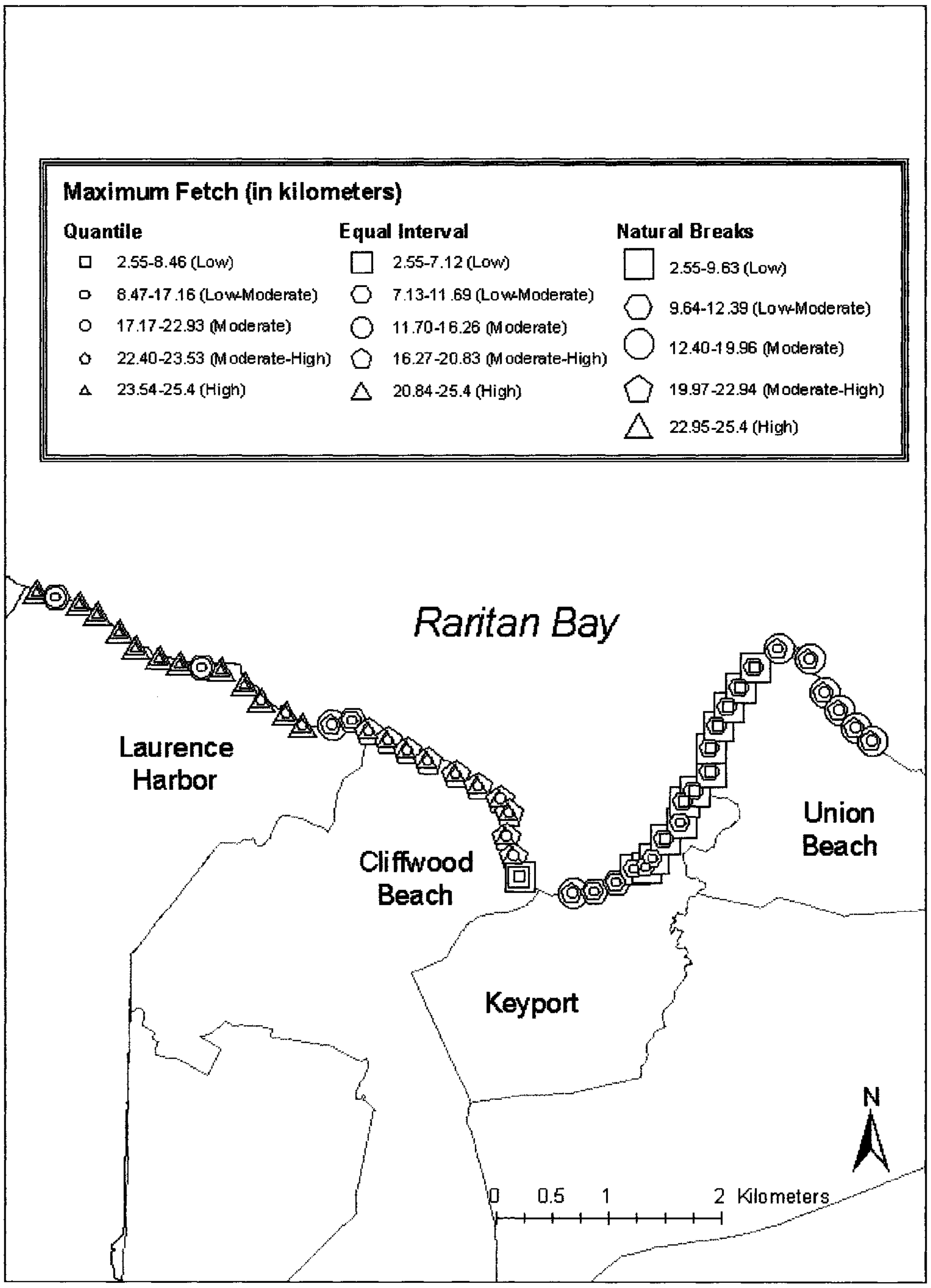


Figure 6.3 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Maximum Fetch.

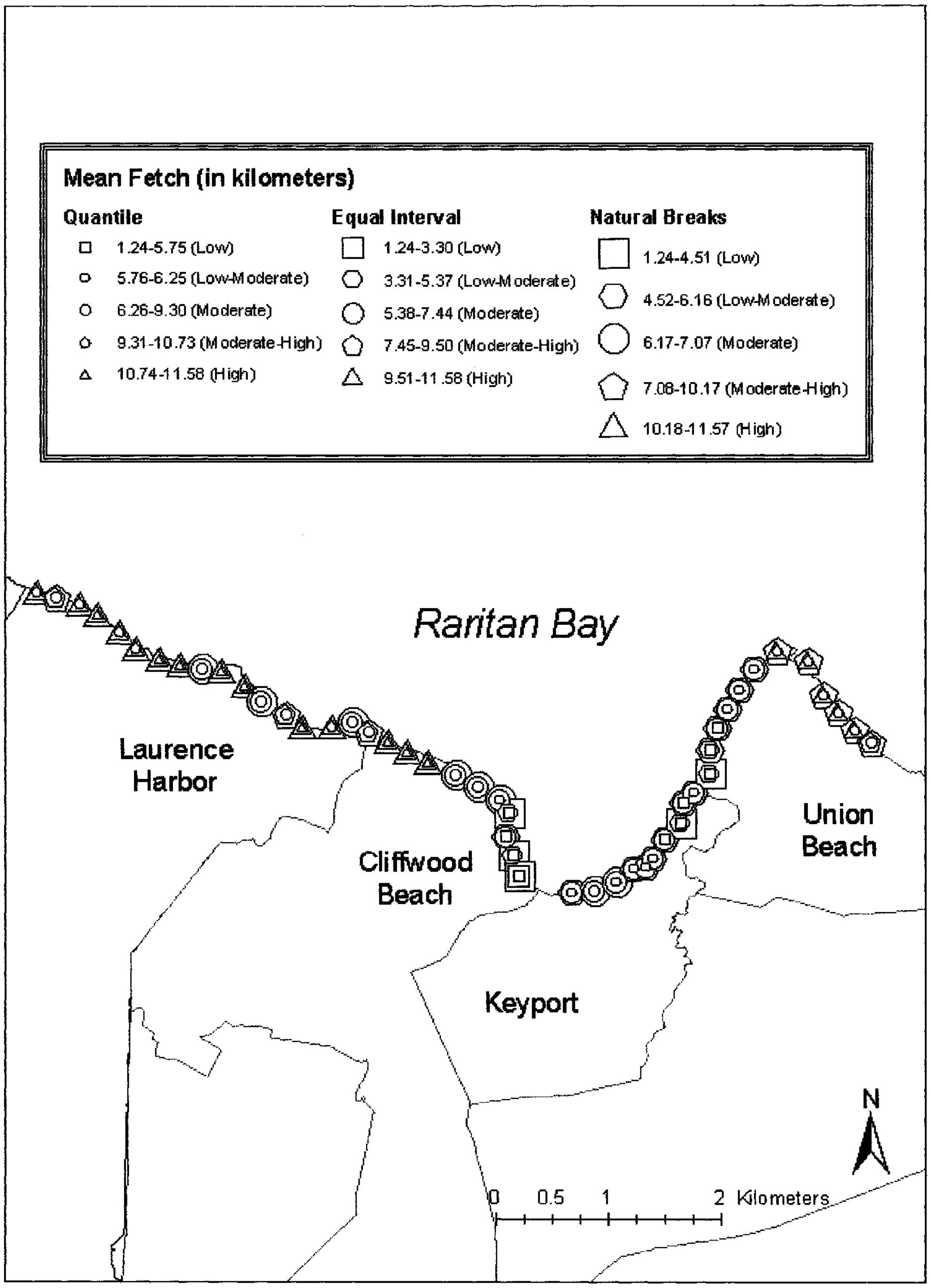


Figure 6.4 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Mean Fetch.

classified as highly susceptibility to inundation (Figure 6.3 and 6.4). Reaches 4 and 5 have moderate and low maximum and mean fetch distances and fall within moderate to low inundation categories. Little difference is observed between statistical methods as 11 sites (Maximum Fetch) and 17 sites (Mean Fetch)

were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Mean Distances to the 6' Depth Contour and from the 6' to 12' Depth Contour

Mean distance to the 6' depth contour correlated to two storm events and mean distance from the 6' to 12' depth contour to water levels to only one storm event. Mean values are determined from three measurements, one taken perpendicular to the shoreline orientation and the other two taken 45^0 from perpendicular, similar to the mean fetch calculation. The mean and median values for the mean distance to the 6' depth contour for the 14 sites with the highest water levels in Table 6.2 are 1.11 km and 0.995 km, respectively. Sites in the highest storm inundation classes for mean distance to 6' depth contour have values exceeding 1 km (Figure 6.5).

The mean and median for the mean distance from the 6' to 12'depth contour for the 14 sites with the highest water levels in Table 6.2 are 3.12 km and 3.02 km, respectively. Sites in the highest storm inundation classes for mean distance from the 6' to 12' depth contour have values exceeding the mean and median (Figure 6.6). Little difference is observed between statistical methods as 27 sites (Mean Distance to 6'

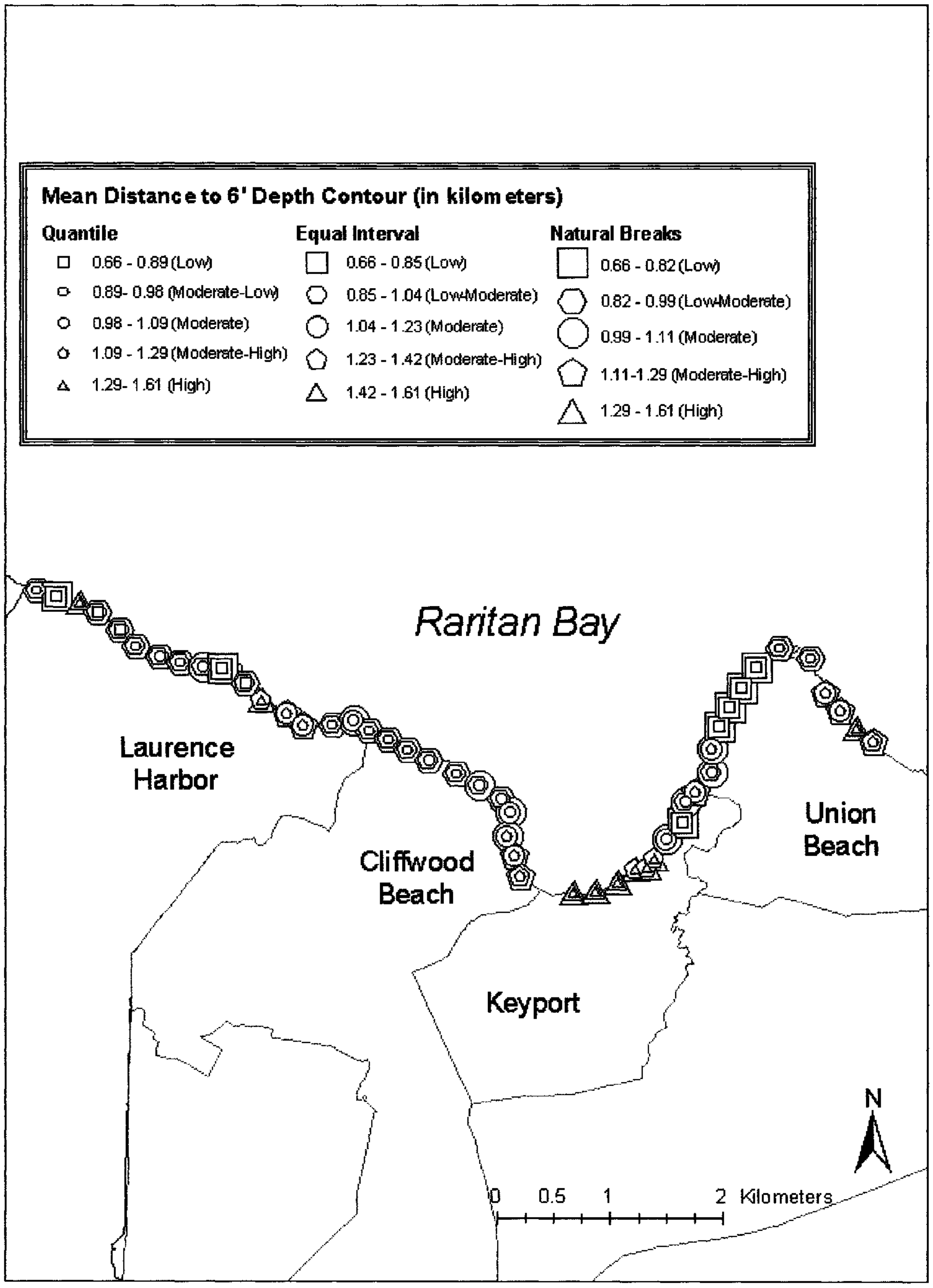


Figure 6.5 –Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Mean Distance to 6' Depth Contour.

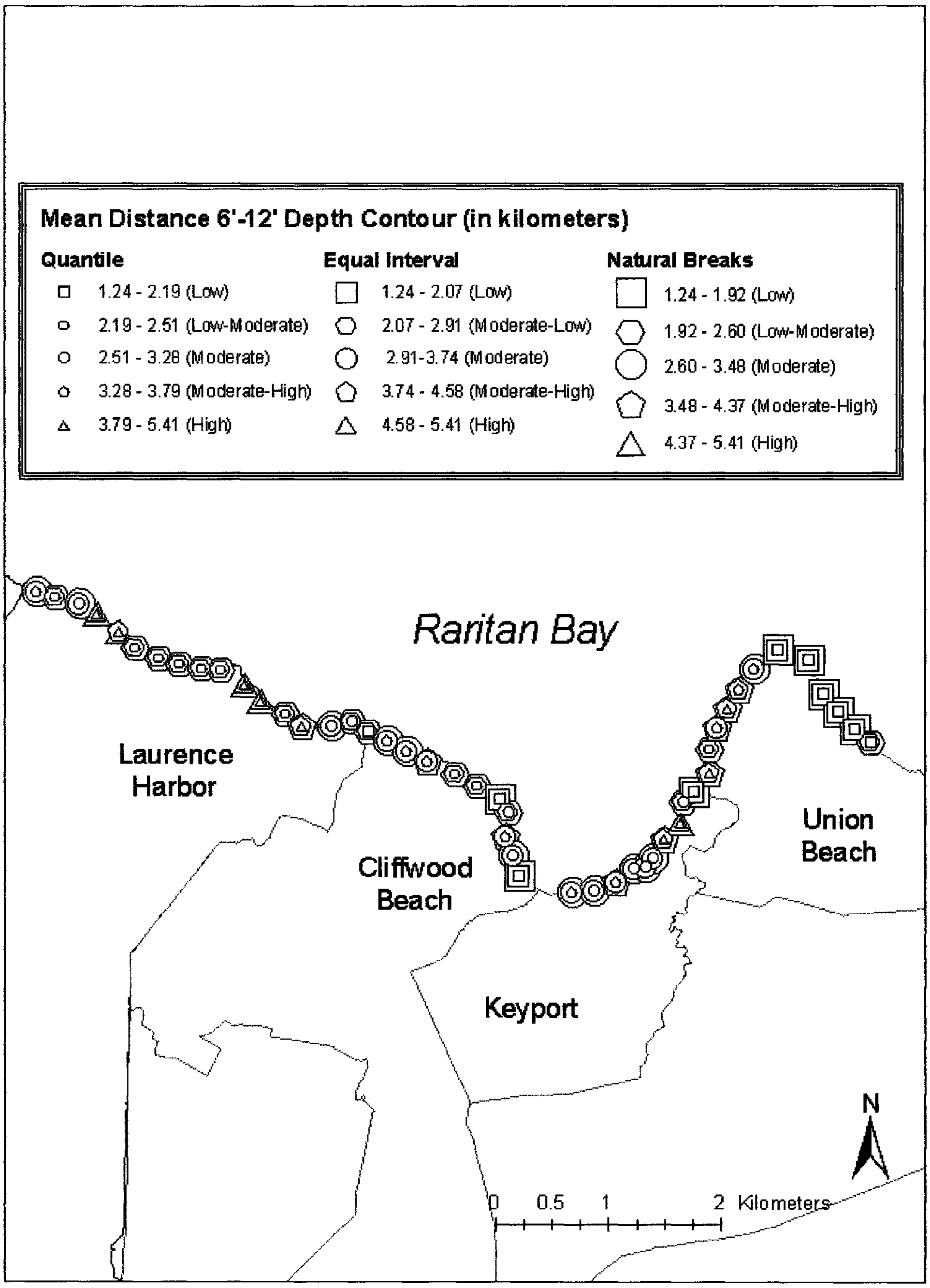


Figure 6.6 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Mean Distance from the 6'to 12' Depth Contour.

Depth) and 29 sites (Mean Distance 6’-12’ Depth) were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Mean distance from the 6’ to12’ contour depth values are higher than the distances from the shoreline to the 6’contour depth, 1.41 to 19.32 km compared to 0.66 km to 1.61 km. The relationship between offshore topography and water levels suggests that long shallow offshore features would tend to dissipate wave energies from storms (Phillips 1986). Therefore, short distances to the depth contour would not attenuate water levels and result in higher susceptibility to inundation, yet Reach 5, a marsh, has low water level observations and short distances to the 6’depth contour. Keyport, also in Reach 5, has long distances to the 6’ depth contour and has historically experienced some of the highest flooding (Figures 6.5 and 6.6). Therefore, the results here are at the least inconsistent with current coastal geomorphic research and perhaps even contradictory in that high water levels are observed in places with broad offshore topographies. One explanation may be that only a few storm events provided water levels with good correlation to the offshore topographic variables. Water levels from only two storms were significantly correlated to the mean distance to the 6’ depth contour and water levels from only one storm with the mean distance from the 6’ to 12’ depth contour. The storms in December 1997 and January 1998 (see Chapter 8) had sustained winds over 10 m/s from the north. A second explanation may be that the broad and smooth offshore topography provides a ramp for shoaling of storm surge that will propagate water levels to high elevations on the shoreline. Therefore, based on the water level observations throughout the study area, sites with long offshore distances to depth contours are considered more susceptible to storm inundation.

Fetch in Storm Wind Directions; North Fetch Distance and Northeast Fetch Distance

Fetch distance in storm wind direction is determined from north (0^0) and northeast (45^0) of each study site. While these variables appear to be critical in the study of coastal storms, they are only correlated to water levels from one storm event. North fetch distance was the only variable correlated to the November 1997 storm, a storm with 14 hours of sustained winds over 10 m/s from 0-10^0 (N-NNE), indicating the control of long northerly fetch distances on water levels from Reaches 3 and 4. The impact of long northerly fetches on water levels is supported by observations of severe flooding in Keyport, in Reach 4, from a northeaster in December 1992 that had more northerly than northeasterly or easterly winds (USACE, New York District 1993). The mean and median values for the north fetch distance for the 14 sites with the highest water levels in Table 6.2 are 5.4 km and 5.2 km, respectively. Sites in the highest storm inundation classes for north fetch distance have values exceeding the mean and median (Figure 6.7).

The mean and median values for the northeast fetch distance for the 14 sites with the highest water levels in Table 6.2 are 13 km and 12 km, respectively. Sites in the highest storm inundation classes for northeast fetch distance have values exceeding the mean and median (Figure 6.8). Little difference is observed between statistical methods as 16 sites (northeast fetch distance) and 13 sites (north fetch distance) were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Reaches 3, 4 and 6, Cliffwood Beach, Keyport and Union Beach, have long north fetch distances (Figure 6.7). Reaches 1, 2, 3 and 6, Laurence Harbor, Cliffwood Beach

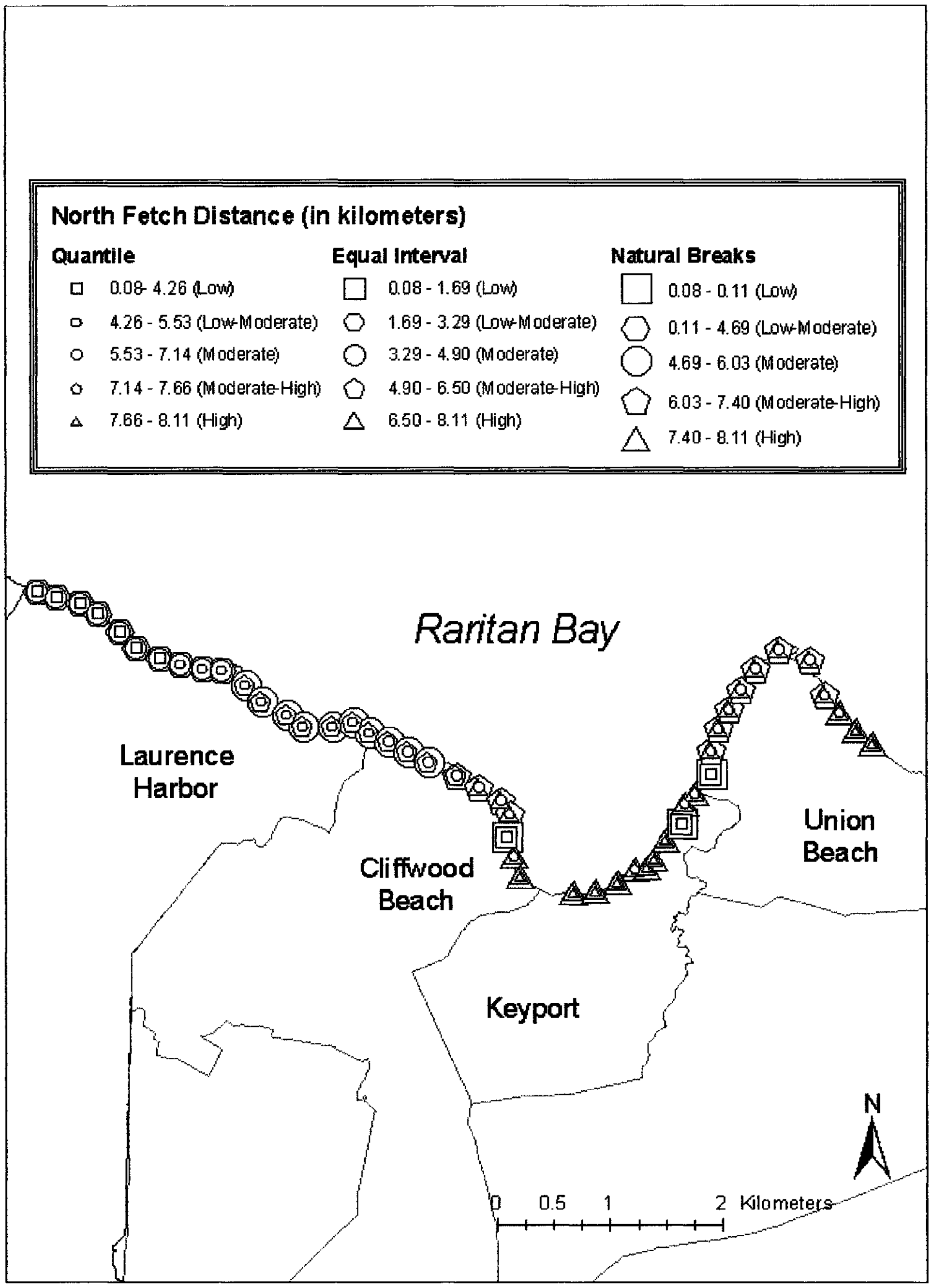


Figure 6.7 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for North Fetch Distance.

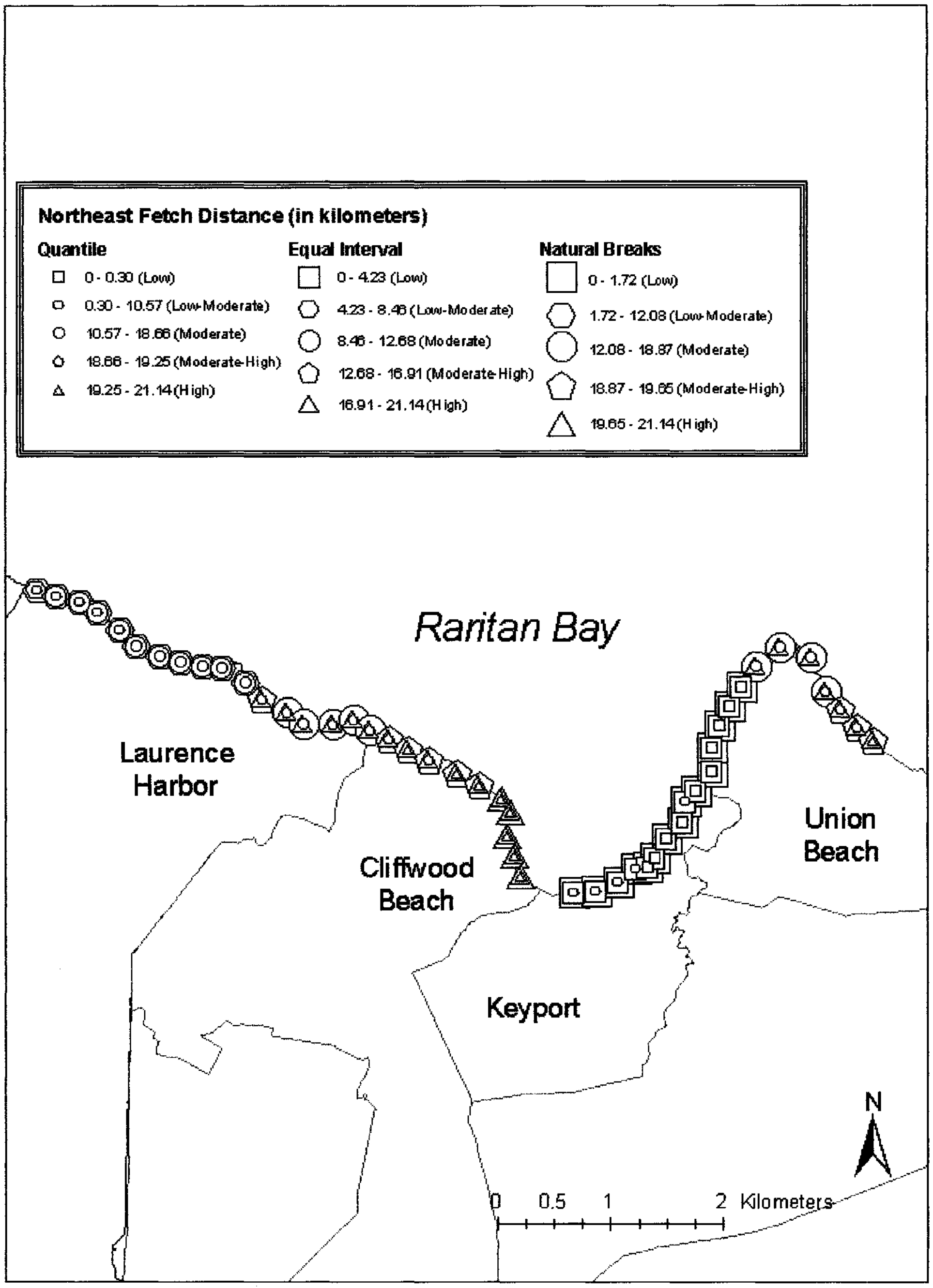


Figure 6.8 –Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Northeast Fetch Distance.

and Union Beach, have long northeast fetch distances (Figure 6.8). Theoretically, sites in Reaches 3 and 6, would be susceptible to inundation from any coastal storms (either north or northeast winds) while susceptibility of sites in other reaches would depend more on specific storm conditions. Sites in Reach 1 would be susceptible to inundation from coastal storms with northeasterly winds, while sites in Reach 4 would be more susceptible to inundation from coastal storms with northerly winds. The role of storm conditions (wind speed, direction and duration) in producing elevated water levels and susceptibility to inundation is further examined in Chapter 8.

Maximum Elevation of the Profile

Maximum elevation of the profile was the only onshore variable correlated to water levels for more than one storm event. Maximum elevation on the profile correlated to water levels from all storm events and to the range of water levels at each site between storm events. Reaches 1, 3, 4 and 6, Laurence Harbor, Cliffwood Beach, Keyport and Union Beach have the highest profile elevations and are also highly modified shorelines with extensive artificial beach fill and dunes, revetments, bulkheads and seawalls (Figure 6.9). Reaches 2 and 5 have the lowest elevations and are more natural estuarine shorelines, with some small beaches and large expanses of marsh (Figure 6.9). Most of the study area has been shaped by shoreline protection and stabilization structures, with massive engineered structures built by the USACE, and others that appear to be built by local residents. In both instances, study sites have been built to the highest elevations where storm water levels have historically been the highest. The water level observations

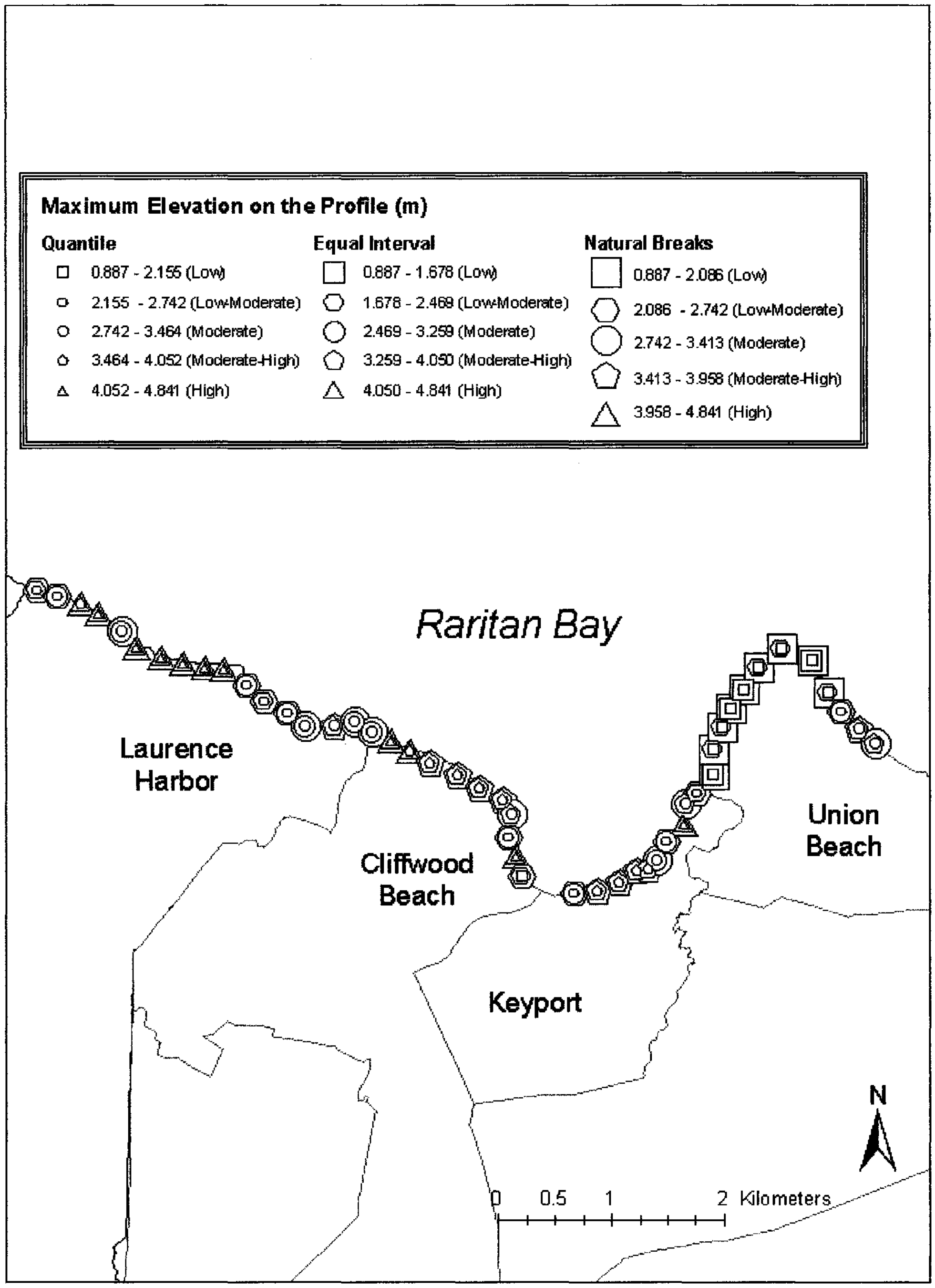


Figure 6.9 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Maximum Elevation on the Profile.

in this dissertation confirm this and therefore sites with high maximum elevation of the profile are considered highly susceptible to inundation. Some of these sites are located within major shoreline protection structures, such as the seawall at Cliffwood Beach, while other sites have shoreline protection structures that are less engineered, as in the south part of Laurence Harbor at Seidler Beach, and in Keyport. The mean and median values for maximum elevation for the 14 sites with the highest water levels in Table 6.2 are 3.8 km and 4.0 km, respectively. Sites in the highest storm inundation classes for maximum elevation of the profile have values exceeding the mean and median (Figure 6.9). Little difference is observed between statistical methods as 29 sites were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Shore Zone Width

Shore zone width correlated to water levels from only one storm event and to the range of water levels between storms. The highest values range from 50 to 105 meters for sandy platforms of artificial beach fill. Some sites with extensive shore zone widths, such as Sites 2-5 in Reach 1 and Sites 17, 18 and 19 in Reach 3 are correlated to high water levels, suggesting that nourished beaches and dunes are in place as a response to past experience with coastal flooding (Figure 6.10). However, high water levels are also more commonly found at sites with little if any shore zone width such as the seawall at Cliffwood Beach (Reach 3) and bulkheads and revetments at Sites 7-9 (Reach 1), Sites 29-30 and 32 (Reach 4) and Site 48 (Reach 6). Therefore, despite high water levels at some sites with wide shore zones, these sites are considered less susceptible to inundation

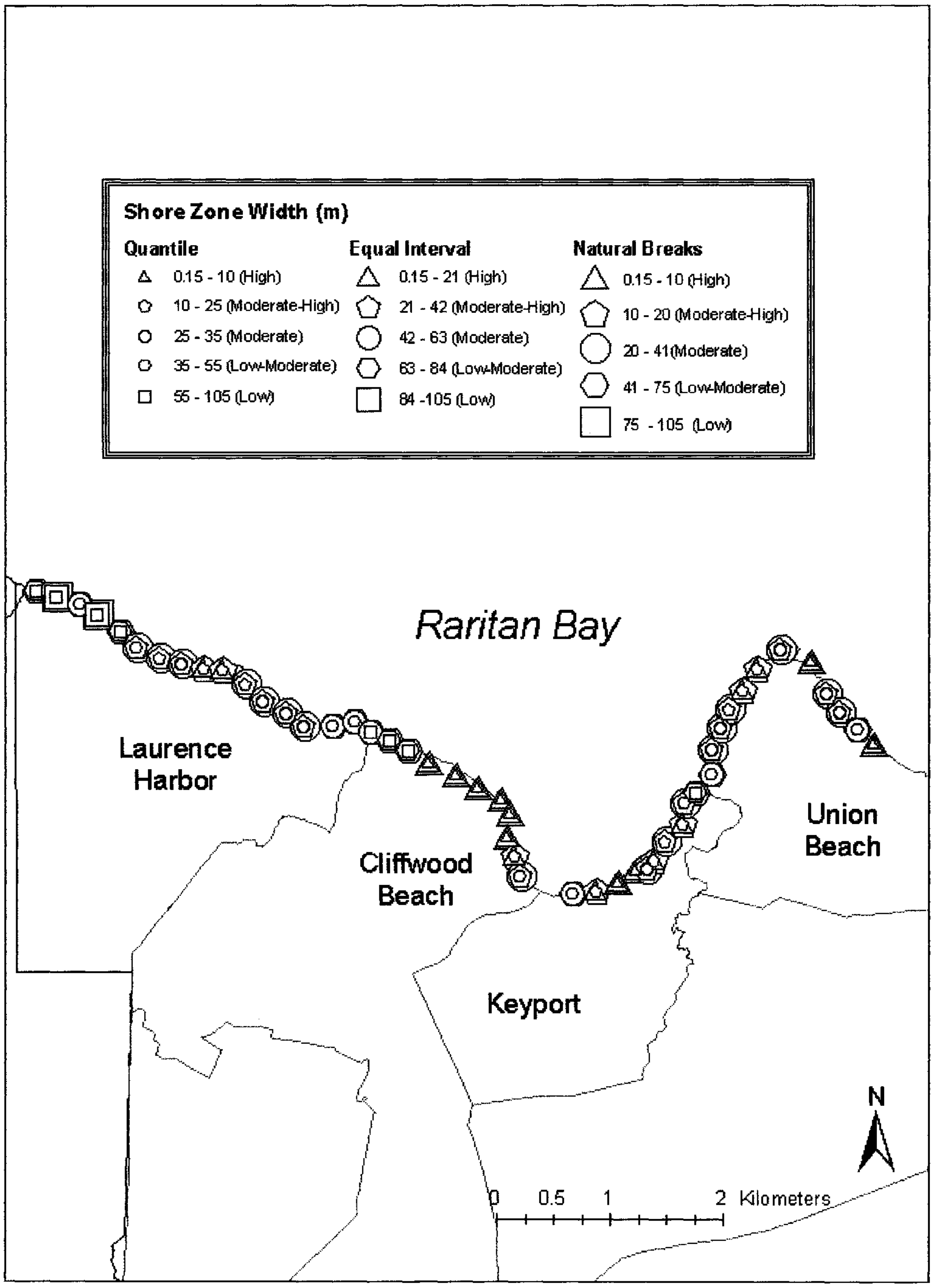


Figure 6.10 –Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Shore Zone Width.

than sites with narrow shore zones. The mean and median values for shore zone width for the 14 sites with the highest water levels in Table 6.2 are 47 m and 43 m, respectively. Sites in the highest storm inundation classes for shore zone width have values less than the mean and median (Figure 6.10). Little difference is observed between statistical methods as 12 sites were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Dune Crest Elevation and Dune Width

Dune crest elevation and dune width are only correlated to the range of water levels between storms. The only dunes that are not the direct result of artificial dune building are the natural dunes located between Sites 11, 12 and 14 and 31.5. The natural dunes are not high, less than 3 m, or wide, generally less than 10 m (Figure 6.11). The large dunes at Sites 3 and 4 in Reach 1, Laurence Harbor, at Sites 18 and 19 in Reach 3, Cliffwood Beach and at Site 47 in Reach 6, Union Beach exceed 3.33 m and exceed 10 m in length (Figure 6.12). Sites with high and wide dunes are considered less susceptible to inundation than sites lacking dunes and placed in the low storm inundation classes. This classification is not flawed by the fact that marsh environments would have no dunes (and therefore be placed in high susceptibility classes) because marshes are expected to flood periodically while the dunes are in place as a means of shoreline protection to prevent inundation and should be evaluated as such. Dune characteristics are different from the maximum elevation of the profile because the dune has both a height and width component. The mean and median values for dune elevation for the 14 sites with the

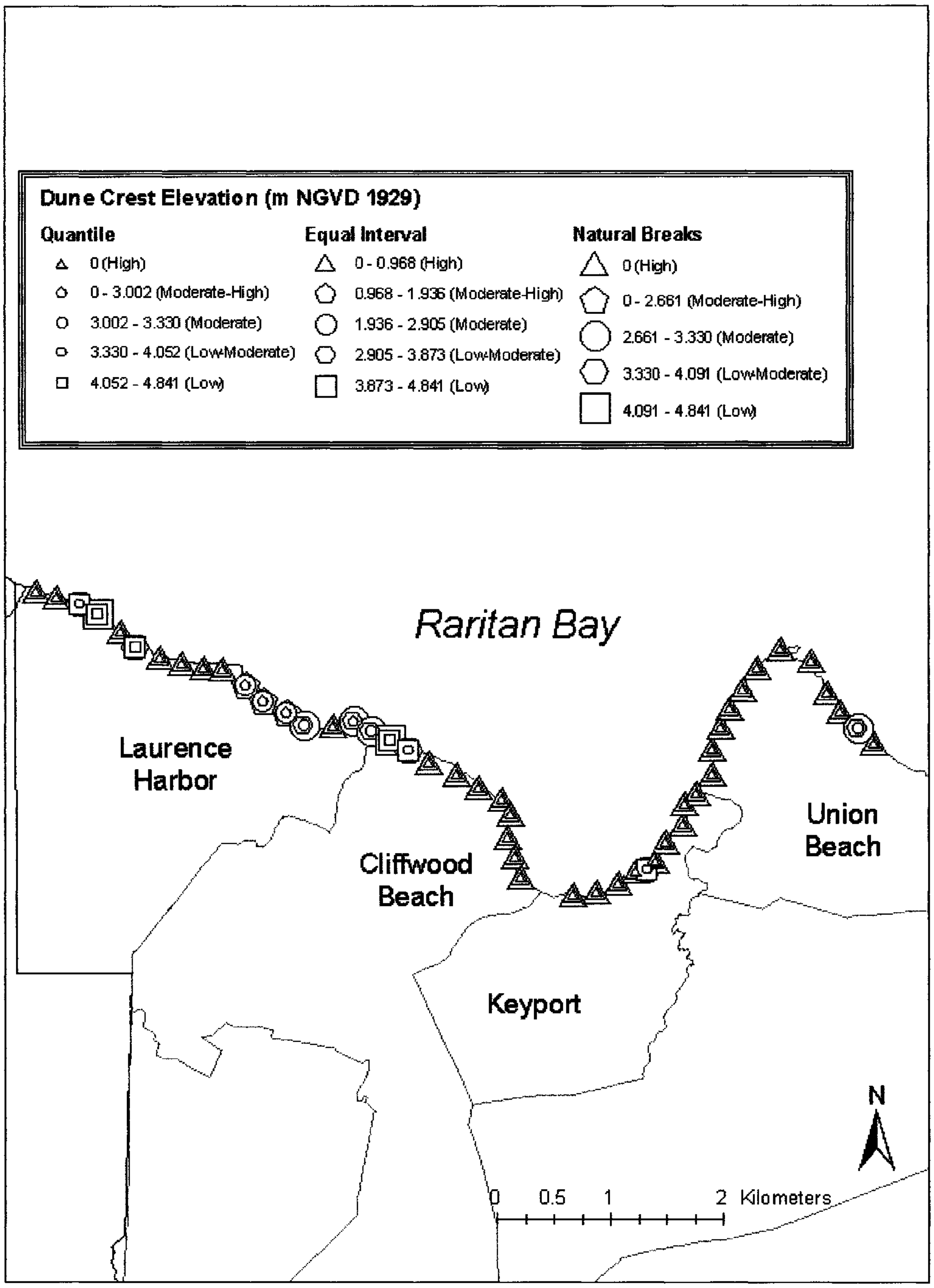


Figure 6.11 –Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Dune Crest Elevation.

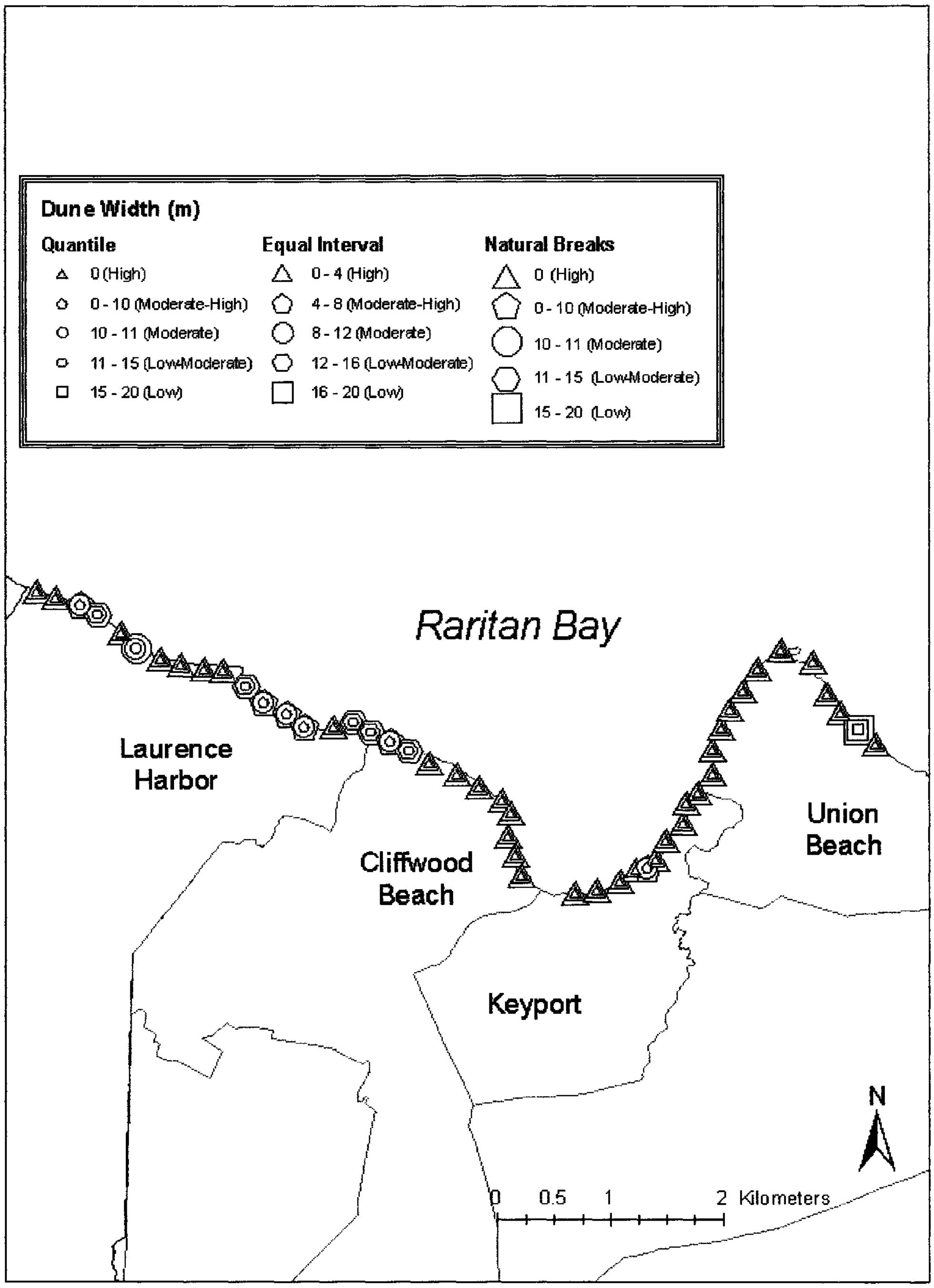


Figure 6.12 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Dune Width.

highest water levels in Table 6.2 are 2.1 m and 2.6 m, respectively. Sites in the highest storm inundation classes for the dune elevation have values less than the mean and median (Figure 6.11).

The mean and median values for dune width for the 14 sites with the highest water levels in Table 6.2 are 7 m and 10 m, respectively. Sites in the highest storm inundation classes for dune width have values less than the mean and median (Figure 6.12). Little difference is observed between statistical methods as 38 sites (Dune Crest Elevation) and 42 sites (Dune Width) were classified the same way for all methods in Arcview GIS and no sites changed more than 2 classes.

Berm Elevation, Foreshore Slope and Sand Width

Berm elevation and foreshore slope correlate to water levels from only one storm event. Developed foreshores with sandy berm deposits and mild gradients are not conspicuous along natural estuarine shorelines, which tend to be narrow and steep with coarse deposits. High berm deposits are found on the beach fill in Reach 1 at Laurence Harbor with moderate foreshore slopes (Figure 6.13, Figure 6.14). Sand width correlates to water levels from only one storm event and to the range of water levels between storm events. Like large dunes, wide sandy beaches are the result of shoreline protection projects in Raritan Bay and are not natural geomorphic features of estuarine shorelines. Reaches 1, 3 and 6 have extensive sandy beaches ranging from 45 to 90 m and all are the result of artificial beach nourishment (Figure 6.15). Sites with berm deposits, mild foreshore gradients and long sand widths are considered less susceptible to inundation

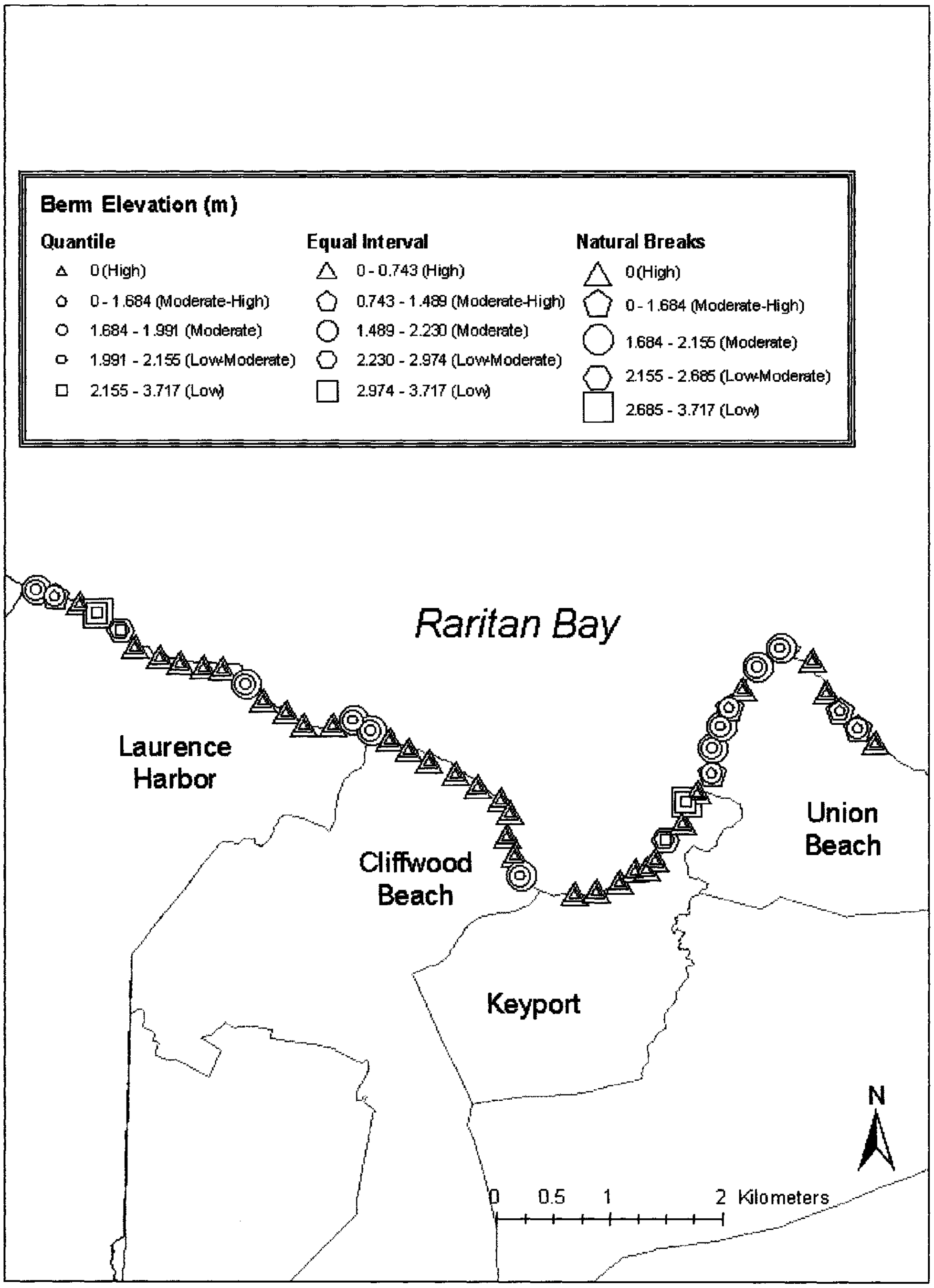


Figure 6.13 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Berm Elevation.

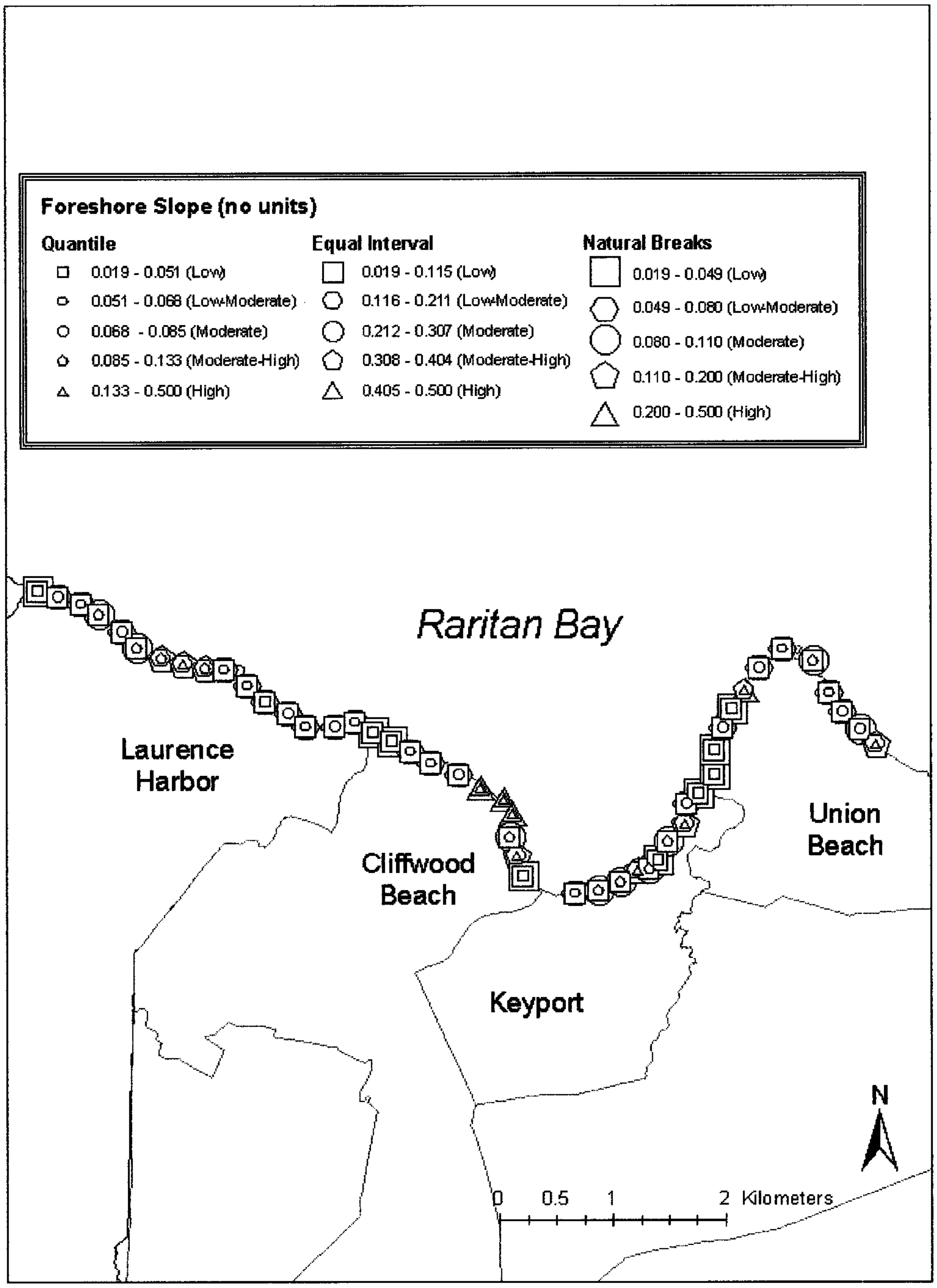


Figure 6.14 – Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Foreshore Slope.

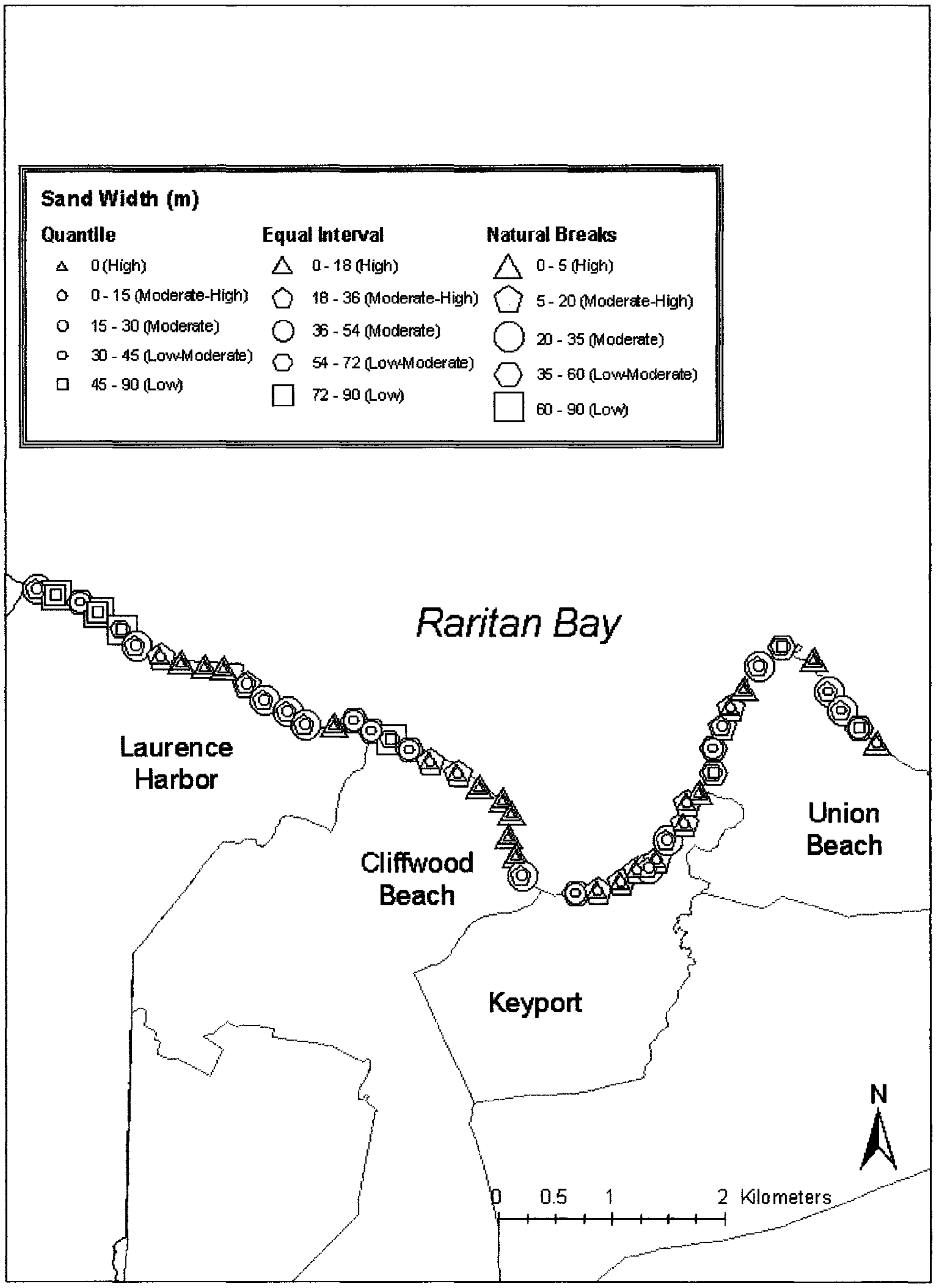


Figure 6.15 –Susceptibility to storm inundation classes at each site using different classification methods in Arcview for Sand Width.

than sites without these features and placed in low storm inundation classes. The mean and median values for berm elevation for the 14 sites with the highest water levels in Table 6.2 are 0.7 m and 0 m, respectively. Sites in the highest storm inundation classes for berm elevation have values less than the mean or no berm deposit (Figure 6.13). The mean and median values for foreshore slope for the 14 sites with the highest water levels in Table 6.2 are 0.35 m and 0.08 m, respectively. Sites in the highest storm inundation classes for foreshore slope have values exceeding the mean and median (Figure 6.14). The mean and median values for sand width for the 14 sites with the highest water levels in Table 6.2 are 34 m and 30 m, respectively. Sites in the highest storm inundation classes for sand width have values less than the mean and median (Figure 6.15). Little difference is observed between statistical methods as 38 sites (Berm Elevation), 26 sites (Foreshore Slope) and 13 sites (Sand Width) were classified the same way for all methods in Arcview GIS and no class changed more than 2 classes for these variables.

Summary and Discussion of Variables

Correlation of the onshore and offshore variables to water level observations in the field is expected because these variables have been theorized as critical for causing storm surge and flooding in estuaries. The complexity of the site-specific controls on water levels along estuarine shorelines is illustrated by the lack of correlation of many onshore and offshore variables to water levels and because most of the correlated variables did not correlate to water levels from every storm. Onshore variables are strongly controlled by human interventions in the form of hard and soft shoreline protection structures. The best correlation (0.50) exists between water level observations and maximum elevation of the profile. Sites with the highest maximum elevations are sites that have been altered to protect homes or property in close proximity.

The spatial distribution of topographic highs and lows may be one of the controlling factors in overwash and erosion along barrier islands and paradoxically, areas prone to overwash and erosion may control the position of the topographic highs and lows (Fisher, Dolan, and Hayden 1984). The implications for flooding are not as obvious along estuarine shorelines that lack the homogeneity of barrier islands and where site-specific controls are critical (Jackson 1995; Phillips 1986). Therefore, a more diverse set of onshore and offshore variables is required to identify areas along the shoreline that are susceptibility to inundation. The location of topographic highs and lows along the study area in Raritan Bay have been identified in this dissertation but it is not clear if the highs are positioned in the areas of highest susceptibility to water levels and inundation. The results of the field study suggest that people have placed high shoreline protection structures where historic flooding has occurred, chiefly through local-scale projects. The elevations of these structures are not based on spatial variability and onshore and offshore controls.

Other onshore variables that could be described as foreshore and backshore geomorphology, including dune and beach characteristics, correlate to water levels but not as highly or for as many storm events as the maximum elevation of the profile variable. Large dunes and expansive beaches are not natural geomorphic features on estuarine shores yet they are widely found in the study area, especially where homes and property are located. Water level observations were relatively low at sites with large dunes and wide, sandy beaches. The highest water level observations occurred at sites with high elevations and steep slopes in the foreshore, indicating that hard shore protection structures such as revetments, bulkheads and seawalls may exacerbate water levels.

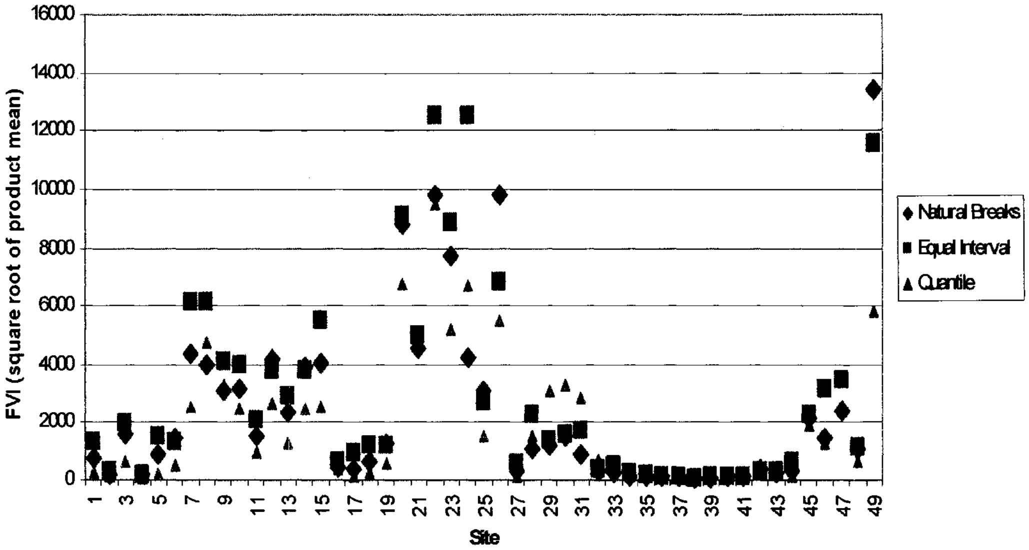
Profile orientation is an onshore variable that is linked for discussion with the offshore variables because the offshore variables are considered relative to shoreline orientation. Maximum fetch within a 90^0 window from profile orientation correlates to water levels from four storms. Profile orientation and azimuth of maximum fetch correlate to water levels from three storms. The observation of high water levels at sites with long maximum fetch distances within a 90^0 window, long mean fetch distances and profile orientations in north and northeasterly directions is consistent with research suggesting that orientation and fetch are critical to creating high water levels (Miller 1988; Jackson 1995).

Desktop GIS, such as Arcview, are capable of adequately classifying site-specific data and producing maps useful for hazard assessment. The use of different statistical methods in Arcview GIS did not change the classification of variables in the study area because many sites remained in the same class and few changed more than 2 classes. Two storm inundation indices are discussed in Chapter 7. The first index is derived from the onshore and offshore variables discussed in this chapter and assesses susceptibility to actual inundation. The second index is derived from only the offshore variables discussed in this chapter and assesses the susceptibility of the potential inundation of the shoreline due to exposure to storm conditions. The second index may be useful for beginning site-specific coastal storm hazard assessment because it is obtained without a detailed field study. However, the second index may be limited in application to highly developed shores because it only evaluates susceptibility from exposure to storm conditions and not the modification of water levels by onshore factors. The role of human alterations in the study area is determined by comparing susceptibility to actual and potential storm inundation.

VII- Classification and Storm Inundation Indices

Derivation of the Storm Inundation Indices

Two different storm inundation indices are calculated from the square root of the product mean using correlated variables, a calculation used in other coastal risk and vulnerability indices (Gornitz et al. 1994). The first index represents susceptibility to actual inundation and is derived from seven onshore and eight offshore variables that were correlated to water levels. The second index represents susceptibility to potential inundation and is derived from only the eight offshore variables that were correlated to water levels. Three statistical techniques in Arcview, natural breaks, equal interval and quantile, are used to group the storm inundation indices into five susceptibility classes, high, moderate to high, moderate, moderate to low, and low. Quantiles are used in other coastal vulnerability indices (Gornitz et al 1994). Despite using different statistical techniques to classify the data, statistical correlations of R^2=0.95-0.99 exist for the susceptibility classes between sites. Sites highly susceptible to inundation are clearly evident in Figure 7.1, regardless of the classification technique used. The first storm inundation index is the most complete measure of susceptibility because it includes both human (e.g., beach fill) and natural influence (e.g., fetch) because the index is determined from onshore and offshore variables for each study site. The focus of discussion in this chapter will be the storm inundation indices classified by natural breaks and comparisons of the first index derived from the entire set (15) of correlated variables and the second index derived only from the correlated offshore variables. The entire set of variables



	Natural Breaks	Equal Interval	Quantile
Natural Breaks	1		
Equal Interval	0.9	1	
Quantile	0.87	0.93	1

Figure 7.1 – Comparison of different classification techniques in Arcview GIS (with correlation coefficients).

represents human development and natural susceptibility and the offshore variables represent only the natural susceptibility. Comparison of the two indices gives insight to the relationship between human development and susceptibility to inundation.

A change in the classification of a site in the two indices indicates a difference in susceptibility to actual and potential inundation. No change indicates little difference in susceptibility to actual and potential inundation. Eighteen sites remained in the same class while 31 changed classes. Of these, 21 sites changed only 1 class (Figures 7.2 and 7.3), 8 sites changed 2 classes, 1 site (Site 4) changed 3 classes and no site changed 4 classes (the most possible). Sites that changed one class are evaluated based on either increasing or decreasing susceptibility. 17 sites were placed in a lower susceptibility class in the second index. 14 sites were placed in a higher susceptibility class in the second index. Sites that changed by 2 or more classes are listed in Table 7.1 and illustrate that most change occurred at sites where beach nourishment and dune building reduce susceptibility to inundation.

Trends in susceptibility to inundation are evident in both indices. In the first, susceptibility increases away from marshes towards built shorelines, such as from sites 15 to 20 in Cliffwood Beach (Figure 7.2). While it is accepted that marshes are created and maintained by flooding, the actual water level in the marsh is lower than the actual water level at locations with hard or soft shoreline protection structures. Susceptibility to inundation is decreased because the marsh dissipates wave energy and the propagation of water inland. A similar trend is seen in the second index although for overall higher susceptibility classes (Figure 7.3).

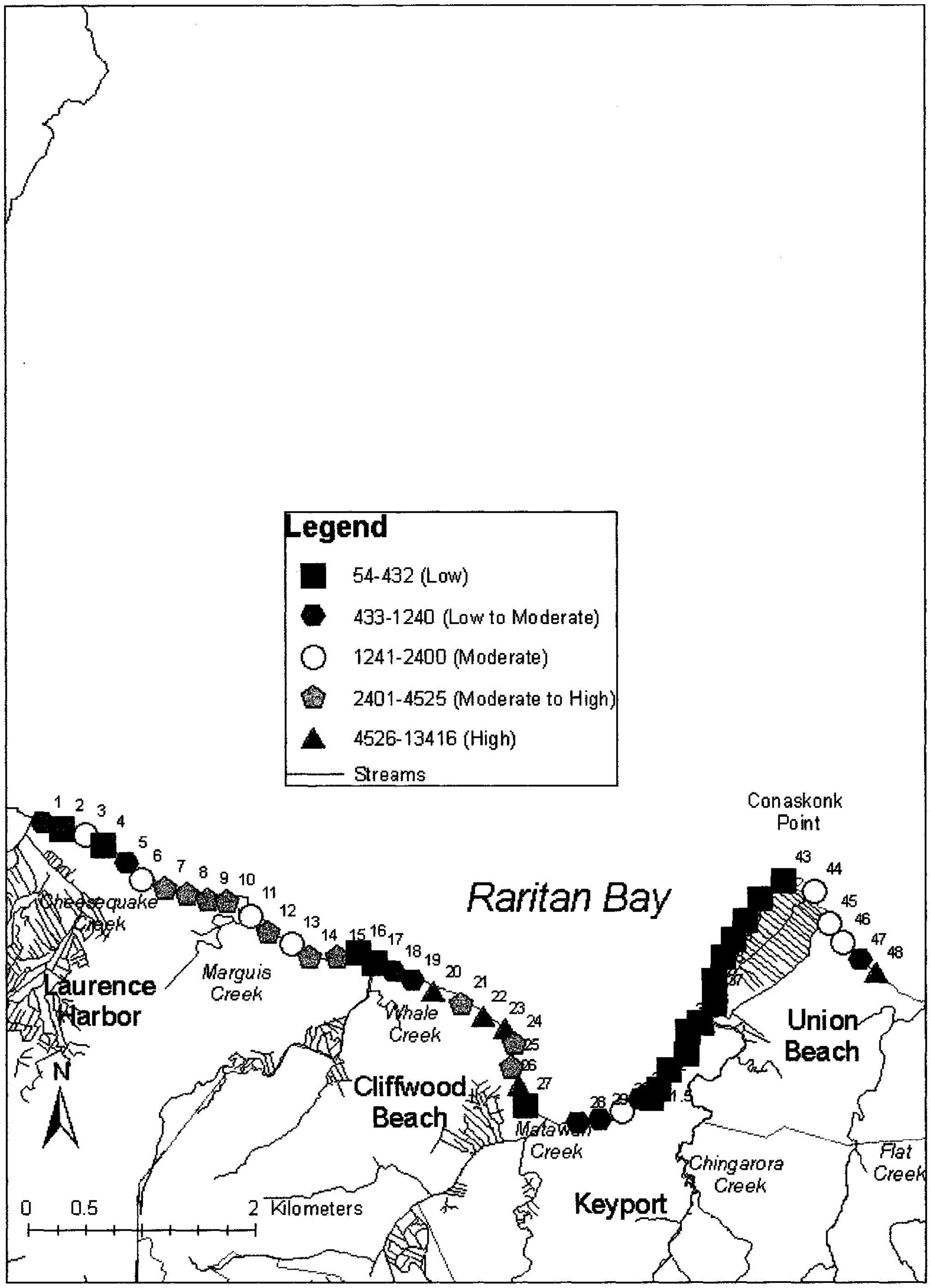


Figure 7.2 – The first storm inundation index for each site derived using all correlated onshore and offshore variables representing susceptibility to actual inundation resulting from human alterations along the shoreline and exposure to storm conditions.

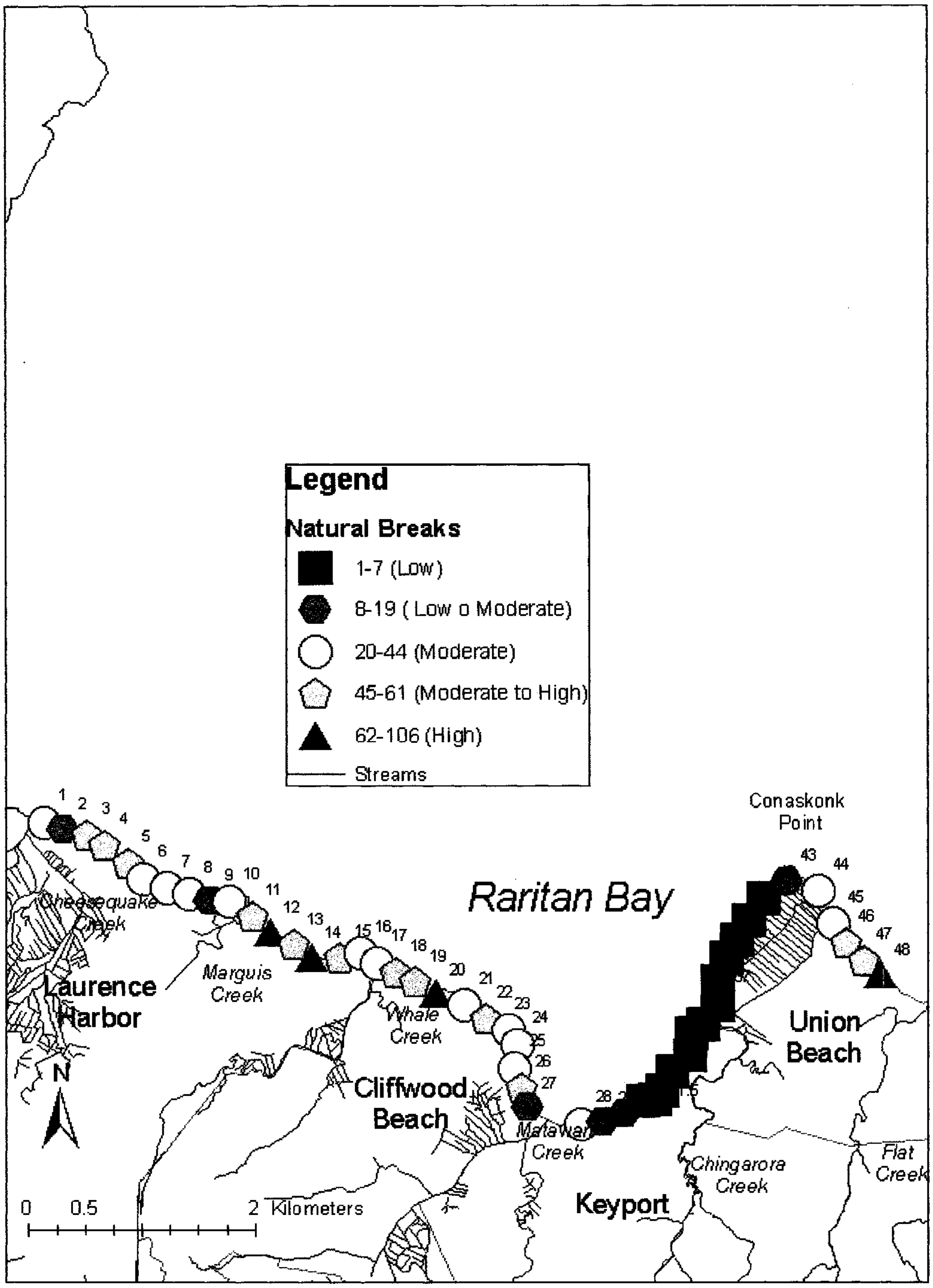


Figure 7.3 – The second storm inundation index for each site derived using only correlated offshore variables and representing susceptibility to potential inundation resulting from the exposure of each site to storm conditions.

Table 7.1 - Sites that changed two or more classes between the second and first storm inundation index (SII) and the change as an increase or decrease in susceptibility caused by human alteration of the shoreline.

Site	Reach	First SII -both onshore and offshore variables	Second SII – only offshore variables	Change in vulnerability from human alteration
4	Laurence Harbor	low	Moderate to high	decrease
5	Laurence Harbor	Low to moderate	Moderate to high	decrease
9	Laurence Harbor	Moderate to high	Moderate to low	increase
16	Cliffwood Beach	low	moderate	decrease
17	Cliffwood Beach	low	moderate	decrease
18	Cliffwood Beach	Moderate to low	Moderate to high	decrease
19	Cliffwood Beach	Moderate to low	Moderate to high	decrease
23	Cliffwood Beach	high	moderate	increase
47	Union Beach	Moderate to low	Moderate to high	decrease

The second storm inundation index is based on offshore information that is readily available from maps. Detailed geomorphic information in coastal research comes from expensive, site-specific studies (Jackson 1995) that could prohibit developing an index similar to the first storm inundation index. Digital topographic data may serve as a surrogate for field studies but readily available digital topographic data is too coarse for local studies of developed estuarine shores. Data determined from digital maps may be used to assess potential inundation, but detailed field studies are needed to assess actual inundation.

Description of the First Storm Inundation Index and Actual Inundation for Reaches and Sites (Figure 7.2)

Laurence Harbor (Reach 1)

The classification of Site 1 as low to moderate susceptibility is expected because marsh environments dissipate coastal storm impacts more than beach environments (Pethick and Crooks 2000). Historical observations indicate that the profile at Site 2 was overtopped by the December 1992 storm. However, the susceptibility of Sites 2 and 4 to actual inundation is classified as low, because these sites have broad beaches with berm development that mitigate the elevation of water levels. Contrarily, Sites 3 and 6 have narrow beaches with no berm development and are classified as moderately susceptible to actual inundation. The moderate classification is supported by observations of erosion of the active foreshore at Site 3 (Figure 7.4). The rubble revetment at Sites 7-10 creates a

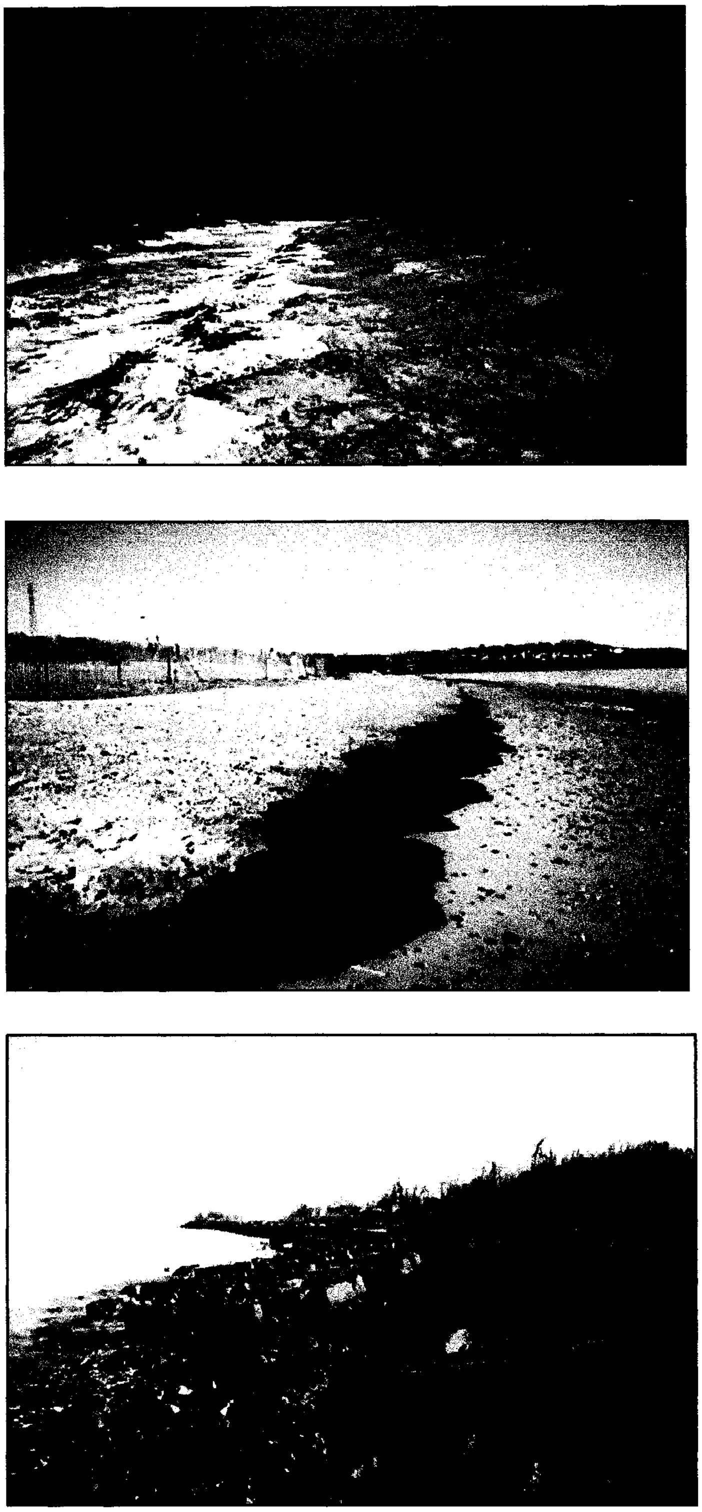


Figure 7.4- Erosion of a beach nourishment project from storms in 1998 at Site 3 and Rubble Revetment Sites 7-10 in Laurence Harbor.

short, steep foreshore with little beach sediment (Figure 7.4) resulting in a moderate to high flood susceptibility to actual inundation classification.

Seidler and Cliffwood Beach (Reaches 2-3)

Sites 11-14 in Seidler Beach vary from moderate to high susceptibility to actual inundation because these sites are predominantly natural estuarine beaches with narrow, steep, coarse beaches and small, low dunes. The storm inundation index varies greatly in Cliffwood Beach because the shoreline changes from marsh at Site 15 to beaches with dunes at Sites 17 through 19 to a seawall at Sites 20 through 24. The elevation of water levels is lowest at the sites with marsh, moderate at the sites with beaches and dunes and highest at the sites with seawalls. Sites 25-26 represent the terminus of the seawall and the continuation of shoreline protection in the form of a rubble revetment and moderate to high susceptibility to inundation. A marsh exists at Site 28 and the change in shoreline orientation to the south limits fetch distances and results in a low susceptibility to inundation classification.

Keyport (Reach 4)

Water levels are highest in Keyport following major coastal storms in Raritan Bay. Sites 28, 29 & 31 are classified low to moderate and Site 30 classified as moderate with the remaining sites from 31.5 – 36 classified as low. The truncation of the active foreshore by replacing the natural, small beaches with vertical structures at Sites 29, 30 and 31 results in higher water levels and susceptibility to actual inundation than at Sites 32-36 consisting of marsh. However, the orientation of the shoreline shelters sites from easterly storm winds, therefore limiting the influence of the fetch variables and resulting in moderate susceptibility when compared to sites with vertical structures in other reaches.

Union Beach (Reaches 5-6)

Conaskonk Point (Site 43) creates a dramatic change in shoreline orientation, with sheltered sites on the west side (Reach 5) and low water levels, and unsheltered sites on the east side (Reach 6) and moderate to high water levels. The shoreline on the west side of Conaskonk Point consists of marsh with some beach deposits and primarily commercial development 1 km from the shoreline. The shoreline on the east side of Conaskonk Point consists of a new beach nourishment project at Sites 45- 47, an older bulkhead which starts at site 48 and residential development that abuts the shoreline. Susceptibility to actual inundation is classified as low to moderate at Site 47, a nourished beach, however the susceptibility is higher (classified as moderate) at Sites 45 and 46 where the beach is not nourished and protects individual lots. A groin separates Sites 47 and 48 and a bulkhead extends from the groin to Flat Creek, protecting development in Union Beach. The susceptibility of Site 48 to actual inundation is high.

Comparisons of the First and Second Storm Inundation Indices and Potential Inundation (Figures 7.1 and 7.2)

Laurence Harbor (Reach 1)

Sites 2 - 4, consisting of beach nourishment, are classified as more susceptible to potential inundation than Sites 7-10, consisting of rubble revetment. Susceptibility to actual inundation is lower at Sites 2-4 and higher at Site 7-10 based on the first index. The difference in classification of these sites between the first and second index indicates that beach nourishment was put in place to combat the exposure of this shoreline from Sites 2-4 to potential inundation. The beach nourishment reduces the susceptibility to actual inundation. The makeshift rubble revetment was placed where susceptibility from exposure to storm conditions and potential inundation is lower but the disruption of the foreshore by the structure may be exacerbating water levels and increases the susceptibility to actual inundation. This revetment is currently being refurbished by the NJDEP (Figure 7.5).

Seidler and Cliffwood Beach (Reaches 2-3)

Sites 11-14 are unaltered, relatively natural estuarine shores that are classified as moderate to high and high susceptibility to potential inundation. The susceptibility of Sites 11-14 to actual inundation is lower, based on the first index. The difference in classification of these sites between the first and second index indicates that natural geomorphic conditions mitigate water levels; however, the decrease is rather minimal,

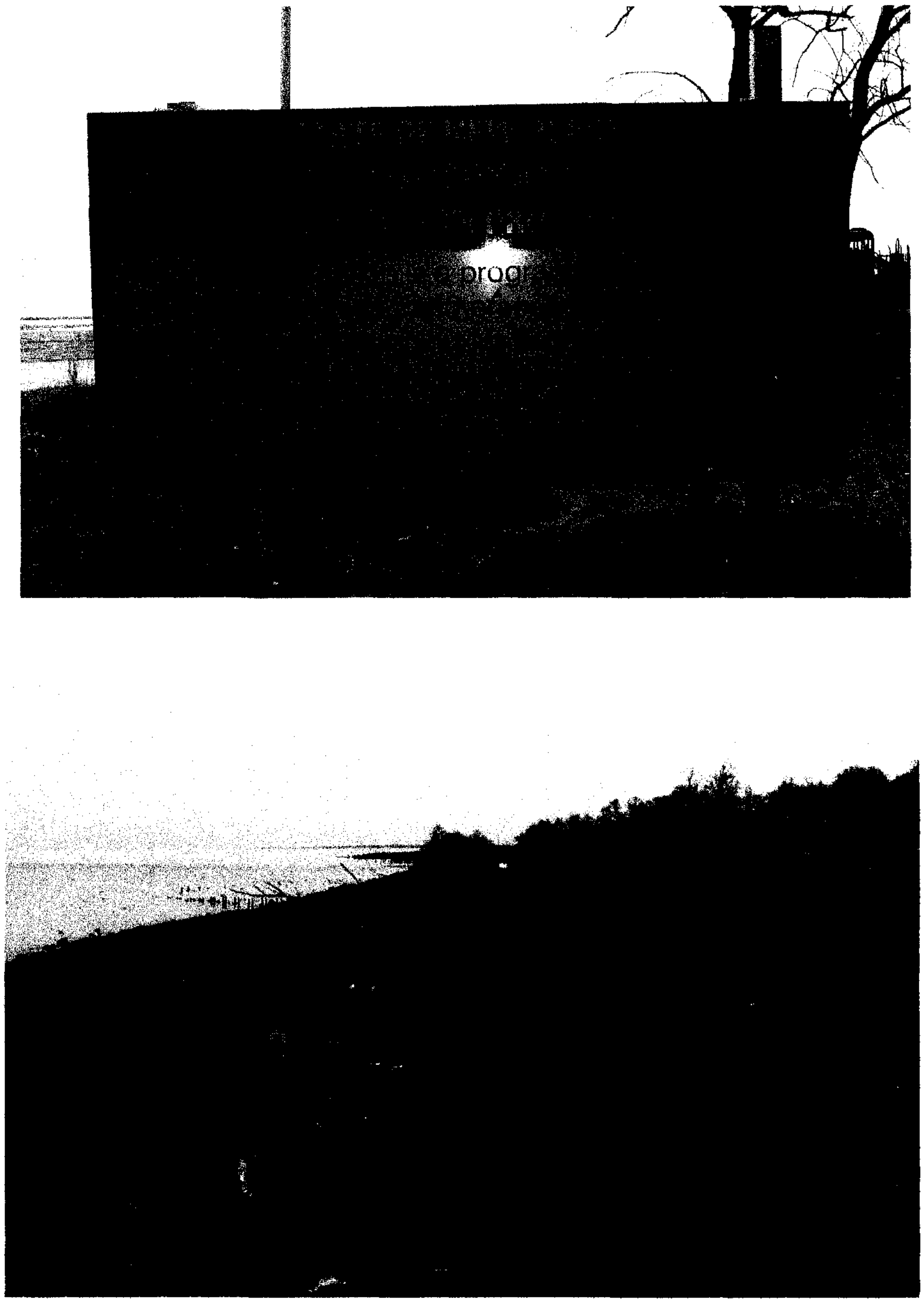


Figure 7.5 – Picture of Shoreline Protection Project underway in 2002-2003 at Laurence Harbor.

only one class from either high down to moderate to high or from moderate to high down to moderate. Beach fill has not been placed at these sites because most homes are situated inland of the shoreline and at higher elevations outside the active foreshore. Site 15 is classified as low susceptibility to potential inundation but moderately susceptible to actual inundation, which is inconsistent with other marsh sites in the study area. The marsh at Site 15 is not as expansive as marsh at other sites and is flooded by a single creek, Whale Creek.

Sites 16-27 are moderately to highly susceptibility to potential inundation because the orientation of the shoreline exposes sites to storm conditions. The susceptibility of Sites 16-19, consisting of beach nourishment, to actual inundation is lower, based on the first index. The susceptibility of Sites 21-26, consisting of seawalls and revetments, to actual inundation is greater. Two different shoreline protection strategies, soft and hard, are used at sites with the same potential for inundation. The results suggest that the seawall increases water levels and susceptibility to actual inundation and the beach nourishment decreases water levels and susceptibility to actual inundation. The large artificial dunes at Sites 18 and 19 also reduce susceptibility to actual inundation. The area inland of Sites 18 and 19 floods from moderate storms but the cause is from inundation by tidal creeks and not overtopping or breaching of the dunes (Personal Observation).

Keyport (Reach 4)

Sites 28-30 are classified as moderate and low to moderate susceptibility to potential inundation. Sites 31-36 are classified as low. Long northerly fetch distances at Sites 28-30 near Matawan Creek and in front of the downtown and residential area of Keyport increase the susceptibility of these sites to potential inundation. Sites 31-36 are sheltered to the northeast and have the lowest potential for inundation. Susceptibility to actual inundation is lower at Site 28 and greater at Sites 29 and 30, based on the first index, while the rest of the sites remained in the same class. Site 28 consists of a relatively unaltered beach while Sites 29 and 30 are protected by vertical structures, indicating that small concrete seawalls or wooden bulkheads increase susceptibility to actual inundation. Both storm inundation indices for Sites 33-36 are low, where marsh is sheltered from storm impacts by Conaskonk Point.

Union Beach (Reaches 5-6)

Sites 44-48 are classified from moderate to high susceptibility to potential inundation because the orientation of the shoreline exposes sites to storm conditions. Susceptibility to actual inundation is lower at Sites 46 and 47, based on the first index, while the remaining site stayed in the same class. A beach nourishment project exists at Site 47 and reduces water levels and susceptibility to actual inundation. Sites 45 and 46 consist of beaches adjacent to the project but do not benefit from direct beach nourishment. Sites 45 and 46 are classified as moderate in both indices. The bulkhead at

Site 48 is classified as high storm inundation in both indices. Water levels and susceptibility to actual inundation are highest at sites with bulkheads where there is little dissipation of waves and storm surge by the nearshore and foreshore. The impact of the change in shoreline orientation around Conaskonk Point is evident in both indices, with low susceptibility to inundation on the sheltered west side and high susceptibility on the exposed east side.

Summary

The two storm inundation indices reveal differences between actual and potential inundation between sites. It is clear that human alterations affect the actual inundation classification. The onshore variables used in the first index include maximum elevation of the profile, shorezone width and slope, dune and berm characteristics which are primarily human artifacts in the study area. For example, the susceptibility of Site 47 in Union Beach to actual inundation is classified as low to moderate as compared to the high susceptibility to actual inundation classification of Site 48. Sites 47 and 48 are both highly susceptible to potential inundation. The reason for the disparity in susceptibility to actual inundation across a short scale (200m) is an artificial beach built at Site 47. Site 48 has a bulkhead with a cobble beach serving as toe protection exposed during low tide. Since human alterations of the shoreline occur on small, interrupted scales, understanding the variability in susceptibility to potential and actual inundation at local scales along estuarine shorelines is critical. Arguments have been made that flood defense measures increase the risk of coastal flooding (Doornkamp 1998). Support for this argument is found by comparing sites in Cliffwood Beach. Sites 20-24 are highly susceptible to actual and potential inundation and consist of a rock seawall with little or no beach. Sites 18 and 19 are highly susceptible to potential inundation but are low to moderately susceptible to actual inundation and consist of an artificial beach and dune building.

The storm inundation classification of sites in a developed estuary assesses actual water levels based on onshore and offshore variables. Low susceptibility to actual inundation occurs at sites with broad and gently sloping, but not necessarily high, beach fill with berm development and dune projects, and limited offshore fetch distances and exposures to storm winds. High susceptibility to actual inundation occurs at sites with steep artificial structures, such as revetments or seawalls with little beach deposits and long offshore fetch distances and exposures to storm wind directions. The two storm inundation indices illustrate the complexity of built environments. Potential inundation is represented by an index derived from offshore variables that assess the exposure of the shoreline to storm conditions. Actual inundation is represented by an index derived from both onshore and offshore variables. The onshore variables are highly modified by people in developed estuaries. Historical evidence suggests that the shoreline has been altered where people have experienced flooding, but the water level observations and the storm inundation indices indicate that the type of alteration used may cause higher water levels on the profile. Comparisons of the two different indices demonstrate that hard, vertical shoreline protection structures like seawalls, bulkheads and revetments increase water levels and susceptibility to actual inundation. The results suggests that low, broad, beach fill projects are better at reducing water levels and susceptibility to actual inundation in developed estuaries, than other practices such as rubble revetments, bulkheads, and seawalls.

VIII- Evaluation of Storm Conditions and Water Levels

Introduction

The incorporation of storm wind conditions in coastal hazard research has previously been limited to the use of pressure gradients for broad-scale storm surge predictions (Oey, Mellor, and Hires 1985, Jarvinen and Lawrence 1985) or to develop wave power indices (Dolan and Davis 1992). In this chapter, wind duration, direction and speed from five storms are compared to water level observations and the storm inundation indices at sites where differences in water level observations are observed. Hourly sustained wind speed and direction data for each storm is graphed using 72 hourly observations to determine and compare the potential strength of each storm. Peak gust wind speeds are not graphed but are used to evaluate storm intensity (Table 8.1). Water level observations and the storm inundation indices at 10 of the study sites are evaluated from each storm event. The selection of the ten sites is based on transect profiles where wrack lines are located at distinctly different locations on the cross-shore profile for different storms. Eight of the ten sites have sandy beaches and the other two sites are rubble revetments. Wrack lines are labeled with letters that correspond to the storm event (Figure 8.1 a-d).

The spatial distribution of the storm producing the highest water level at sites is mapped in a GIS (Figure 8.2) for comparison to storm conditions and shoreline characteristics. Between-storm variability in water level observations is determined using single factor analysis of variance (ANOVA) and determined to be significant at the 95% confidence level (Table 8.2). Evaluating the significance of between-storm

Table 8.1 – Comparison of storm conditions using sustained and peak wind speed, direction and duration from Bergen Point, NY. Storms A, B, and E occurred during neap tides, Storms C and D during spring tides.

Date (Letter ID on profiles)	Maximum hourly sustained wind m/s (rank)	Hourly peak gust m/s (rank)	Hours of sustained winds over 10 m/s; direction; (rank)
3/31-4/2/97 (A)	13.8 (1)	18.6 (1)	14; 0^{0} - 10^{0}; (1)
11/7-9/97 (B)	10.5 (5)	15.1 (4-tie)	1; 48^{0}; (4-tie)
12/28-30/97 (C)	11.2 (3)	17.4 (2)	1; 2^{0}; (4-tie)
1/28-30/98 (D)	10.8 (4)	15.1 (4-tie)	6; 11^{0} – 21^{0}; (3)
2/4-6/98 (E)	11.6 (2)	16.5 (3)	7; 43^{0} - 46^{0}; (2)

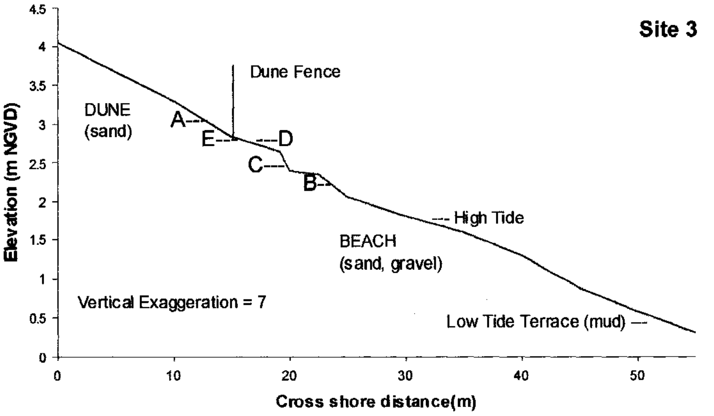
Table 8.2 – ANOVA- Single Factor for water level observations.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Storm E	49	117.899	2.406102	0.161072
Storm A	37	94.433	2.552243	0.180999
Storm B	49	109.744	2.239673	0.167546
Storm C	49	111.46	2.274694	0.166429
Storm D	49	113.483	2.31598	0.141126

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.597417	4	0.649354	3.995777	0.003744	2.411241
Within Groups	37.05232	228	0.16251			
Total	39.64973	232				



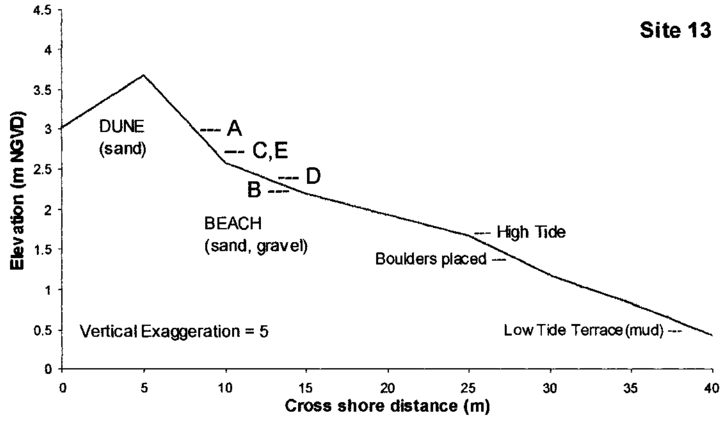


Figure 8.1(a) – Cross-shore profiles for sites 3 and 13 with storm wrack lines identified for five storms. Storm A - 3/97, Storm B - 11/97, Storm C - 12/97, Storm D - 1/98 and Storm E 2/98.

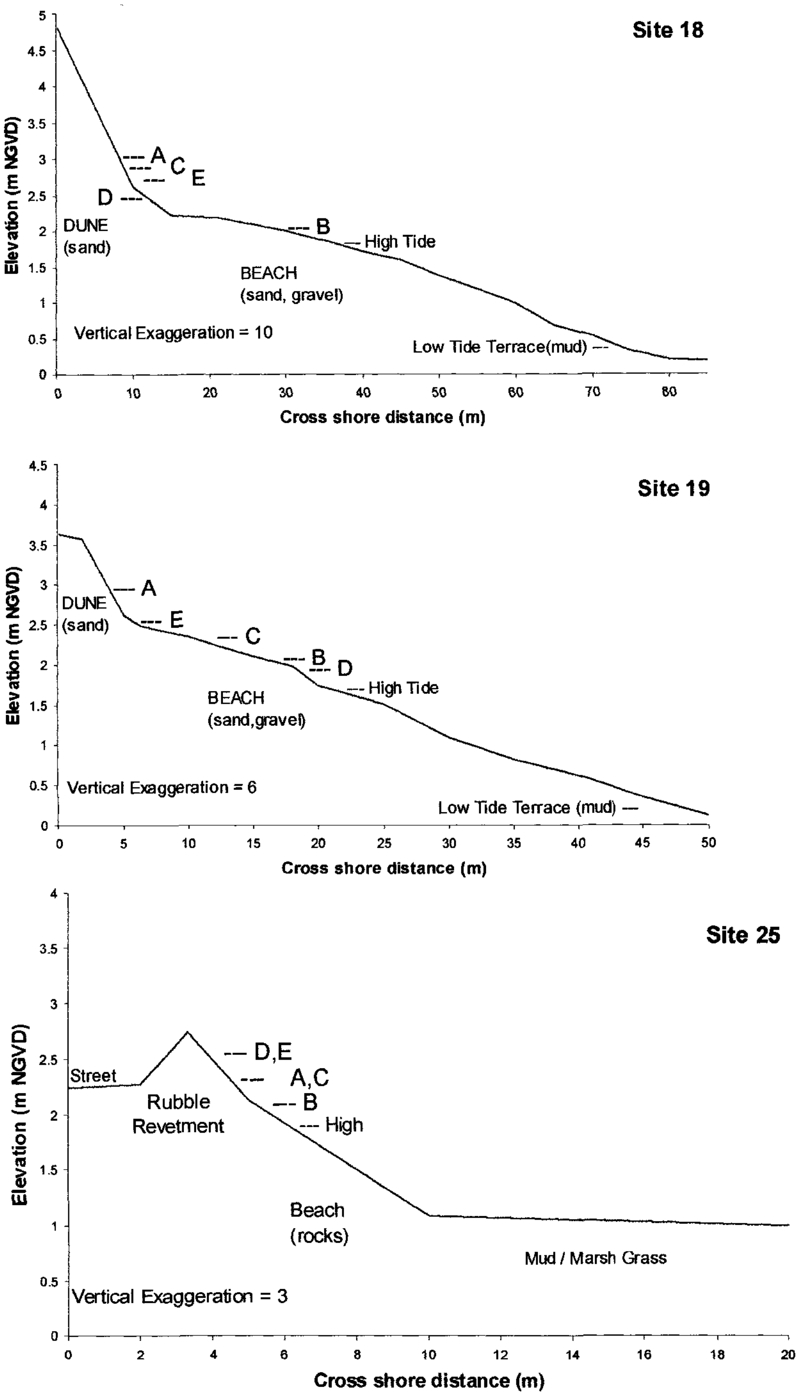
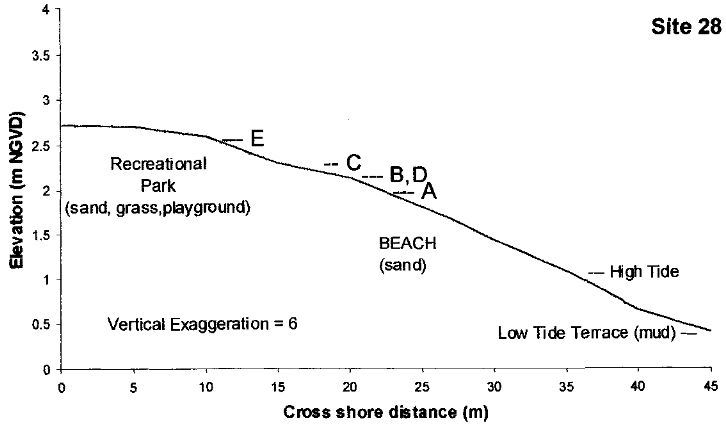


Figure 8.1(b) – Cross-shore profiles for sites 18, 19 and 25 with storm wrack lines identified for five storms. Storm A - 3/97, Storm B - 11/97, Storm C - 12/97, Storm D - 1/98 and Storm E 2/98.



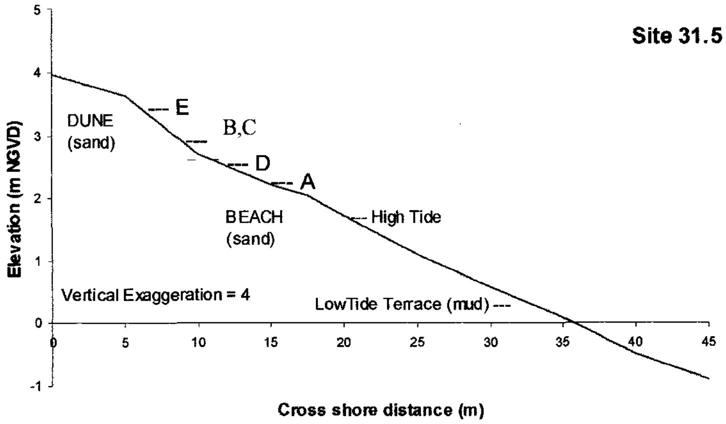


Figure 8.1(c) – Cross-shore profiles for sites 28 and 31.5 with storm wrack lines identified for five storms. Storm A - 3/97, Storm B - 11/97, Storm C - 12/97, Storm D - 1/98 and Storm E 2/98.

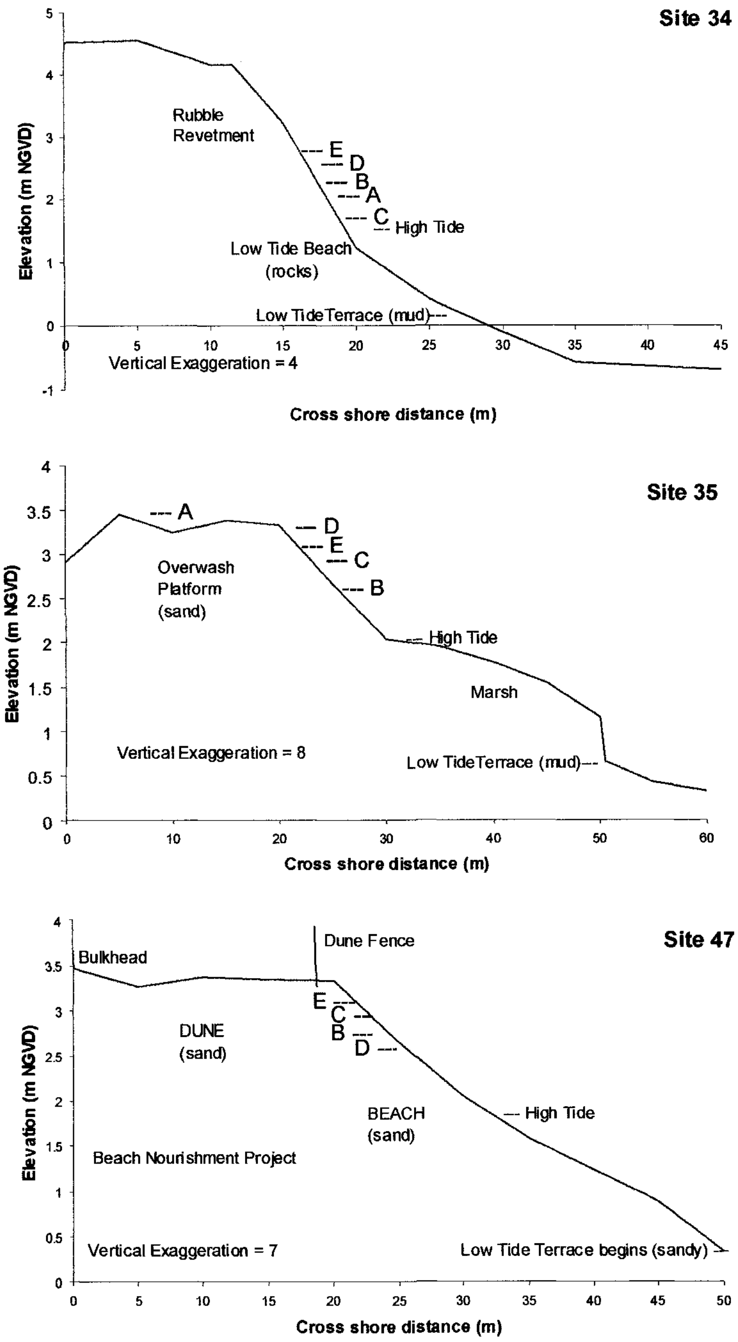


Figure 8.1(d) – Cross-shore profiles for sites 34, 35 and 47* with storm wrack lines identified for five storms. Storm A - 3/97, Storm B - 11/97, Storm C - 12/97, Storm D - 1/98 and Storm E 2/98. * Storm A not determined.

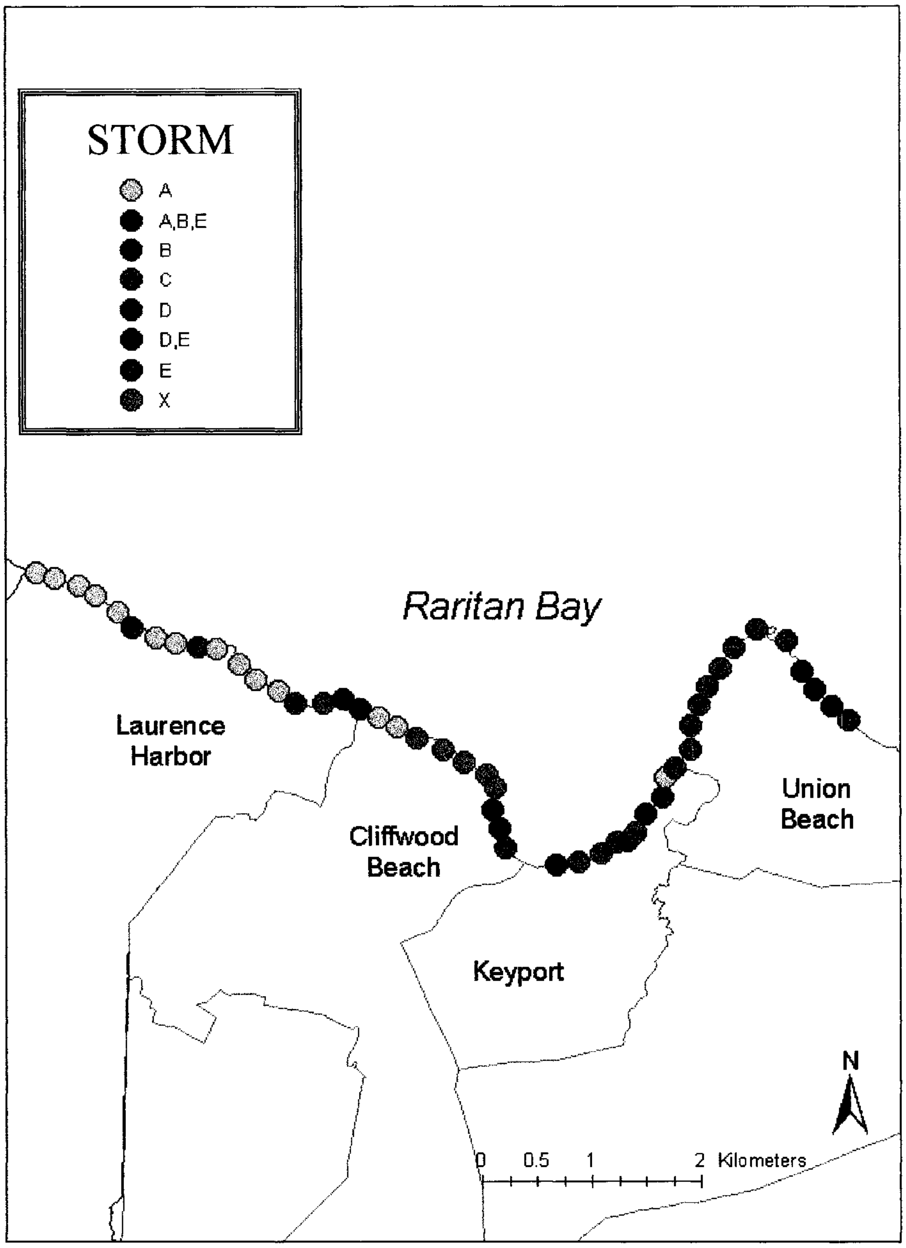


Figure 8.2 – Distribution of storms producing the highest water level at each site. Sites labeled "X" did not have different wrack lines deposited in distinguishable locations on the foreshore for different storms.

variability in water levels is important because this indicates that no single storm produced the highest water level observation simultaneously at all sites and that onshore and offshore controls either reduce or increase susceptibility to inundation at local scales for a given set of storm conditions. Transect azimuth (profile orientation), maximum fetch distance and fetch distances to the north and northeast of each site are used to represent the relationship between onshore and offshore controls and storm conditions (Table 8.3). These variables are identified as critical to potential and actual inundation and were significantly correlated to water level observations in Chapter 6.

Astronomical effects must be considered in an analysis of storm conditions and spatial variability in water levels. Storm A – (March 31 – April 2, 1997), storm B (November 7 – 9, 1997) and storm E (February 4-6, 1998) occurred during neap tides while storm C (December 28-30, 1997) and storm D (January 28-30, 1998), occurred during spring tides. The expectation is for moderate water levels during neap tide and extreme variability in water levels during spring tide. Between-storm variability in water level observations is not explained solely by the astronomical effects and is further examined for each storm in the following sections. Water level records taken from a tide gage at Sandy Hook are used to evaluate the broad-scale relationship between storm conditions and storm surge in the entire bay.

Storm A – March 31 – April 2 1997

Data from weather observations at Bergen Point in Raritan Bay reveal that Storm A had the greatest wind speed and longest duration of the observed storms. The highest

Table 8.3 – Ten study sites and selected storm-related variables.

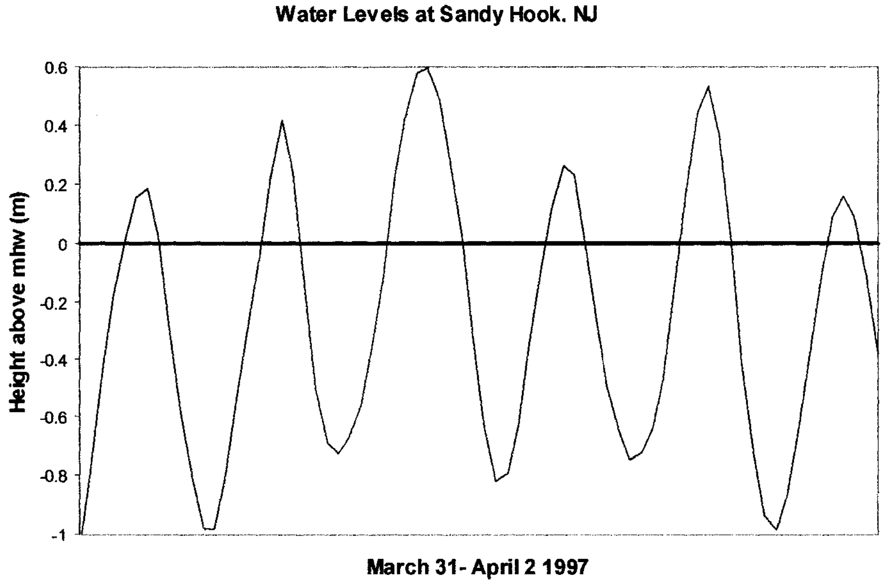
Location and Site Number	Shore Type	Transect Azimuth 0^0=N	Maximum Fetch Distance (km)	Maximum Fetch Distance Northeast (km)	Maximum Fetch Distance North (km)	Storm Rank (bold-highest)
Laurence Harbor Site 3	Nourished beach and dune	16	24.68	8.88	3.79	**A**, (E,D), C,B
Aberdeen Site 13	Natural beach/dune	44	23.53	18.72	5.3	**A,** C,E D,B
Cliffwood Beach Site 18	Nourished beach and dune	25	22.84	19.25	5.65	**A**,C E, D,B
Cliffwood Beach Site 19	Nourished beach and dune	21	22.84	19.37	5.65	**A**, E C, B, D
Cliffwood Beach Site 25	Rubble revetment	79	22.19	20.5	0.11	**(D,E),** A, C,B
Keyport Site 28	Natural beach	9	19.5	1.72	8.11	**E**, C (B,D) A
Keyport Site 31.5	Natural beach/dune	330	9.63	0.3	8.1	**E**, (B,C) D, A
Keyport Site 34	Rubble revetment	314	8.52	0	0.08	**E**, D, B, A, C
Keyport Site 35	Beach and marsh	301	8.43	0.37	7.63	**A**, D, E, C, B
Union Beach Site 47	Beach nourishment	43	19.6	19.13	7.85	**E**, C, B, D

sustained hourly winds were 13.8 m/s from the north. Sustained wind speeds exceeded 10 m/s for 5 consecutive hours and for a total of 14 hours primarily from the north and northeast, $0^0 - 45^0$. The strongest winds were produced from the north, $0^0 - 10^0$. Other storms had more persistent but weaker north and northeast winds.

Water levels at Sandy Hook exceeded 0.5 m above mean high water for a total of three hours during one tidal cycle with a peak water level of 0.597 m above mean high water (Figure 8.3). Neap tide conditions resulted in relatively moderate water levels at the Sandy Hook tide gage, but Sites 3,13, 18 and 19 from Laurence Harbor to Cliffwood Beach and Site 35 in Keyport had the highest water levels from any of the five storms (Figures 8.1a-d). Sustained storm winds were predominantly from the north, but Sites 28 and 31.5 in Keyport had the lowest water levels of all storms, despite northerly fetch distances of 8 km. Despite the 14 hours of sustained winds over 10 m/s from the north, the strong, persistent northwesterly winds preceding and following served to mitigate water levels at Sites 28 and 31.5 in Keyport where Matawan Creek enters the bay. Water levels were the highest at 14 of the study sites, where high winds (13.8 m/s sustained; 18.6 m/s peak gust) were effective in moving water up the foreshore (Figure 8.3).

Storm B – November 7 – 9, 1997

Data from weather observations at Bergen Point in Raritan Bay reveal that Storm B had the weakest wind speeds and shortest durations. The highest sustained hourly winds were 10.5 m/s, with peak gusts of 15.1m/s. Sustained winds over 10 m/s from a northeasterly direction (48^0) persisted for only one hour during the storm. Wind speeds lower than 10 m/s persisted for 68 hours from the north, northeast or east, $0^0 - 90^0$. The



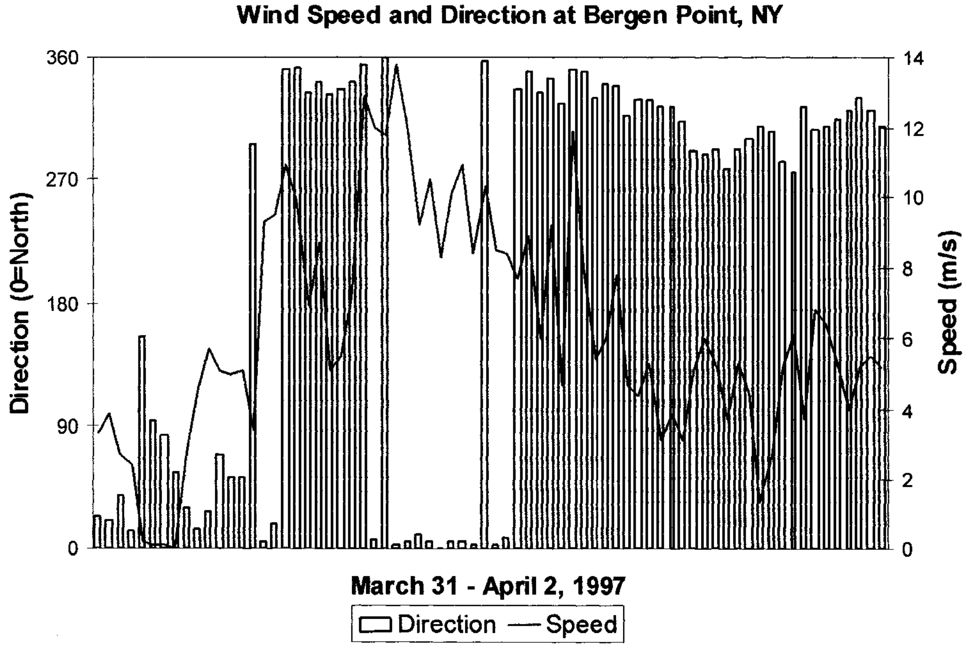


Figure 8.3 - Storm conditions for storm A based on hourly sustained wind speeds and directions at Bergen Point, New York and water level observations from the Sandy Hook tide gage from March 31 - April 2, 1997.

duration of persistent but weak northeasterly winds (less than 10 m/s) produced water levels at Sandy Hook over 0.5 m mean high water for two tidal cycles with durations of 2 to 3 hours and peaks of 0.544 m and 0.619 m above mean high water (Figure 8.4).

The water levels at sites 3, 13, 18, 25 and 35, from Laurence Harbor to Keyport were the lowest for any of the storms and the second lowest for any storm at sites 19 and 47, at Cliffwood Beach and Union Beach, respectively (Figures 8.1a-d). The low wind speeds produced by this storm resulted in minimal water levels at most sites but the 68 hours of weak winds from the north and northeast produced moderate water levels at Sites 28 and 34 in Keyport. The long duration of northeasterly wind produced higher water levels at the Sandy Hook gage than Storm A. Storm B indicates that long durations of weak winds (less than 10 m/s) can produce high water levels at sites with narrow shorezones and limited fetch distances, but stronger winds are needed to propagate waves and cause inundation at sites with wide shorezones and long fetch distances.

Storm C – December 28 – 30, 1997

Storm C had hourly sustained winds of 11.2 m/s and a peak gust of 17.4 m/s, which rank 3 and 2 respectively among the five storms. The impact of the relatively high sustained wind speed and peak gust is mitigated by the low duration of the storm with only one hourly observation exceeding 10 m/s and only 20 hours of weaker winds from the north or northeast. The duration of winds from the north, northeast or east, $0^0 – 90^0$, was 13 hours. The direction of the highest sustained wind and peak gust was from the north 2^0, but that was preceded by winds from a more northeasterly direction, $31^0 – 51^0$.

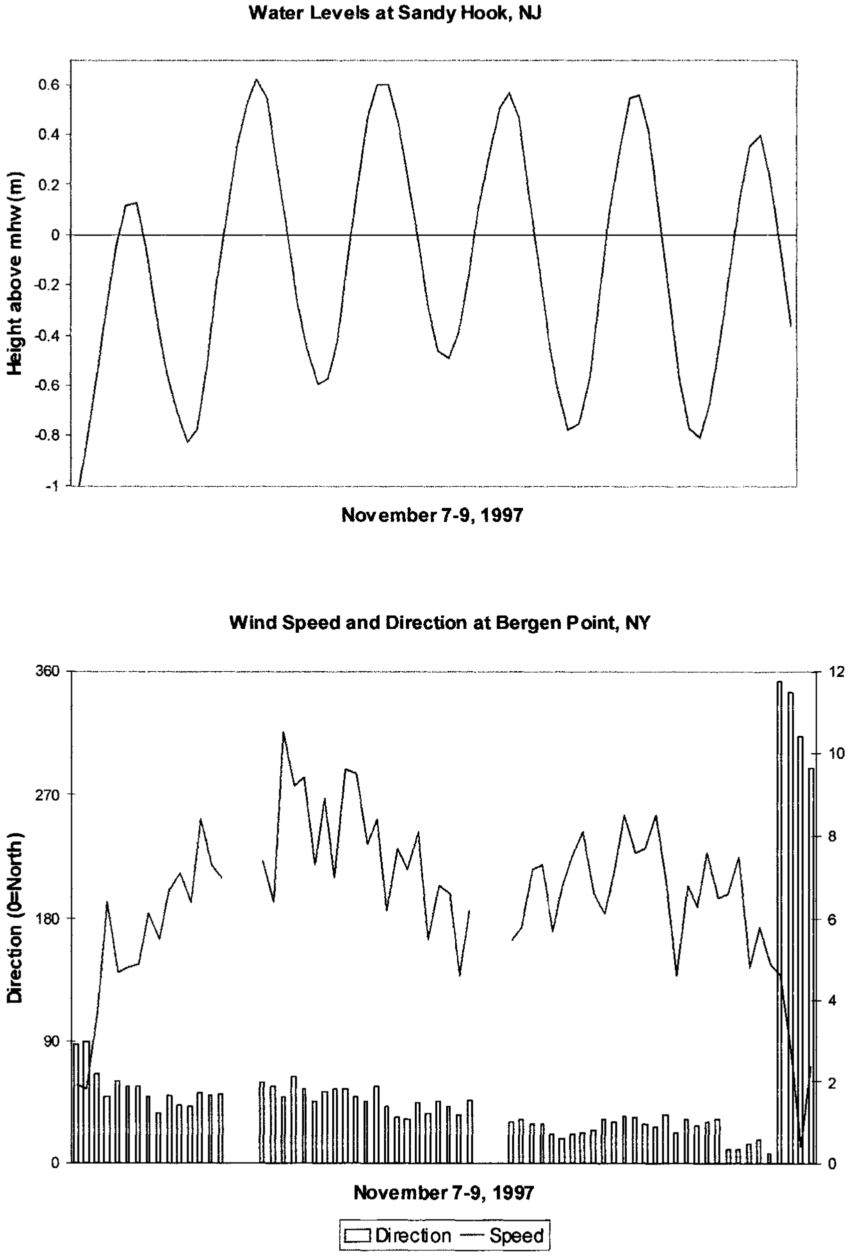


Figure 8.4 - Storm conditions for storm B based on hourly-sustained wind speeds and directions at Bergen Point, New York and water level observations from the Sandy Hook tide gage from November 7 – 9, 1997.

Water levels at Sandy Hook exceeded 0.5m mean high water for three hours with a peak of 0.647 m above mean high water, a value higher than observed at Sandy Hook for the previous storms because of spring tide conditions (Figure 8.5).

Sites 13, 18, 28 and 47 experienced the second highest water levels for this storm while water levels at the other sites ranked from 3rd through 5th (Figures 8.1a-d). Sites 13, 18 and 47 have long northeasterly fetch distances corresponding to the northeast direction of the storm winds. Astronomically high tide conditions produced high still water levels at the tide gage at Sandy Hook but the low duration of the storm winds were not effective in propagating water up the foreshore, thereby resulting in moderate water levels at most sites. High water levels were produced from this storm near Matawan Creek and at a cove (Site 14) near Whale Creek where sustained and peak winds blowing over long northerly fetches work with tidal effects.

Storm D – January 28 – 30, 1998

Storm D had hourly sustained winds of 10.8 m/s and a peak gust of 15.1 m/s which rank 4th and tied for last respectively among the five storms. The duration of moderate winds (less than 10 m/s) from the north, northeast or east was 30 hours and winds exceeding 10 m/s winds persisted for 5 consecutive hours and a total of 6 hours. The duration of wind from the north and northeast direction ranks 3rd compared to the other storms. Water levels at Sandy Hook exceeded 0.5 m mean high water for 2 to 4 hours over two tidal cycles with peak water levels of 0.589 m and 0.650 m above mean high water because of spring tide conditions (Figure 8.6).

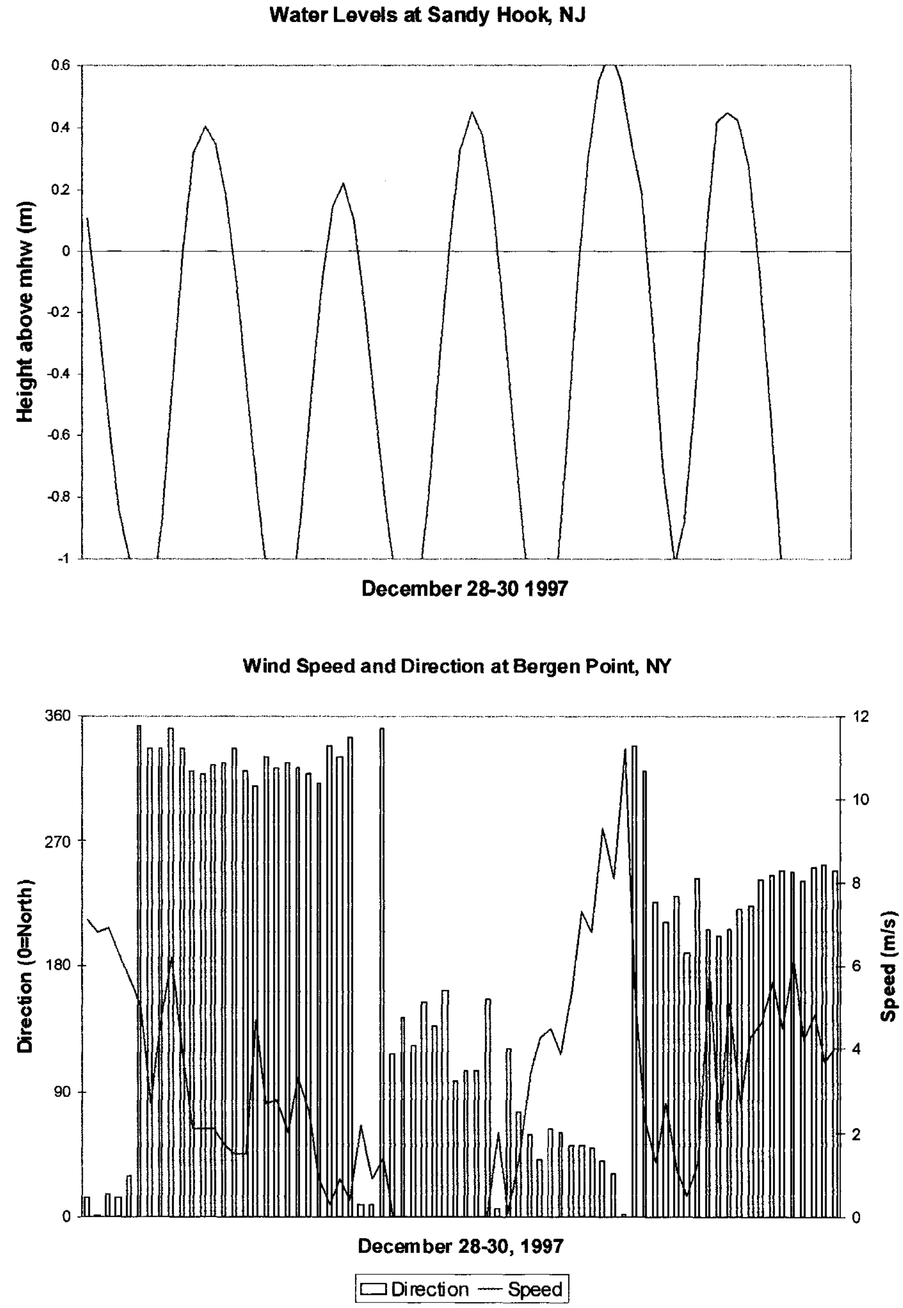
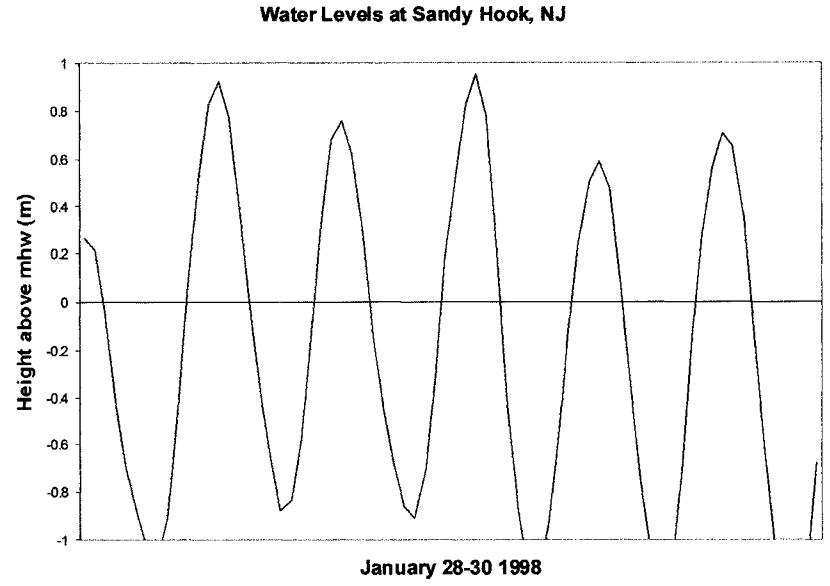


Figure 8.5 - Storm conditions for storm C based on hourly-sustained wind speeds and directions at Bergen Point, New York and water level observations from the Sandy Hook tide gage from December 28-30, 1997.



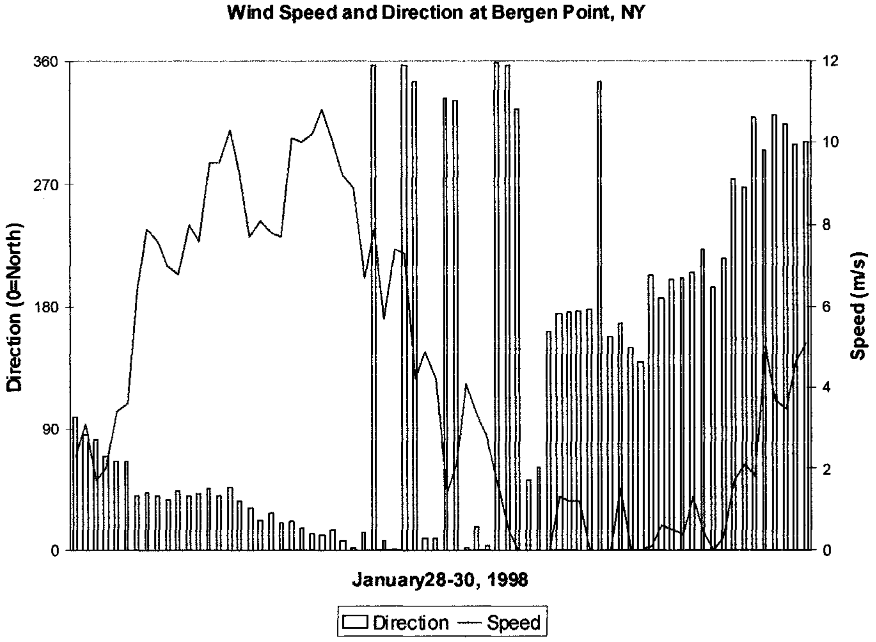


Figure 8.6 - Storm conditions for storm D based on hourly-sustained wind speeds and directions at Bergen Point, New York and water level observations from the Sandy Hook tide gage from January 28-30, 1998.

Site 25 in Cliffwood Beach, with a shoreline orientation of 79^0, experienced the highest water levels for this storm (Figure 8.1b). Sites 34 and 35 in Keyport experienced the second highest water levels while the remaining sites experienced low water levels (Figure 8.1d). Long durations of north, northeast and east winds create high levels without the highest wind speeds in Keyport. Water levels are low at sites with long, northeasterly fetch distances and wide, sandy foreshores such as Laurence Harbor, Cliffwood Beach and Union Beach. The effect of onshore characteristics on water levels at local scales is evident. Sites 25 and 34 are revetments with steep slopes and narrow foreshores that are not effective in dissipating water levels. Water levels are high at sites with steep, hard foreshores because of the long duration of winds from the north, northeast, and east and spring tide conditions. Strong onshore winds are needed to propagate water up broad, gently sloping foreshores and create high water levels at sites with wide, sandy beaches.

Storm E – February 4 – 6, 1998

Storm E had the second highest sustained hourly winds, 11.6m/s from the northeast, 43^0. Sustained hourly winds exceeded 10 m/s for a total of 7 hours during the storm, starting from the northeast, 45^0, for 3 consecutive hours but shifting to the north-northeast, 22^0. The duration of winds from the north, northeast or east, $0^0 – 90^0$, was 72 hours. Water levels at Sandy Hook exceeded 0.5m above mean high water for intervals of 4 to 5 hours over 1 ½ tidal cycles with peak water levels from 0.763 m to 0.907 m above mean high water, the highest for all observed storms, despite neap tide conditions (Figure 8.7).

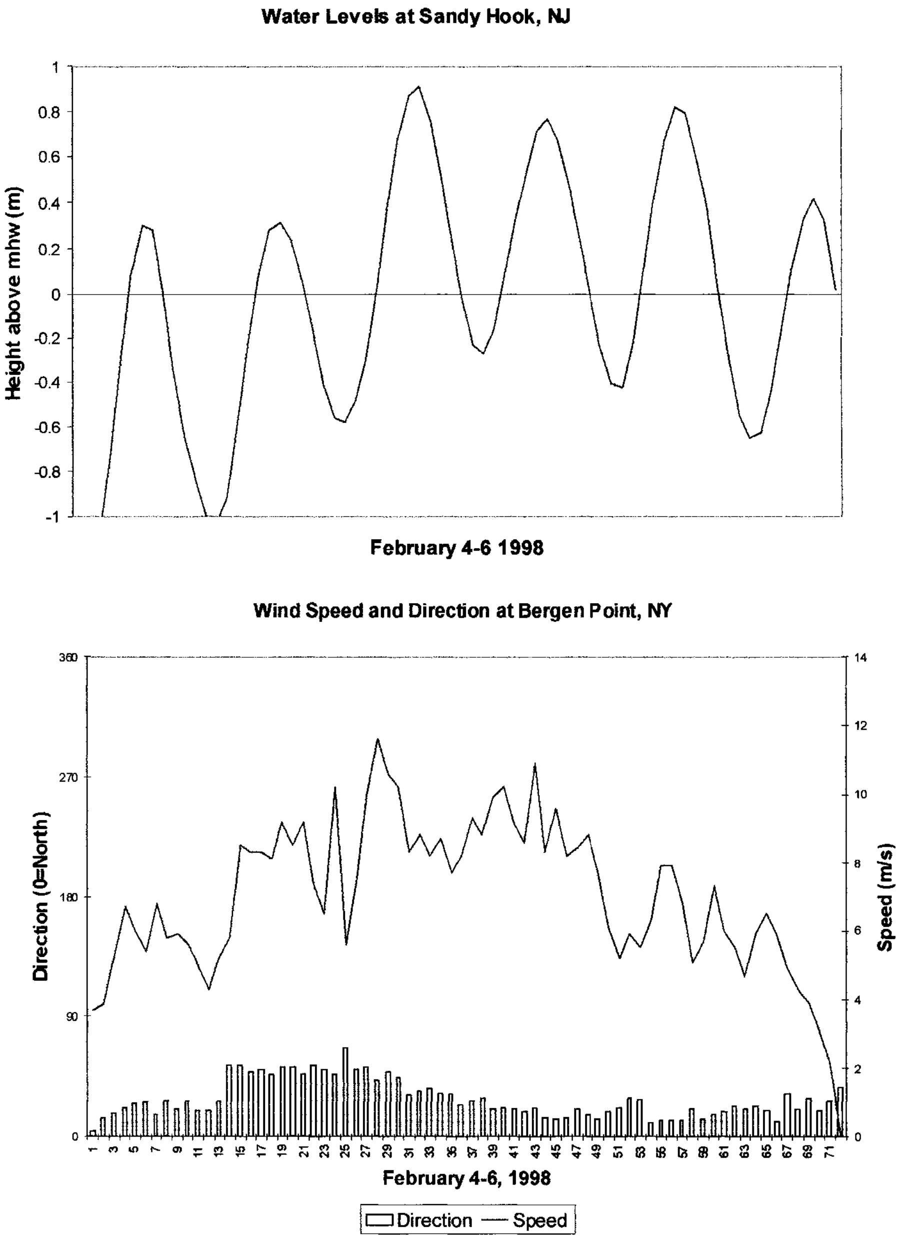


Figure 8.7 - Storm conditions for storm E based on hourly sustained wind speeds and directions at Bergen Point, New York and water level observations from the Sandy Hook tide gage from February 4-6, 1998.

Sites 28, 31.5 and 34 in Keyport and site 47 at Union Beach experienced the highest water levels for this storm (Figure 8.1c-d). Water levels at sites 3, 13, 18 and 19 from Laurence Harbor to Cliffwood Beach ranked 2nd and 3rd for all storms (Figures 8.1a-b). The combination of high wind speed and long duration (rank 2) caused high water levels at many sites despite neap tide conditions. However, the maximum sustained hourly wind over 10 m/s was only 0.4 m/s greater than that of storm C and the duration of the sustained winds only 1 hour more than storm D. Storm E had a long duration of northeasterly winds less than 10 m/s. The impact of the long duration is evident at two sites with rubble revetments, Site 9 in Laurence Harbor and Site 34 in Keyport, where water levels were higher for storm E than storm A (Figure 8.2). Sites in Union Beach had the highest water levels from storm E, but observations for storm A are not available for comparison.

Summary

The spatial variability in water levels produced by coastal storms in developed estuaries is not explainable if the complexity of storm dynamics and the intricacies of the onshore and offshore environment in estuaries are not evaluated and correlated. Theoretically, storm-caused water levels are a function of water brought into a bay by storm conditions and modified within the bay by relationships between storm conditions and onshore and offshore factors (Miller 1988). The temporal and spatial scales of these dynamic relationships have not been explored. I have demonstrated that water levels at sites are correlated to shoreline characteristics and further affected by the relationship between these characteristics and storm conditions. Storm surge results from the combination of wind speed, direction and duration but rarely would all facets line up to produce catastrophic results. Evidence of water levels in Keyport suggests that storm duration is a more critical storm condition than wind speed from a particular direction. The storms observed in this study demonstrate this problem. Some storms had high winds from directions that would build water levels in the bay, but not over a significant duration or a direction that would produce high water levels at sites. Mean water levels were highest following Storms A and E and a majority of sites had the highest water levels for one of those storms (Figure 8.2); however, the storms were markedly different. Storm A had hourly sustained winds exceeding 10 m/s primarily form the north that persisted for 14 consecutive hours with a maximum sustained hourly wind of 13.8 m/s while storm E had hourly sustained winds exceeding 10 m/s primarily from the northeast for 7 non-consecutive hours. The 14 hours of sustained storm winds during Storm A were preceded and followed by 5-10 m/s winds from the northwest, conditions not conducive to building water levels. The 7 hours of sustained storm winds during Storm E were embedded in 72 hours of weaker winds from the northeast that are conducive to building water levels.

The integration of storm conditions and shoreline characteristics is useful for evaluating indices that compare susceptibility to inundation from specific storm conditions. The index provides insight into onshore and offshore variables that reduce or increase water levels that can guide planners and scientists when they consider development or shoreline protection strategies. The evaluation of water levels and storm conditions in this chapter support the storm inundation indices in Chapter 7. Sites with steep, hard structures on the foreshore had high water levels from storms with long durations but not with the highest winds.

Five moderate storms do not provide a definitive conclusion for all possible storm condition scenarios. Water levels were highest at many sites in Reaches 1 2,3 and 5, for Storm A, the storm with the highest wind speed from the north-northeast (Figures 8.2 and 8.3). Storm A had the longest duration of winds exceeding 10 m/s, but other storms had longer durations of weaker winds from the north, northeast or east. Storm E produced the highest water levels at the sites in Reach 4 where between-storm variability was observed. Storm E had weaker sustained hourly wind speeds than Storm A, but had a longer duration of winds less than 10 m/s from the north-northeast and northeast winds. The highest water levels overall in the study area were produced by storms that occurred during moderate neap tide conditions, substantiating the fact that onshore winds are critical for the propagation of waves and water levels on the foreshore. Storm A did not produce the highest water levels at the Sandy Hook tide gage, reaching 0.6 m above mean high water and lasting only one tidal cycle. Tidal effects are obvious in elevated water level observations at sites with offshore factors that limit the influence of storm winds and have onshore characteristics that do not dissipate wave energy.

Coastal studies have incorporated storm parameters in the context of hazards research through derivations of wave power indices (Dolan and Davis 1992) and more qualitatively as a function of duration (Halsey 1986). No attempts have been made to incorporate storm conditions with spatial variability in water level observations and the susceptibility of the shoreline to inundation. The assessment of storm conditions in this chapter indicates that astronomical effects alone do not explain variability in water levels.

The results in this chapter support a relationship between storm wind speed, duration, and direction and shoreline characteristics in producing water levels. Water levels are highest at most sites for storms with high wind speeds and long durations, Storms A & E (Figure 8.2). However, water levels are highest at some sites from storms with weaker wind speeds. The variability in water levels is attributed to the onshore and offshore variables used in the storm inundation indices. Broad, sandy beaches reduce the susceptibility of sites to inundation from storms with high wind speeds. Hard, vertical shoreline protection structures increase the susceptibility of sites to inundation from storms with more persistent but lesser wind speeds.

The potential for incorporating wind speed, duration and direction into a GIS is limited by the temporal variability of the storm parameters. Critical storm wind conditions can be examined using a 72-hour graphic analysis and this graph linked to a GIS. The intensity and duration of peak storm winds and strong winds from directions favorable to building water levels are clearly identifiable. However, the incorporation of the graphic illustration is limited because water levels did not vary between-storms for all sites (Sites labeled "X" in Figure 8.2). GIS can be used to identify the storm that produced the highest water level at a site and the storm conditions associated within the resulting water level. GIS provides a tool for storage and analysis of many more storm wind directions, speeds and durations (attributes); however, only five storm events were observed during the field study in this dissertation.

IX – Conclusions and Implications

The results of this dissertation reveal that in a developed estuary: 1. spatial variability in water levels can be observed at local scales; 2. shoreline characteristics, described and quantified from onshore and offshore variables, may be correlated to water level observations; 3. a susceptibility index formulated using GIS can successfully compare potential and actual inundation; and 4. water level observations may be influenced by different shoreline protection measures. These results lead to conclusions about the evaluation of storm impacts and implications to geographic and coastal hazards research.

1. The establishment of a storm surge penetration line appears to be critical for coastal management.

The water level observations in this dissertation are not used explicitly as a flood line because the storms observed were moderate, resulting in water levels contained by the foreshore and backshore and not propagating inland far enough to reach cultural features. While a storm surge penetration line is a critical need for coastal management (Dolan et al. 1978a), it is not always obvious or identifiable after individual storms. Linear wrack lines were not obvious at marshes, where debris is dispersed throughout marshes by inundation from the bay in conjunction with water flowing in tidal creeks that dissect the marsh. The deposition of wrack in the marsh is more a function of the natural traps that collect debris in horizontal flows than a function of vertical elevation of inundation from storm surge and wave run-up. Wrack lines at sites with hard, vertical structures, like seawalls, are deposited either at the base of the structure or on structural platforms. Wrack lines at sites with these structures represent a minimum water level but may not represent the actual water level. Storm surge and wave run-up from the moderate storms observed in this dissertation did not produce overtopping at sites with hard vertical structures. The ability to evaluate variability between moderate storms at sites with hard, vertical structures is limited because the wrack is confined by the structure and is deposited at the same elevation for the observed storms.

My study quantified the spatial extent of inundation on the foreshore and the elevation of water levels. Evaluating elevation is important because coastal managers working in developed estuaries will encounter hard, vertical structures that effectively prevent inundation. Wave run-up and the storm penetration lines may not be obvious or identifiable at all sites in developed estuaries because vertical structures truncate the foreshore or marshes disperse wrack widely. There are locations that can be identified a priori by coastal managers where storm surge penetration is visible, such as along sites with beaches and dunes, and the elevation of inundation on cross-shore transect profiles should be quantified at these sites following major storms. Studies have identified water lines on ocean beach environments (Leatherman 1983, Dolan and Hayden 1981; 1993, Fletcher et al. 1995, Pajak and Leatherman 2002, Doornkamp 1998), but there are no current standards for post-storm reconnaissance and quantifying water levels in estuaries.

Standards should include establishing a local sub-datum referenced to a standard datum that can be used to compare elevations across large areas. Monitoring foreshore change on estuarine beaches following storms (as in Armbruster et al. 1995) is not as critical as evaluating water levels relative to a sub-datum, because not all estuarine beaches will exhibit geomorphic change from a single storm (Ekwurzel 1990). Wrack deposits are effective as a storm surge penetration line at sites where the shore is broad and sandy. The elevation of wrack lines should be determined using a sampling interval of hundreds of meters on sandy shorelines and geo-referenced for use in GIS to create timely maps of post-storm water levels. Coastal managers should consider the use of water level elevations for assessing inundation at built sites in developed estuaries. Pressure transducers or video photogrammetry should be used to evaluate the elevation of water levels at sites with marsh or hard, vertical structures. Data partnerships should be established between municipalities for sharing time, equipment, expenses and knowledge.

2. More effective response or mitigation requires a detailed understanding of the relationship between physical processes and human response.

No real hazard mitigation can take place outside federal and state legal constraints. Flood hazard information in individual legislative acts in the United States and in New Jersey is critical to the assessment of coastal storm flood impacts because this information sets response and mitigation in motion. However, no one piece of legislation at any government level adequately addresses the spatial variability of inundation from coastal storms along estuarine shorelines. Variability in water level observations between sites is related to shoreline type and orientation and these variables have been documented in studies of physical processes and estuarine shoreline geomorphology (Phillips 1986; Jackson 1995). The relationship between the physical processes and human response has not been documented. Higher water levels are observed at sites with hard, vertical structures than at sites with artificial beaches and dunes or marsh within and across reaches. High water levels at sites with hard, vertical structures occur during storms with moderate wind speeds but long durations. Wetlands and marshes across multiple, adjacent sites in Keyport and at individual sites in Laurence Harbor, Cliffwood Beach and Union Beach have the lowest water levels and the lowest storm inundation classification. High water levels at sites with beaches only occur during storms with high-sustained wind speeds and long durations. Hard structures are commonly used in developed estuaries, but soft practices, such as beach nourishment or maintaining natural estuarine shores like marshes, are more beneficial, as indicated in previous studies (Trembanis and Pilkey 1998; Pethick 2002). The onshore characteristics of marshes and beaches reduce water levels and these alternatives therefore should be the preferred coastal management practice. Both of these alternatives require space to form, survive, and achieve their protective functions, indicating that the horizontal, as well as the vertical dimension, is critical in achieving protection from storm inundation.

3. The spatial scales used for mitigation are not the same as the scales of the physical processes that cause elevated water levels.

The legislation and policies in the United States that focus on coastal zone management and flood hazard mitigation have been developed at broad scales (federal and state) and then applied at local scales (municipality). Spatial variability in susceptibility to flooding has been identified on coastal hazard maps at broad scales (barrier islands, estuary) (Gornitz et al 1994; Anders, Kimball, and Dolan 1985), but policy is not implemented at broad scales. Spatial variability has not been identified on maps at local scales such as within a singular landform (beaches, marsh) but policy is implemented across many different spatial scales at this level. Broad scale coastal policies, such as the New Jersey Shore Protection Management Plan exist, but individual plans of different scales (single lot, municipality) are conditionally acceptable on a case-by-case level. Implementation of the Shore Protection Management Plan is problematic because the orientation of the shoreline of Raritan Bay is highly irregular and the onshore and offshore characteristics are variable at local scales. For example, rip-rap revetments, loosely placed large pieces of rock, are commonly used as a contingency plan to protect small stretches of the shoreline of Raritan Bay (NJDEP 1985). Seven sites in the study area are buffered by rip-rap revetments as a means of shoreline stabilization. Rip-rap revetments placed in Laurence Harbor consist of large boulders or steel reinforced concrete creating an unattractive and poorly connected means of shoreline protection. My data provide a better indicator of current mitigation strategies because it consists of water level and shoreline information gathered at sites 200 m apart that is closer to the lot scale where the strategies are implemented. This site level information is set in a study area divided by four municipalities that also employ shoreline protection strategies that are longer than 200 m (e.g. seawall in Cliffwood Beach). The sites and transects in my analysis were represented by points, but tools in the GIS allow lines to be snapped to points to create a continuous shoreline that distinguishes different types and structures (Figure 9.1).

The water level observations and onshore and offshore data collected in the study area describe numerous lots within 4 municipalities in a developed estuary. A 200 m interval has been documented in this dissertation as sufficient for a site-specific storm inundation analysis. My study illustrates the need for coastal municipalities to begin a process of quantifying post-storm water levels at local sites (beaches, backyards that abut the water, streets) to understand the spatial variability in water levels associated with specific physical processes. The derivation of a storm inundation index is not contingent

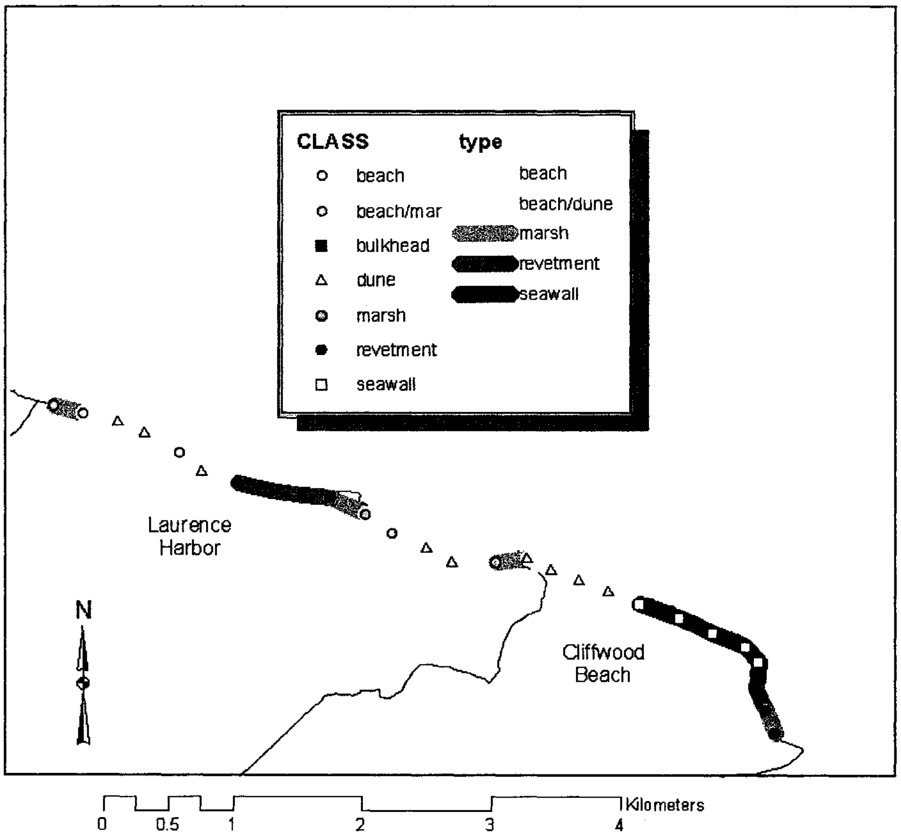


Figure 9.1 – Shoreline types for Sites 1-27(from Laurence Harbor to Cliffwood Beach) identified as points with a continuous shoreline created by snapping lines between points in Arcview.

upon using spatially contiguous shoreline data (raster data). Raster data has been used in relating FEMA flood zones to digital elevation models (Dobosiewicz 2001) and in studies of river flooding using NEXRAD precipitation data with elevation models to simulate flood hydrographs (Bedient and Huber 2002). Previous works such as the US Coastal Hazards Database use vector data. Future studies may expand on the use of post-storm data collection and conversion into vector data and GIS in this dissertation by incorporating raster data for 3-D analysis and to develop real-time coastal hazard monitoring.

4. Site-specific post storm data is not frequently collected and used for policy-making in the United States.

The purpose of the field component of this study was to collect detailed site-specific onshore and offshore data and water level observations referenced to a standard datum. Previous works simply apply a single 100-year flood elevation throughout all of Raritan Bay. My study identifies good and bad practices in shoreline protection within FEMA V zones (which means the elevations are lower than the 100-year flood elevation and wave velocity is a factor) (Figure 9.2). Water level observations and the susceptibility of sites to inundation vary, but every site in the entire study area is within the FEMA V-zone. FEMA needs to address site-specific variability and the impact of shoreline structures on water levels and actual inundation. The local scale data collected at field sites in this dissertation and converted to digital format is suited for implementation in FEMA V zones through the use of additional computer program and GIS. Conceivably, storm conditions of such great magnitude could occur that would produce catastrophic water levels throughout the entire bay, and the spatial variability of

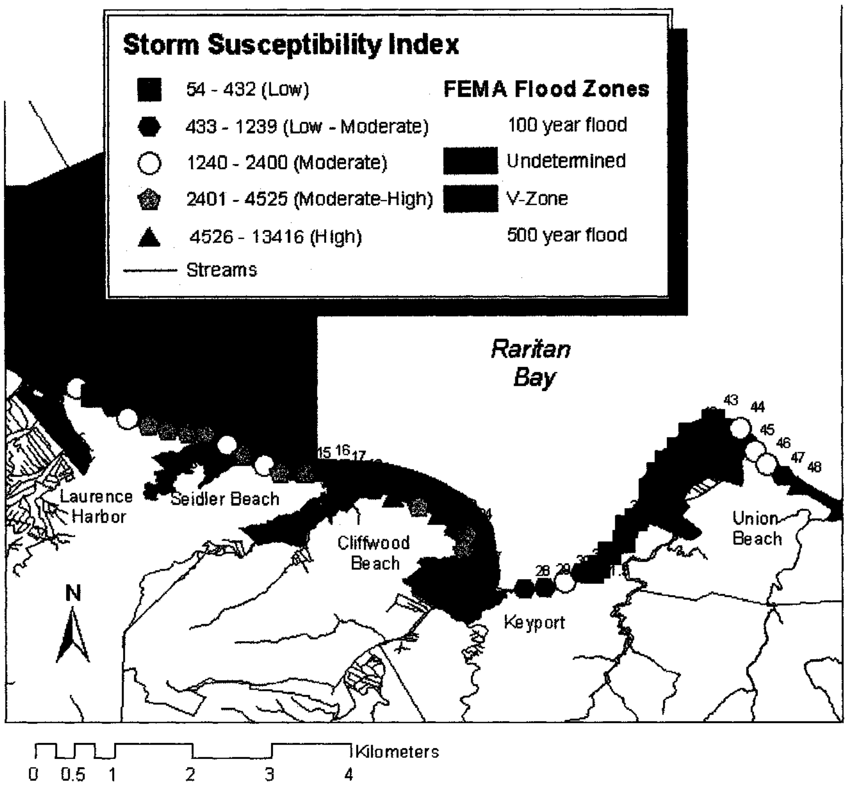


Figure 9.2 – Variability in the susceptibility of sites to inundation from coastal storms within FEMA V zones.

those water levels would be negligible in the foreshore. However, it is not evident how variability in the onshore and offshore characteristics of the shoreline at local scales would affect inundation from smaller storms because FEMA and NJDEP flood zone maps only use a single elevation criterion. My study supports FEMA and NJDEP initiatives to consider local scale onshore and offshore characteristics in flood zone analysis and shows how these characteristics affect inundation during non-catastrophic storms. For example, my correlation of offshore variables to water level observations suggests that fetch distance perpendicular to shoreline orientation at individual sites may not be as important as a maximum fetch from a direction that may be within 45^0 of perpendicular and also in the same direction as sustained storm winds (Figure 9.3).

Storms with similar magnitudes of wind conditions produce significant variability in water levels at sites with graded foreshore profiles, like beaches. Detailed foreshore characteristics are not currently a part of flood zone policy-making. Arcview is a user friendly desktop GIS that provides a suite of statistical methods for classifying, mapping and analyzing site-specific digital data collected at field sites. Hyperlinks in Arcview GIS allow the interactive display of a graphic foreshore profile for each site in the FEMA V zone (Figure 9.4). The “Hot Link” tool in Arcview GIS v3.2 was used to help report post-storm reconnaissance of damage from Hurricane Lenny in St. Croix and convey the report to the local officials (Weberg, Hatheway, and Pitts 2003). Current flood zone assessment and shoreline management, that currently operate at local scales but follow broad scale principles, would be better facilitated through the use of site-specific data that have been correlated to actual water level observations.

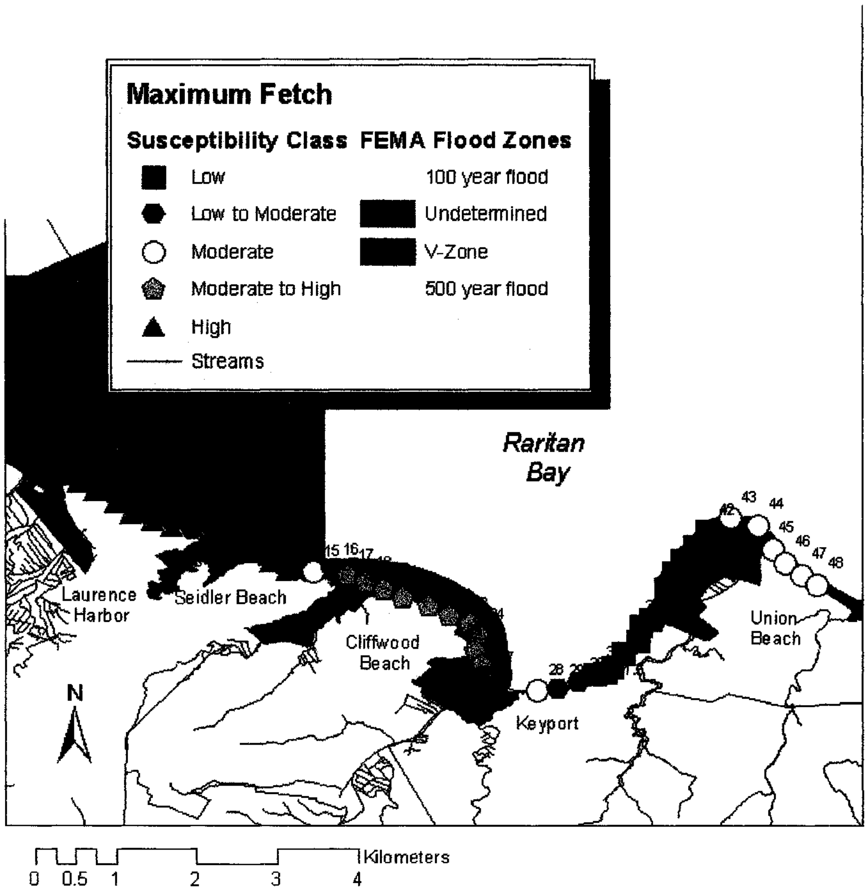


Figure 9.3 – Susceptibility of sites to storm inundation based on maximum fetch within 45^0 window of transect azimuth compared to FEMA Q3 1% probability flood zones (digital data from FEMA 1996).

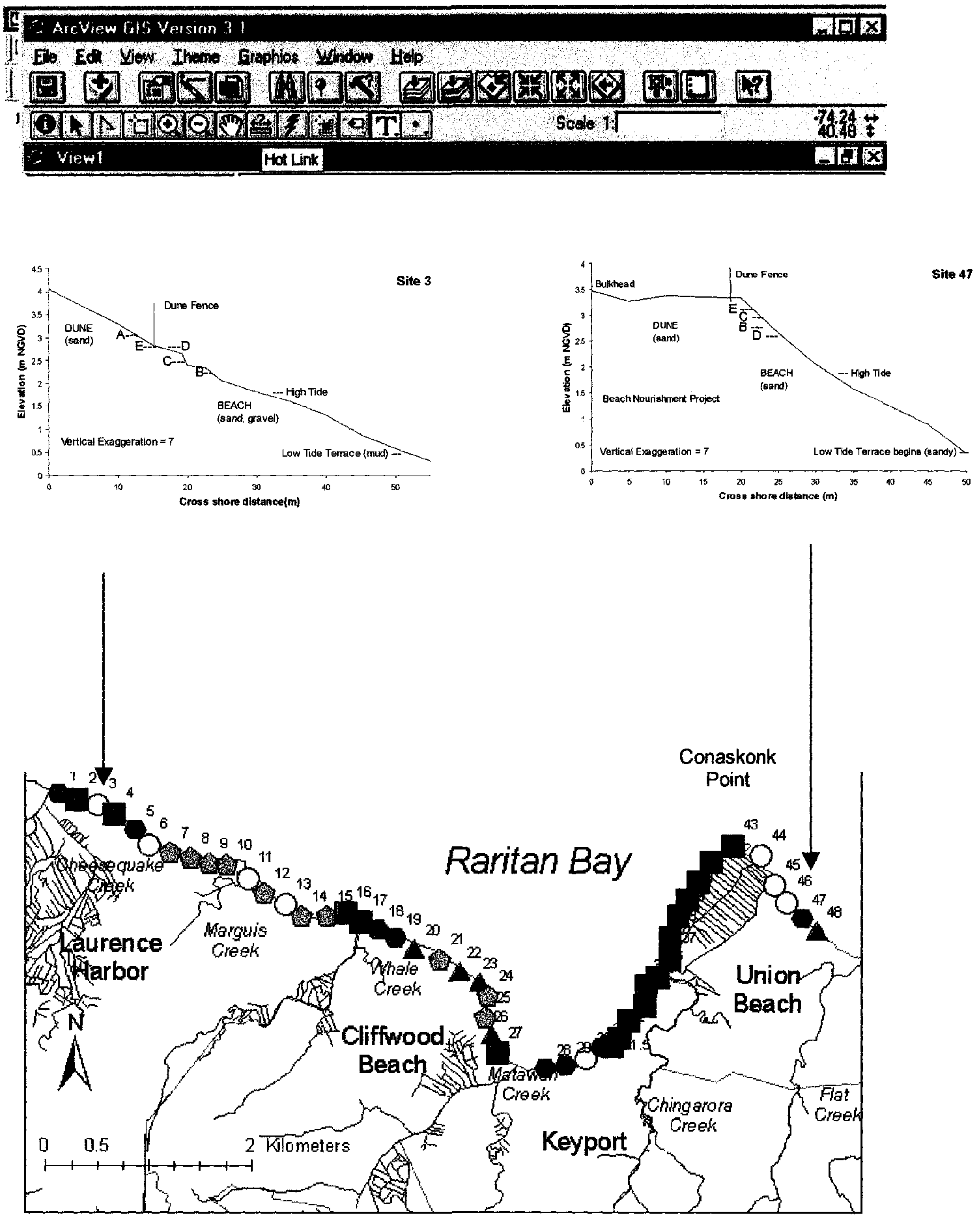


Figure 9.4 – Hyperlinks in Arcview GIS(called "Hot Links" in Arcview 3.x) allow other types of digital data to be accessed through the GIS with a tool button. Cross-shore profiles created in Microsoft EXCEL™ with the locations of storm water levels identified to the storm inundation index at selected sites.

5. Structures are not adequately identified in existing digital data sets.

NJDEP digital data sets that describe shoreline structures and types (www.state.nj.us/dep) lack sufficient detail. The data set has "NO DATA" for the shoreline in Laurence Harbor in Middlesex County. Monmouth County has data but many structures are missing, most notably a massive seawall in Cliffwood Beach which is categorized as beach (Figure 9.5). All seven revetments in my study area are missing. Keyport is categorized as erodable, earthen dike and beach while my study reveals extreme variability at local scales with small seawalls, bulkheads, revetments, pocket beaches and large expanses of marsh (Figures 9.6 and 9.7). The distribution of groins and dunes is represented well but the NJDEP data lacks any other information on these features such as profile elevations or composition.

Hard structures may actually expose more people to coastal hazards because the implementation of a hard structure tends to lessen the risk perceived by people (West and Dowlatabadi 1999). Flood defense measures, in general, may be responsible for increasing coastal flood vulnerability (Doornkamp 1998). There is no evidence to suggest that structures along the Raritan Bay shoreline would contain water levels for larger storms than those observed in this dissertation. My results indicate that water levels are highest at sites with hard structures like bulkheads, revetments and seawalls. These structures are poorly represented in digital data sets. Furthermore, local scale variability has not been considered in technocratic shoreline management practice because seawalls, bulkheads and dunes are just as high in Laurence Harbor as in Cliffwood Beach, Keyport and Union Beach, although inundation levels differ.

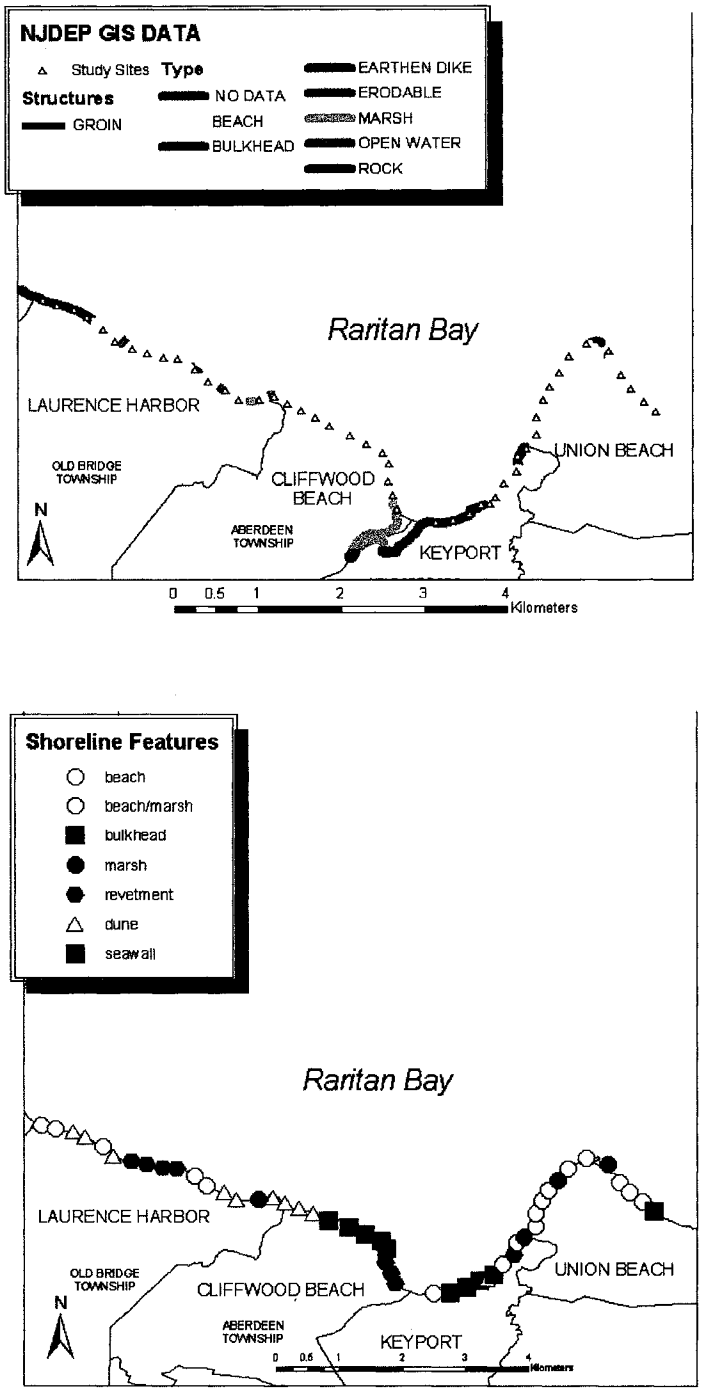


Figure 9.5 – Comparison of NJDEP shoreline types and structures (top) and shoreline types at the field sites in the study area (bottom).

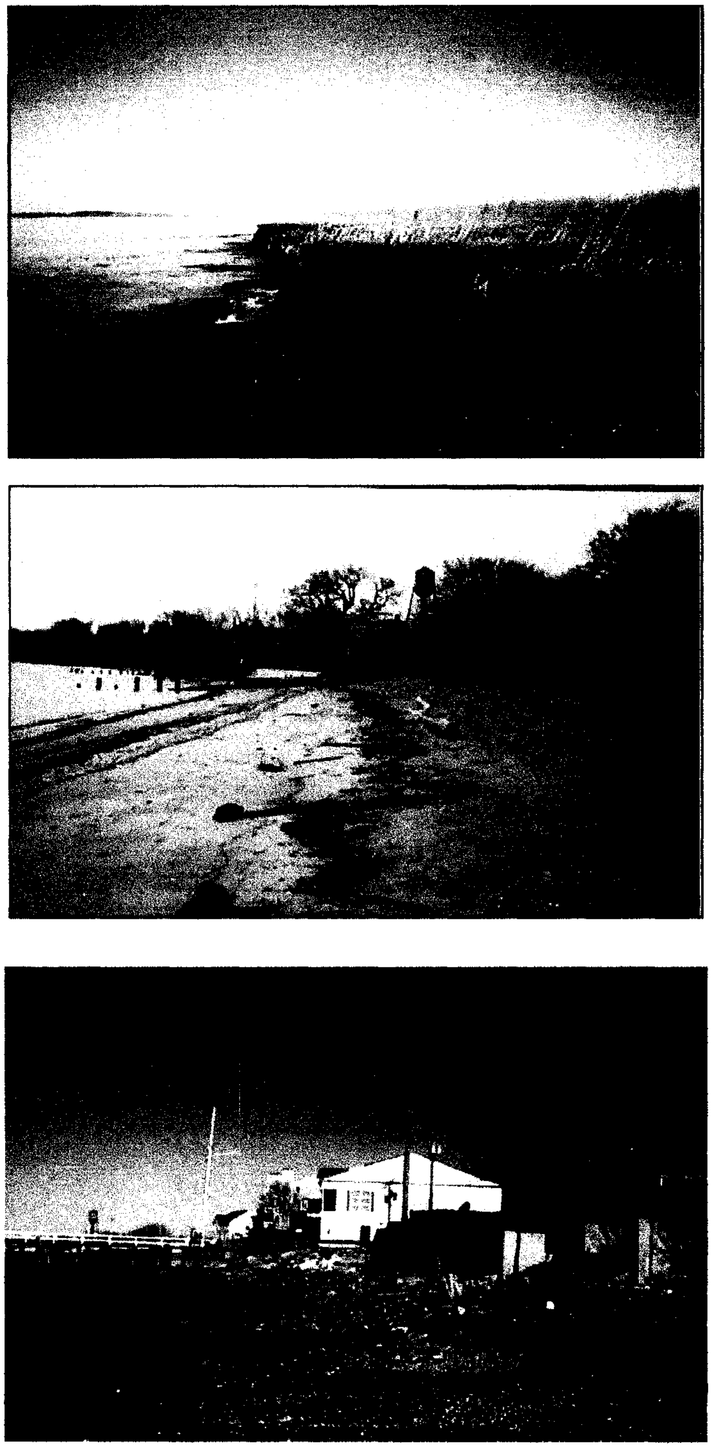


Figure 9.6 – Local-scale variability in shoreline type and structures in Keyport. Marsh (top), natural beach (middle) and seawalls and bulkheads (bottom).

Figure 9.7 – Local scale variability in shoreline structures in Keyport. Small cement and steel vertical structures placed in the foreshore at different lots (top) and a larger bulkhead placed in front of a memorial park (bottom).

6. Indices used to assess risk and vulnerability along the coast need to be evaluated based on performance after storms.

The storm inundation index is derived from detailed onshore characteristics that include soft and hard practices, making it suitable for integration into current policy. My index discriminates many shoreline types, and the onshore and offshore characteristics have been correlated to water levels and related to storm conditions. Other indices (Anders, Kimball, and Dolan 1985; Gornitz et al. 1994) are too broad for affecting policy at local scales and thus perpetuate the use of a single flood zone elevation for an entire bay in decision-making. Furthermore, my storm inundation index is determined from verified relationships between the variables used in the index and actual storm-caused water levels. Other indices (Anders, Kimball, and Dolan 1985; Gornitz et al. 1994) are based on variables that are only theoretically important and described in broad terms such as geology, geomorphology, elevation, wave height and storm surge height that are quantified too generally for site-specific implementation and verification and do not explicitly address the needs on developed shores.

Storm inundation indices are used in this dissertation to evaluate potential inundation, from storm and shoreline parameters, and actual inundation, from onshore characteristics and storm and shoreline parameters. Comparison of the indices provides for gauging human impacts since the characteristics of the shore are determined predominantly from human alterations consisting of hard and soft shoreline protection structures. These comparisons indicate that rubble revetments, such as in Laurence Harbor, increase water levels and the actual inundation may be more than potential inundation because of the position and characteristics of the revetment on the foreshore.

Water levels are low at sites with either marsh, broad sandy beaches with berm development or a combination of beach and marsh, despite many of these sites having long fetch distances favorable to storm surge propagation. Other indices only use an average elevation of the shoreline and would classify sites with nourished beaches in the same class as sites with revetments.

GIS for Local Scale Coastal Hazard Assessment

The statistical methods used in Arcview GIS to classify each variable did not affect the susceptibility categories. Other indices (Gornitz et al. 1994) use only quantile classification techniques, a simple statistical method based on percent groupings. GIS can be used to portray the digital coastal hazard database by Gornitz et al. 1994., but GIS was not used to assign the vulnerability class for each variable in that database. My results suggest that GIS is not only useful for mapping digital data but also provides fast and effective tools for analyzing data using statistical techniques (such as natural breaks) that better classify variables and subsequent indices based on these variables.

The South Carolina pilot study in the national initiative is designed to collect and archive a multitude of coastal characteristics to be used for GIS-based coastal change assessment. Beach profiles are to be obtained for every kilometer of shoreline. A one km sampling interval has been demonstrated as effective for evaluating spatial variability along ocean barrier islands (Dolan, Fenster, and Holme 1992). Shoreline types are labeled every kilometer in Galveston Bay in the Texas Coastal Hazards Atlas (see Figure 1.3 in Chapter 1). Geomorphic change can vary across a spatial scale of as little as 100 m along estuarine shores (Phillips 1986). My research indicates that spatial variability exists in water level observations at sites 200 m apart. The national initiative and other coastal hazard atlases should consider using a finer sampling interval for profiling estuarine shores than for ocean shores.

Future Trends for Digital Data Integration in Coastal Research

Future trends in coastal research emphasize the need for collecting detailed coastal information and integrating new data with pre-existing data in digital format and using GIS to provide solutions to problems threatening the coast (Friel 2003). The onshore and offshore variables and storm inundation indices in this dissertation are stored in digital format that can be integrated with other data using GIS. The results and conclusions fit in the context of using digital data in coastal hazard research (Wright and Bartlett 2000). My digital data sets are available on-line at http://hurri.kean.edu. Technology such as satellite imagery for wetland delineation, airborne LIDAR and aerial photography for beach and shoreline mapping and differential Global Positioning Systems for gathering topographic information are expensive and limited in temporal and spatial scale. Data sets derived from remote sensing techniques may proliferate in some government and private sectors but the detailed local scale data that provides the ground truth for these technologies is lacking.

Future trends emphasize the need to integrate detailed local scale data with current models through GIS. The FEMA Coastal Hazard Analysis Modeling Program (CHAMP) is designed to use detailed transect information, offshore characteristics and wave parameters to predict flood zones along Atlantic and Gulf Coast shorelines. Future studies are considering detailed digital data for assessing coastal hazards in FEMA V-zones, the coastal component of the NFIP (Miglarese et al. 2003), and more seamless connections between programs like CHAMP and Arcview GIS (Smith and Pitts 2003).

The future of this research will consist of defining the alongshore and cross-shore boundaries of the shoreline protection structures in the study area using an inexpensive GPS. This research will be expanded to include shore perpendicular groins and remnants of docks and piers. Modern navigation technology boasts accuracy of less than 3 m for geographic coordinates (but accuracies of 5-15 m are definitive) determined using a WAAS (Wide Area Augmentation System) capable GPS (cost ≈ $200). A more accurate map of the boundaries of each structure in GIS integrated with other coastal information will assist in coastal planning.

High quality elevation models are becoming more accessible. New Jersey has free and downloadable 10 m grid digital elevation models (DEMs) at a watershed scale. 10 m grids are too coarse to represent a shoreline but would be useful for 100-year flood zones (Figure 9.8). My previous study identified roads in flood zones based on elevations from a 30 m DEM but an elevation higher than the historical 100-year flood elevation had to be used in the DEM to achieve the best results in some areas (Dobosiewicz 2001). I have constructed a three-dimensional model for a part of the shoreline in my study area using a TIN (Triangulated Irregular Network) model to approximate terrain by creating triangles from point elevations. My data consists of elevations determined alongshore at 200 m intervals and cross-shore along transects at 5 m intervals. The resulting TIN consists of oblique triangles alongshore resulting in angular contours alongshore. Shoreline features are identifiable on the TIN created for Seidler Beach to Cliffwood Beach (Figure 9.9). The results of my study will be made available to coastal county and municipalities to develop a coastal database that accurately represents the spatial variability in water levels and onshore and offshore characteristics along New Jersey shoreline including protection structures. This dissertation identifies a methodology that should be in place for municipalities to be better prepared for quantifying inundation and assessing damage from severe storms in the future.

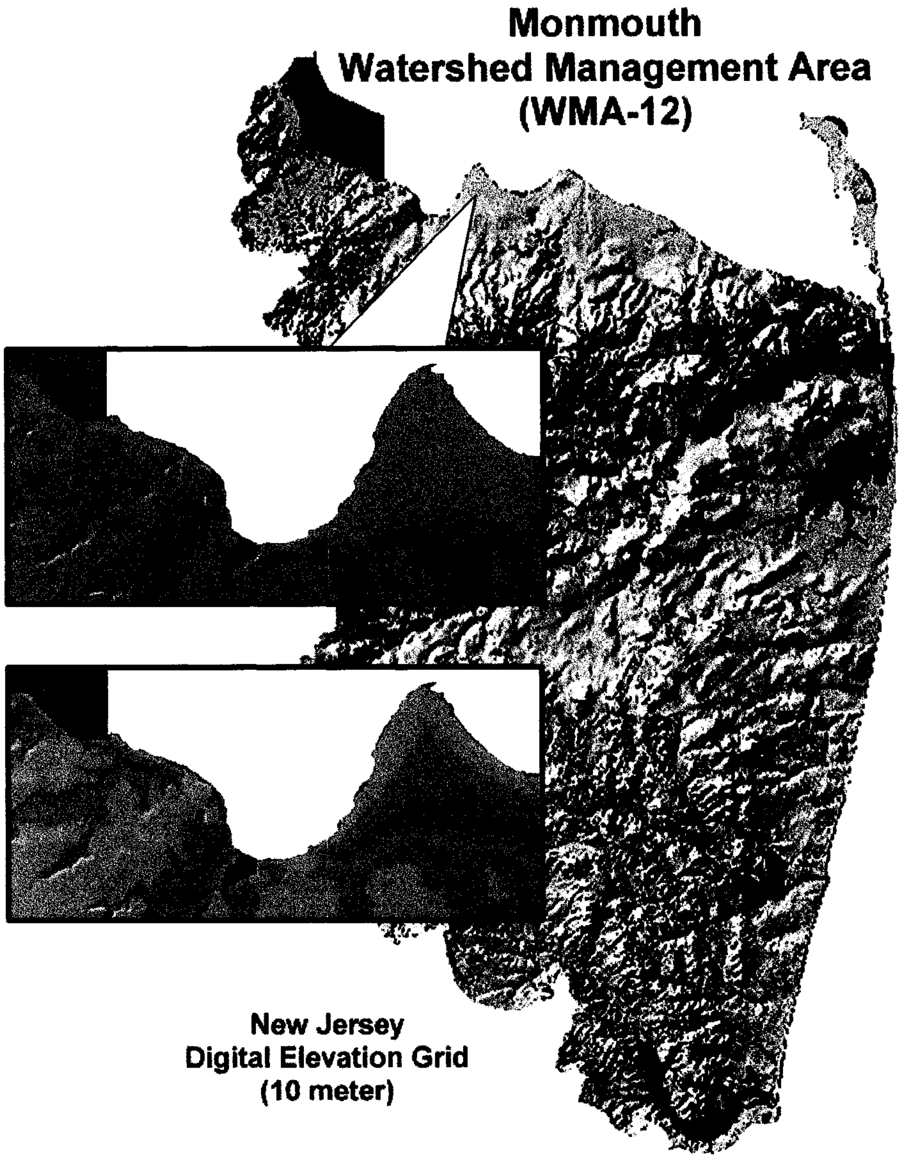


Figure 9.8 – Digital Elevation Model for the Monmouth Watershed Management Area in New Jersey with a grid size of 10 m available from NJDEP (www.state.nj.us/dep/gis). The top inset is a shaded relief map using a 5' interval up to 40' and the bottom inset is a 2' shaded relief map up to 20' for the study area.

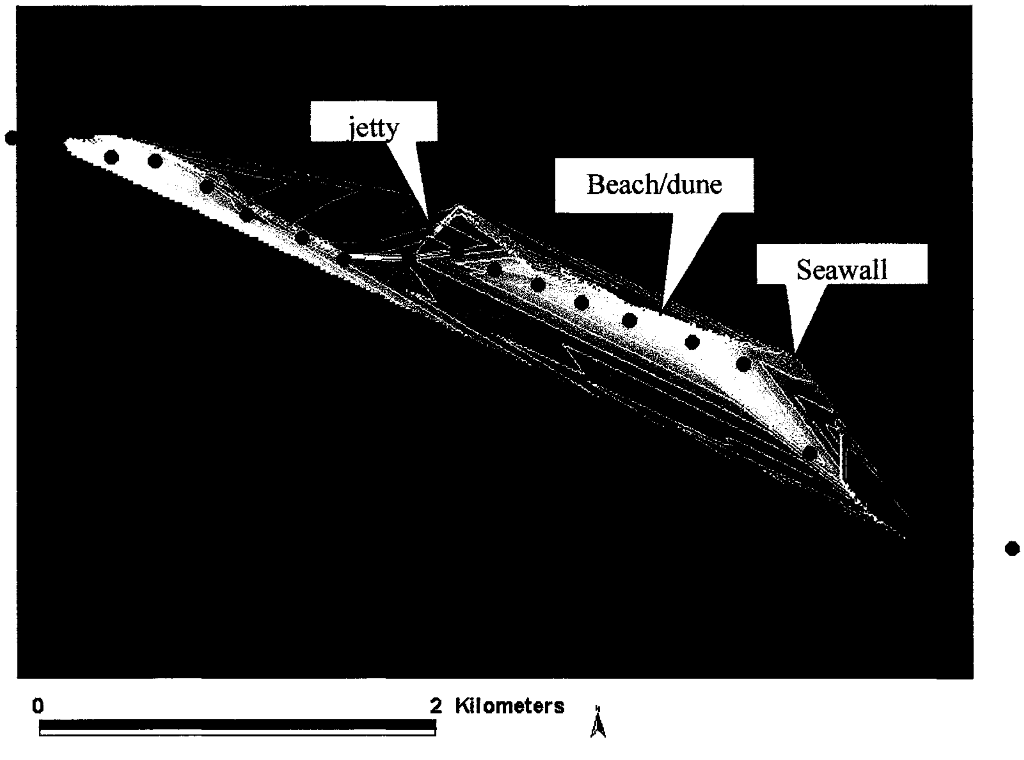
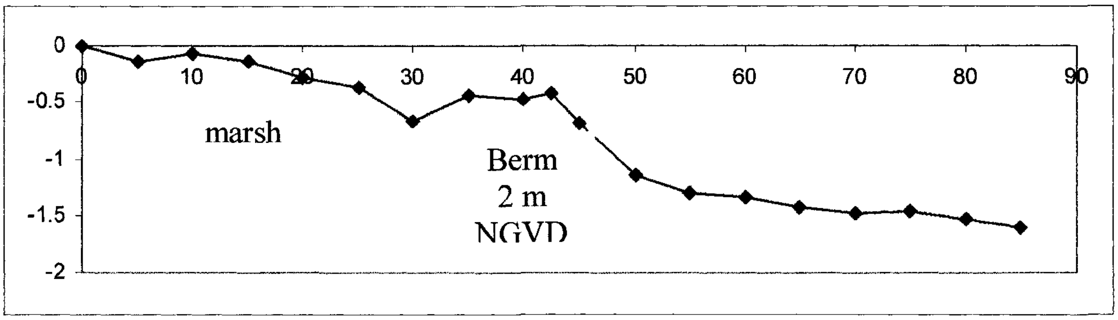


Figure 9.9 – Terrain approximation from Seidler Beach to Cliffwood Beach using TIN model. Contour lines in yellow at a 0.5 m interval (angular shape is a function of the TIN model which is based on triangulation). The location of the sub-datum for each site is represented by blue points.

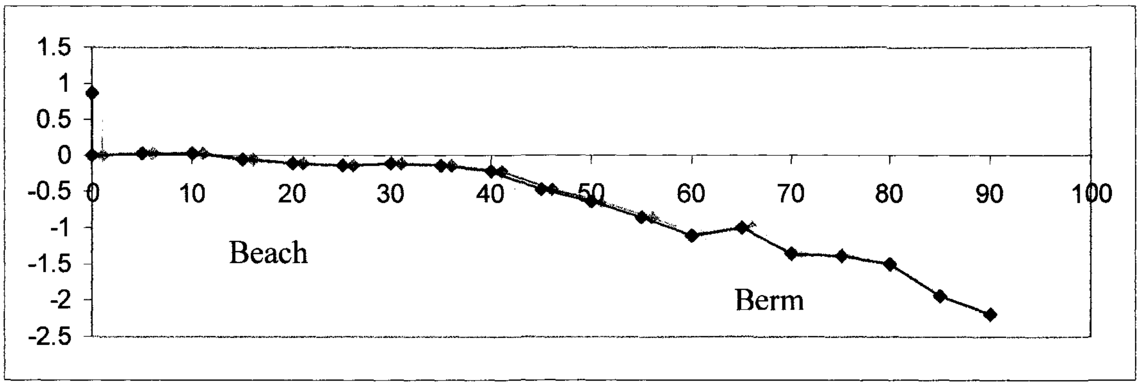
Appendix

Profiles and sub-datum elevations for all field sites (elevations and distances in meters). Transect = the azimuth of the cross-shore profile in degrees from true north (0°)

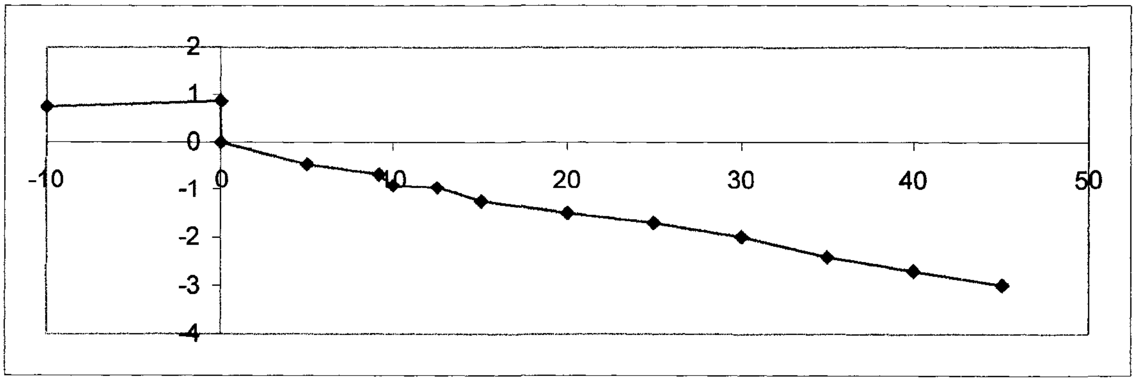
Site 1 transect=30 Bm on bridge=12.88m NGVD 1929
Subdatum= "M" on manhole cover bm-10.588 0= 2.292 m NGVD 1929



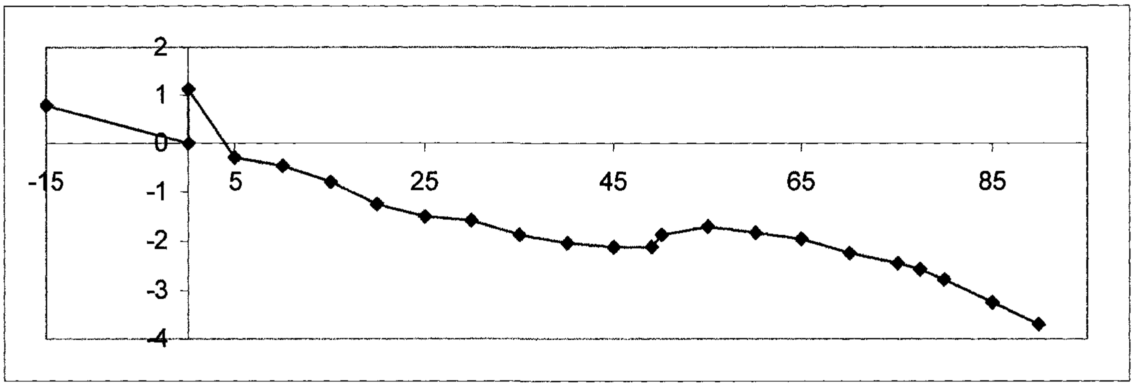
Site 2 transect=21
Subdatum=post in gerrity's tie in=+1.268 0 = 2.694 m NGVD 1929



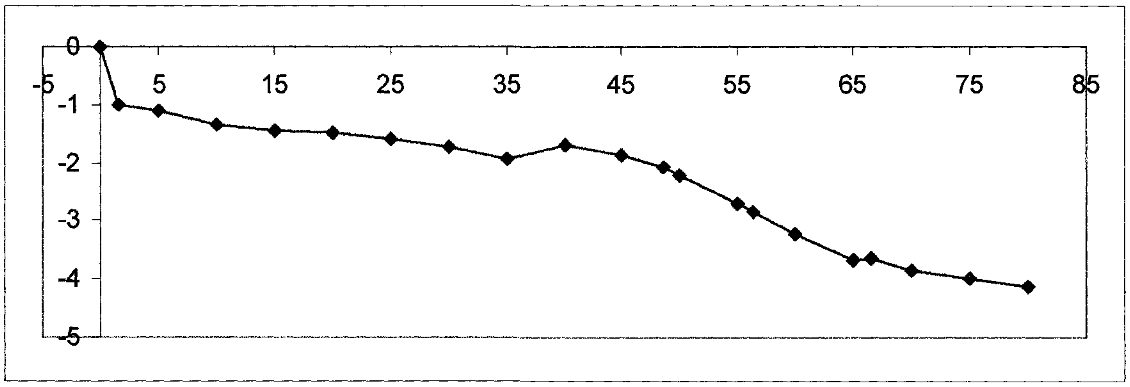
Site 3 transect=29 tie in=+1.873
Subdatum=dune fence post 10th post from right in front of tree burgundy house to left
0=3.304 m NGVD 1929



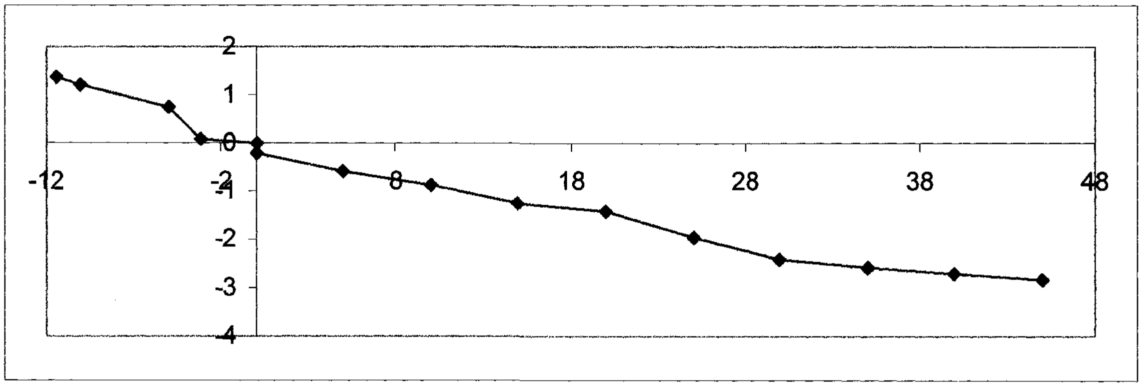
Site 4 Tie= +2.677 transect=56 0=3.824m NGVD 1929
Subdatum=dune fence post between "Y" trees and poles



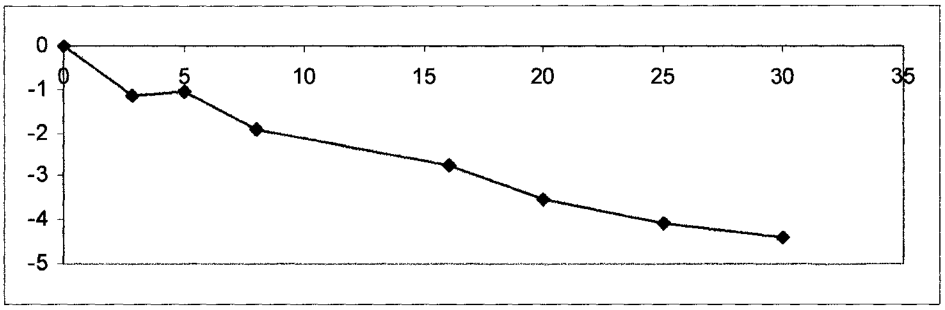
Site 5 transect=53 tie in =+1.311 0 =3.60m NGVD 1929
Subdatum=stick in cliff by gray house



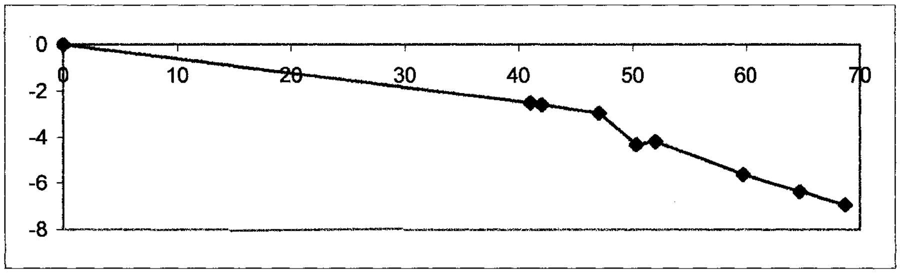
Site 6 0=2.712 m NGVD 1929
Subdatum="X" on bulkhead tie in +.42



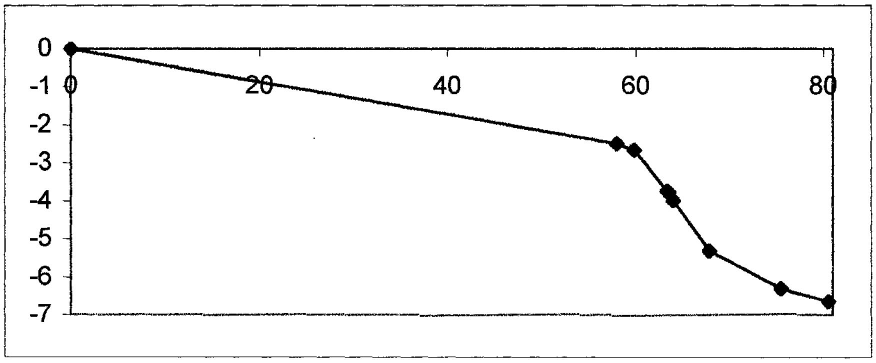
Site 7 transect=28 tie in+3.123 0=5.412m NGVD 1929
Rubble revetment 36.6m



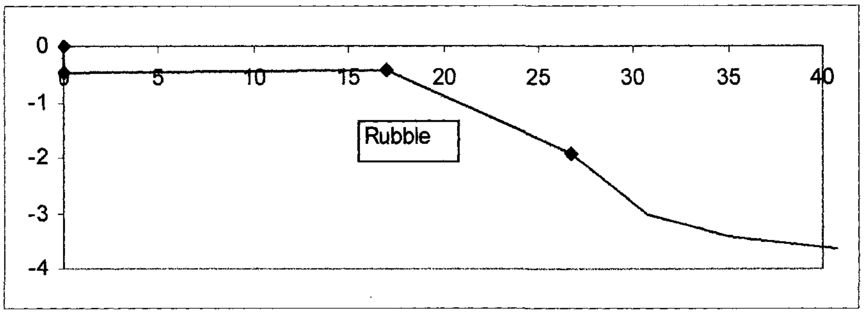
Sites 8 Rubble transect=25 tie-in=4.484 concrete block
0=6.776 m NGVD 1929 2/98 rack at 2.457



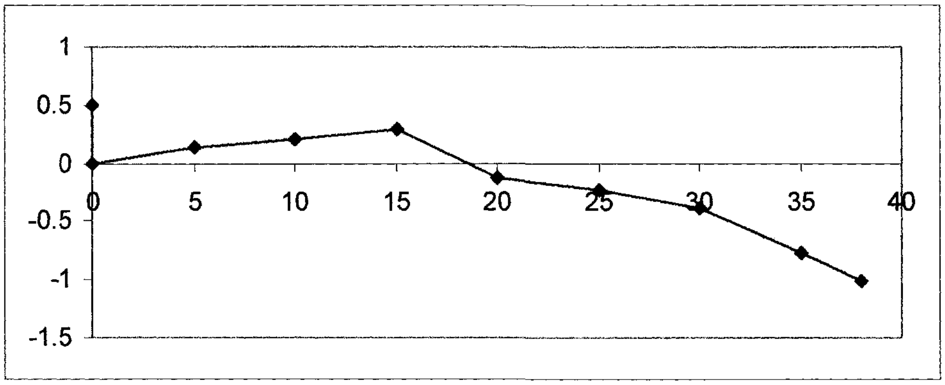
Site 9 Transect 15 tie-in=4.359 Railing 0=6.651m NGVD 1929
2/98m rack at 2.882m ngvd



Site 10 transect 40 more revetment tie-in+2.364 0=4.656 m NGVD 1929

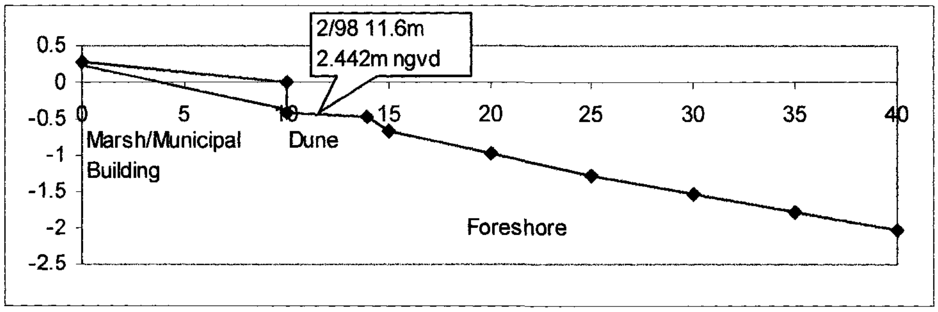


Site 11 11/9/1997 3 sticks transect=53 0=2.257 m NGVD 1929

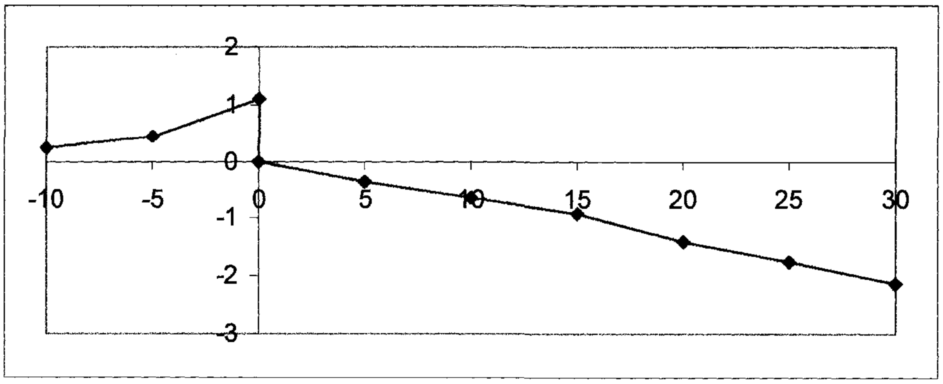


Site 12 transect=56

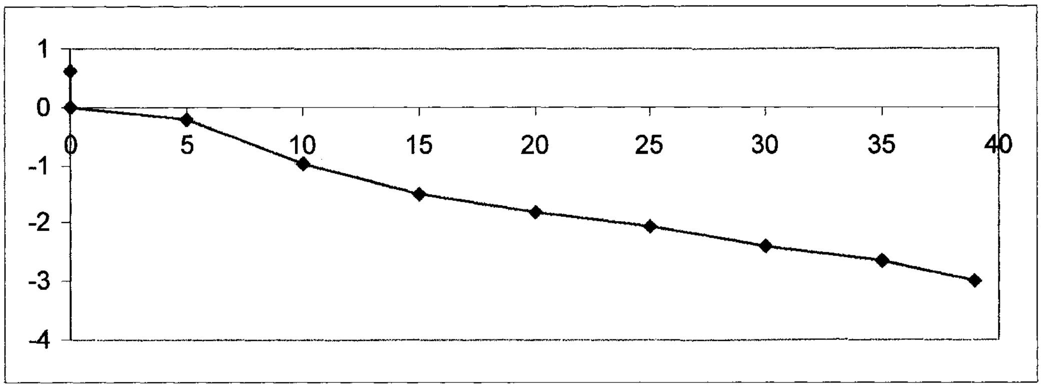
bolt in horizontal piling by municipality top of post at 10m = 2.869m NGVD 1929



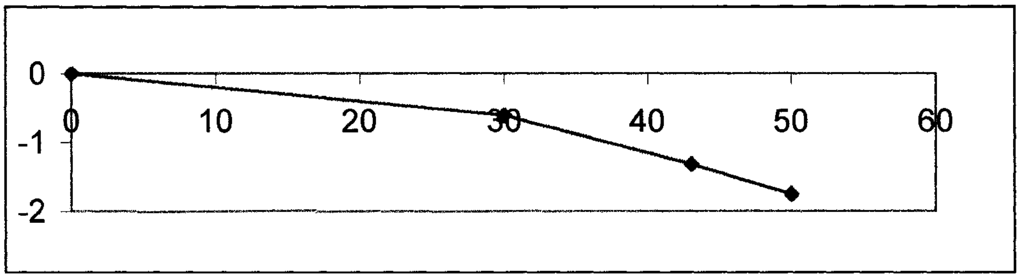
Site 13 end of compound transect=57 0=2.303m NGVD 1929



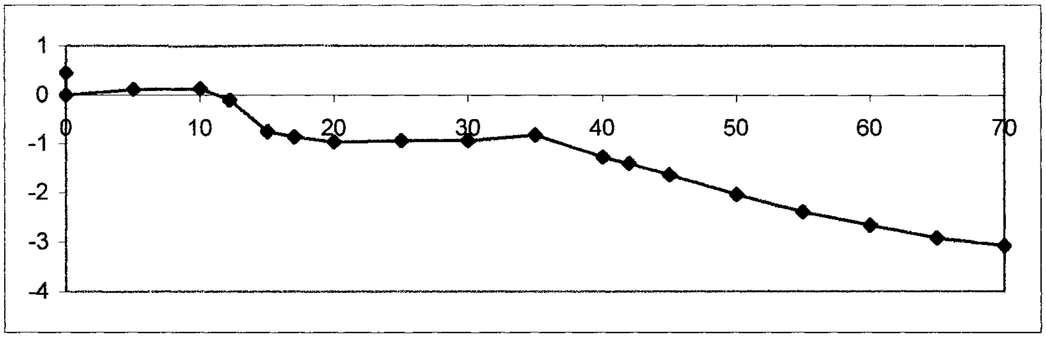
transect=3
Site 14 stake tree trunk=-2.4816 from sea wall I2 dot 6
bm on 0=3.091m NGVD
seawall=12.14 1929



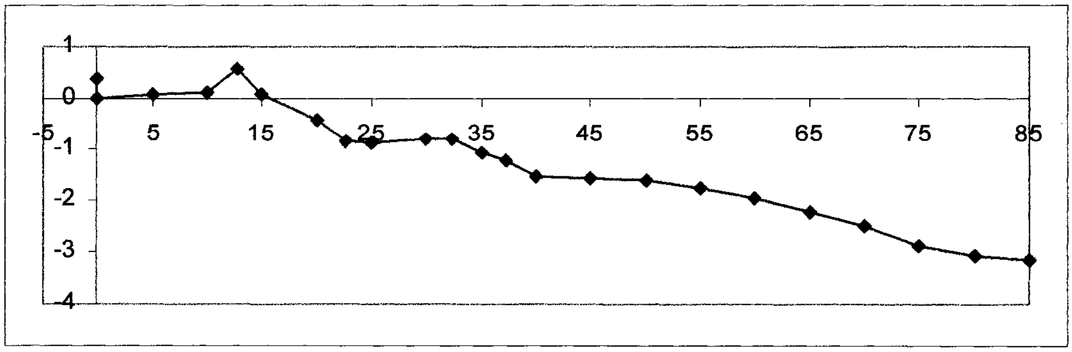
Site 15 Marsh west of whale creek 0=3.367m NGVD
transect 16



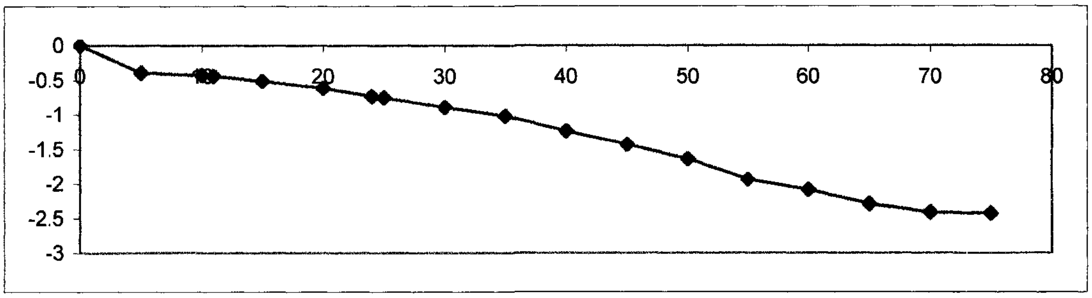
Site 16 Jetty transect = 4 0=2.866m NGVD 1929



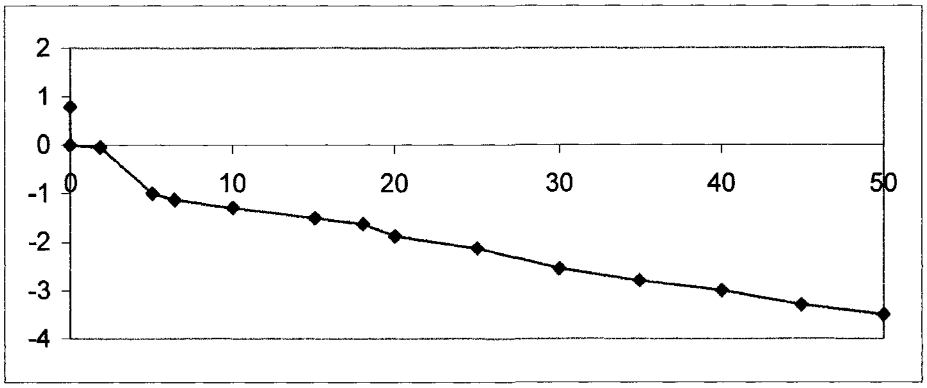
Site 17 0=2.625m NGVD 1929 transect=55 whale creek parking lot railing by no dump



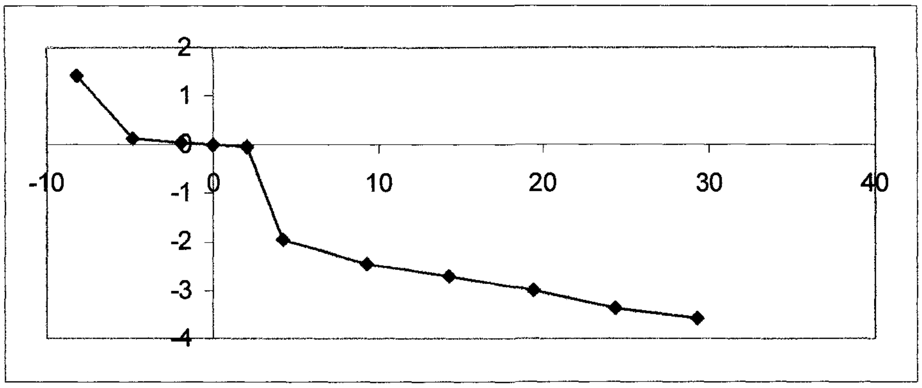
Site 18 0=2.613m NGVD 1929 transect=38 dune fence post



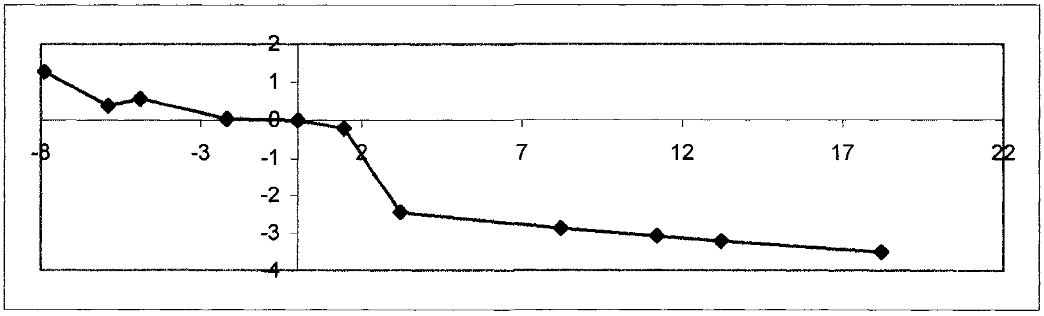
Site 19 dune 10th post transect=34 0=3.525m NGVD 1929



Site 20 seawall at 31 transect=41 0=3.700m NGVD 1929



Site 21 transect 46 seawall at 24+50 0=3.843m NGVD 1929

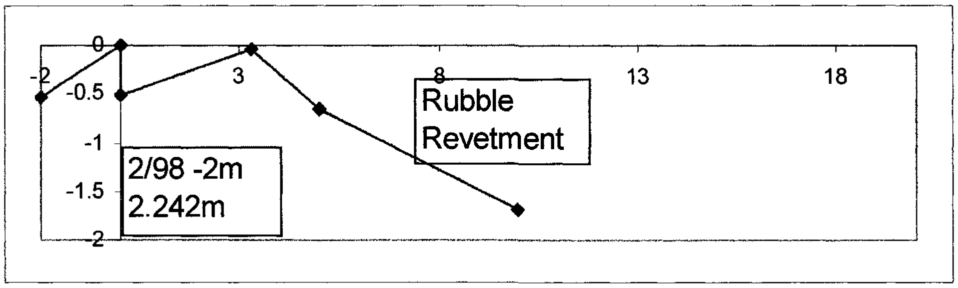


Site 22 I (heart)MO orange x seawall bm 180=3.714m NGVD 1929

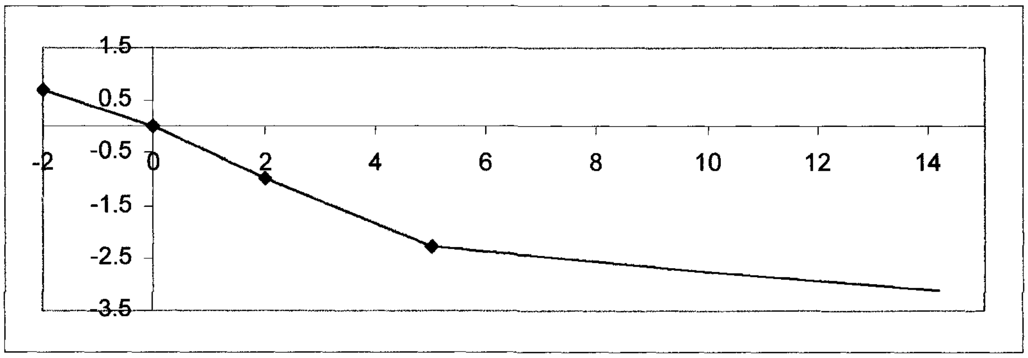
Site23 red flower orange x seawall bm 190 = 3.733m NGVD1929

Site 24 235+ white + seawall cbs=3.324m NGVD 1929

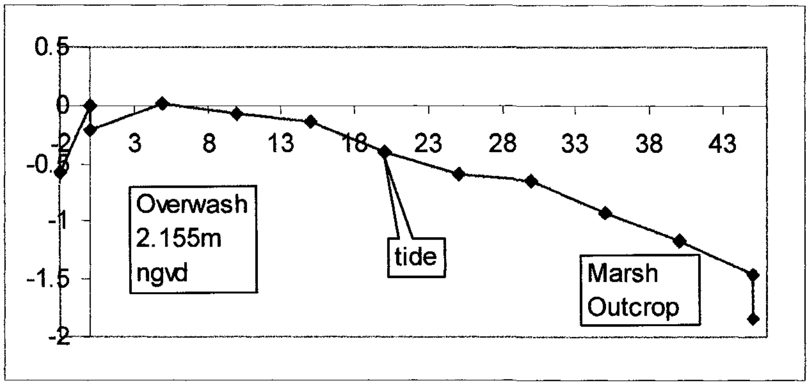
Site 25 Rubble pole 40ABT Top green post=0=2.783m NGVD 1929



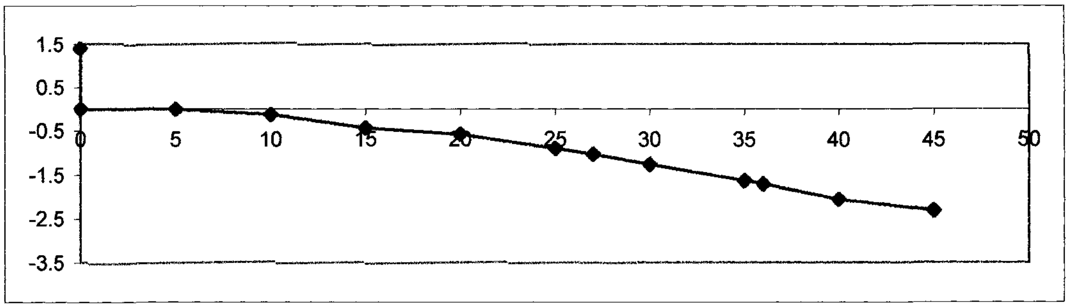
Site 26 Rubble orange x hex block by ghosts=0=3.185m NGVD 1929



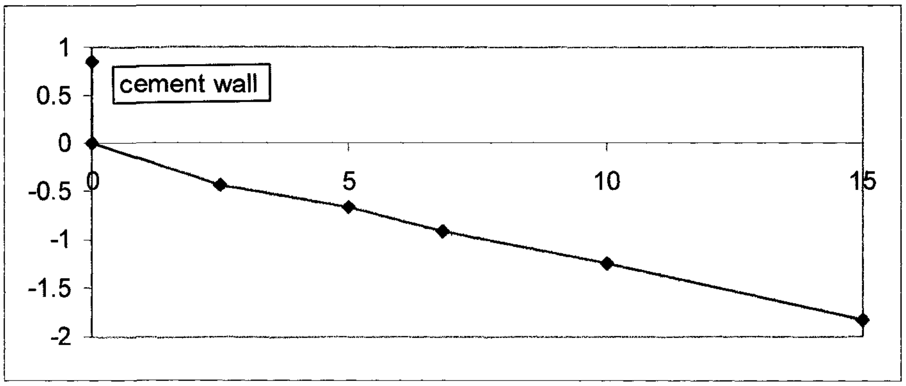
Site 27 Marsh post top of post=0=2.144m NGVD 1929



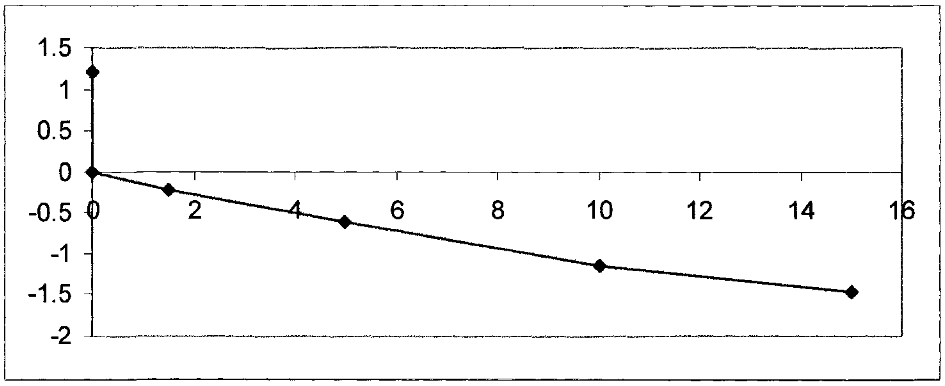
Site 28 Keyport Park transect=22 0=2.717m NGVD 1929



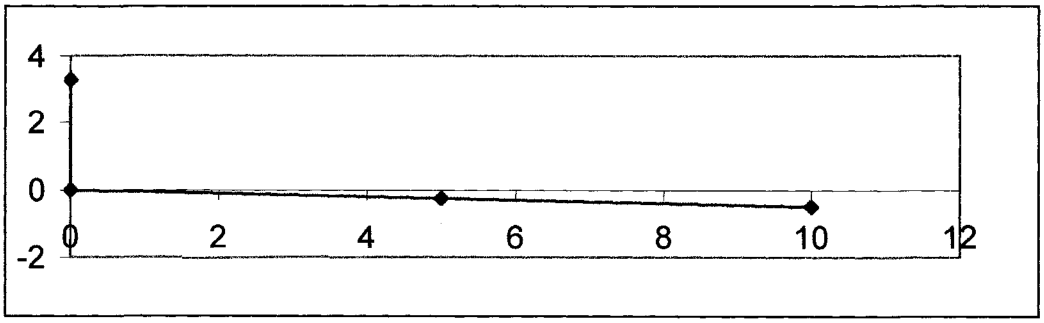
Site 29 transect 351 west of marina SWL hit wall 0=2.639mNGVD 1929 Sub= crack



Site 30 transect=347 Bulkhead 9th east SWL hit bulkhead
2 square bolts height gs to orange bolt 1.215 0=1.301mNGVD 1929

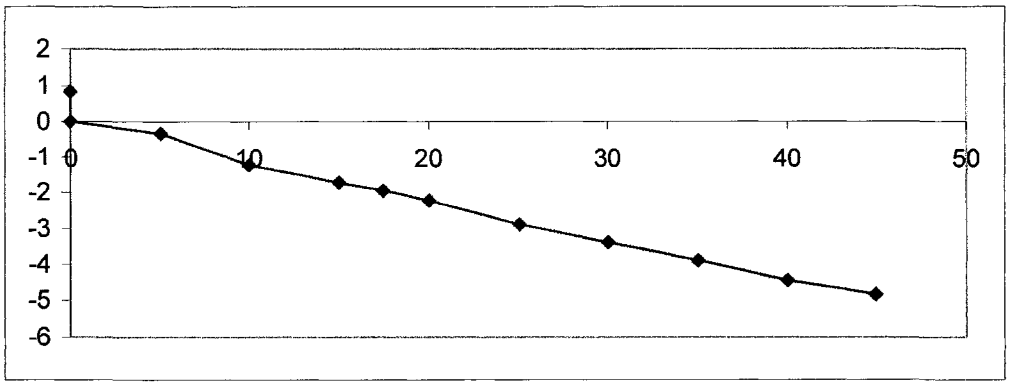


Site 31
Bulkhead at park Top = 3.531m NGVD 1929

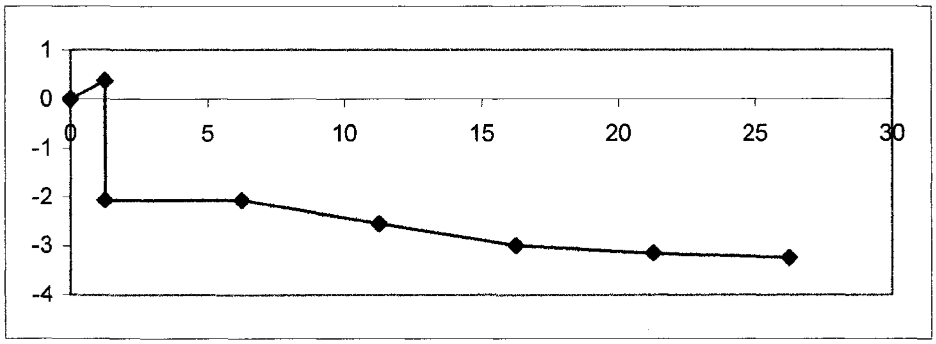


0=5.205m NGVD 1929

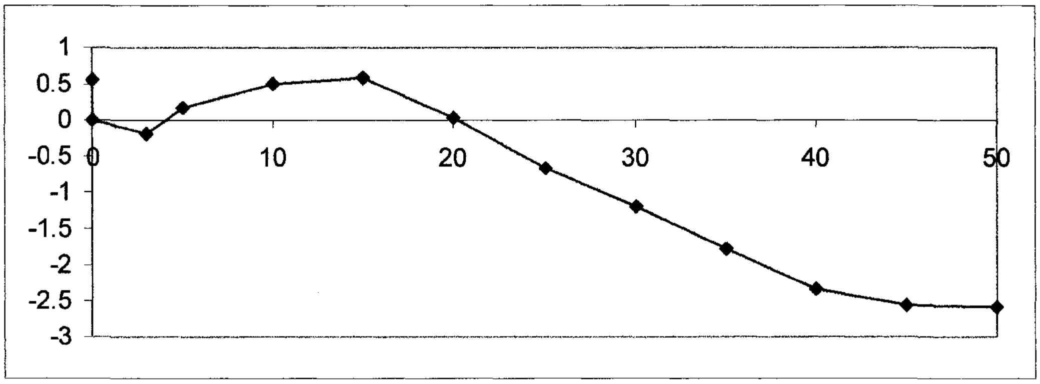
Site 31.5 park transect=343



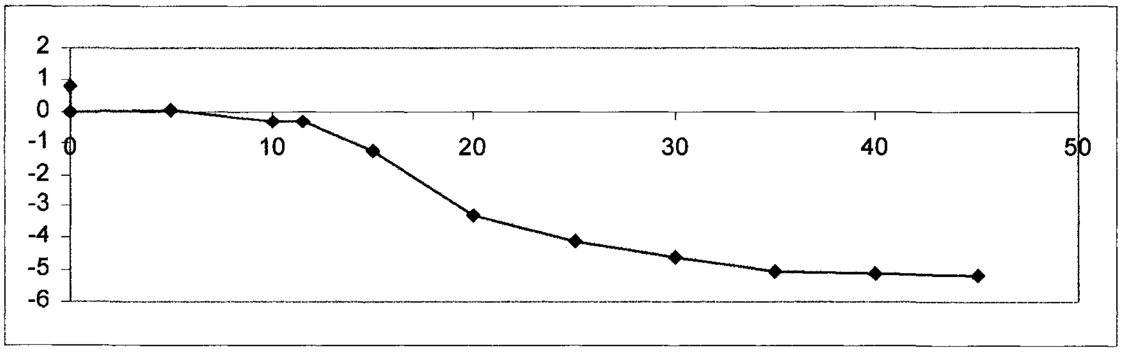
Site 32 transect=332 BM Seawall 0=2.774m NGVD 1929



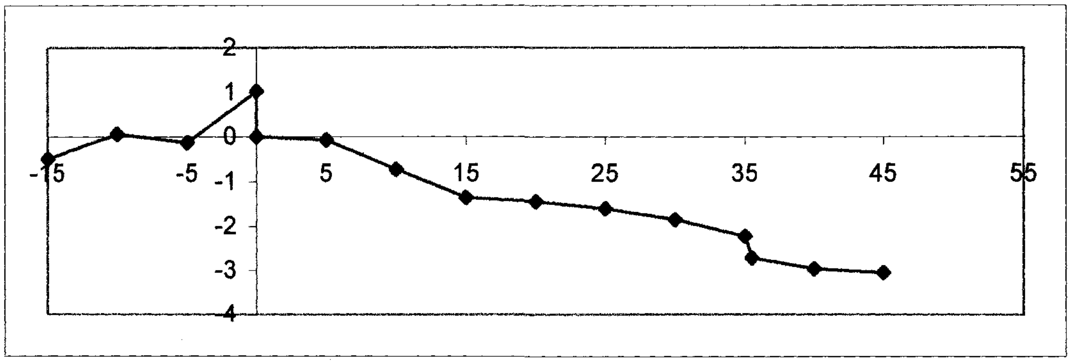
Site 33 marsh concrete block 0=2.101m NGVD 1929 transect=322



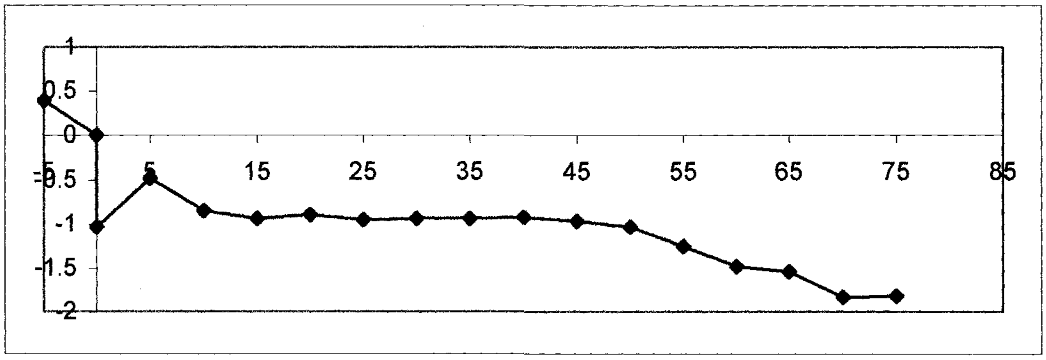
Site 34 riprap transect=327 post=5.702mNGVD 0=4.889m NGVD 1929



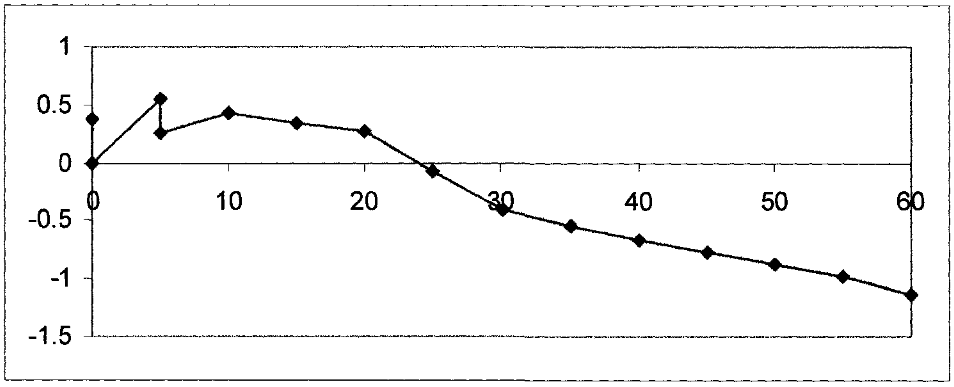
Site 35 transect=314
subdatum top of stump in marsh crest=4.467 0=3.438m NGVD 1929



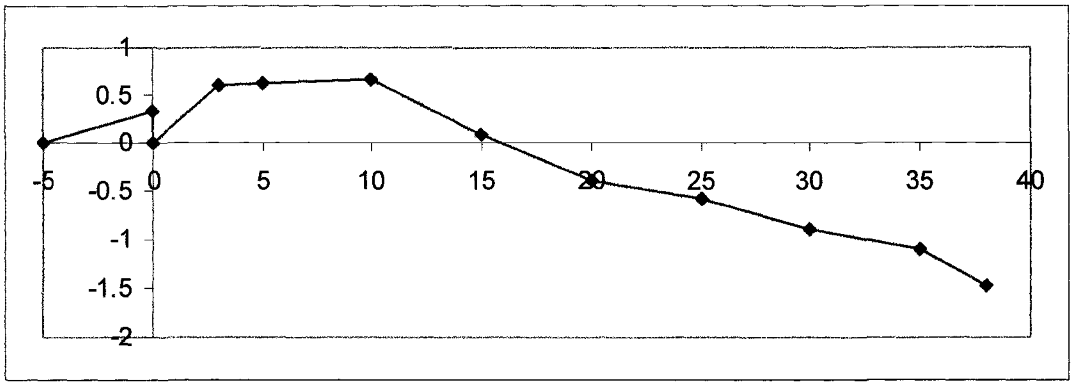
Site 36 marsh by creek transect=316 subdatum "Y" in tree 0=2.859m NGVD



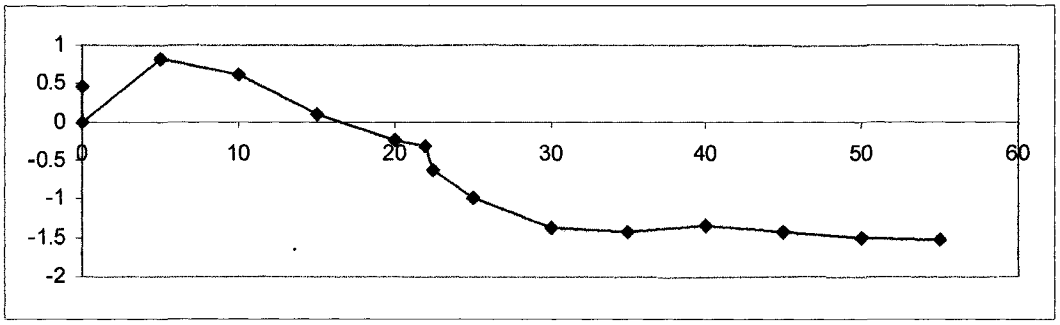
Site 37 marsh 2 stakes in ground transect 283 0=1.423mNGVD 1929



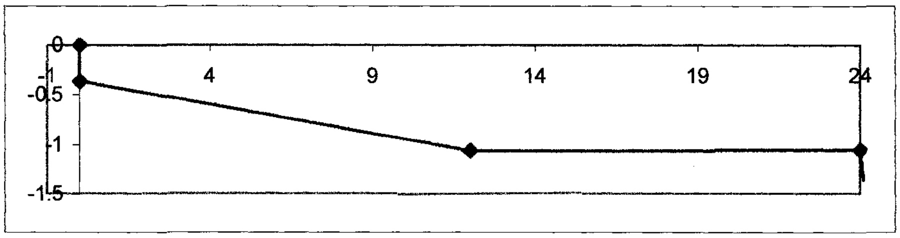
Site 38 marsh transect=254 0=1.306m NGVD 1929 end of sewerage plant



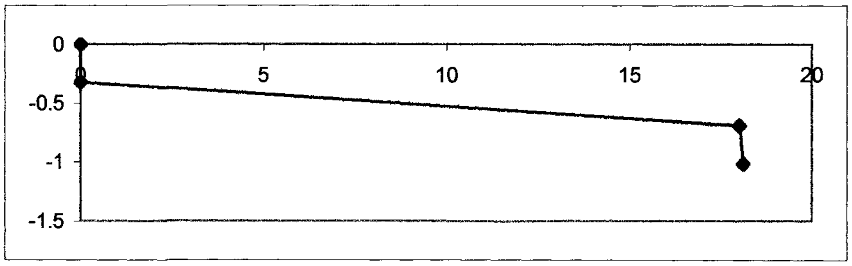
Site 39 transect=316 stake in marsh 0=2.008mNGVD white roof distant pipe



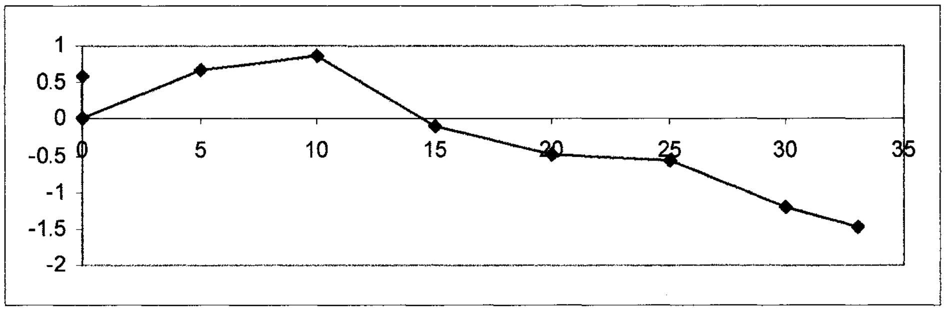
Site 40 grassy knobs transect 312 Subdatum=0=1.978mNGVD



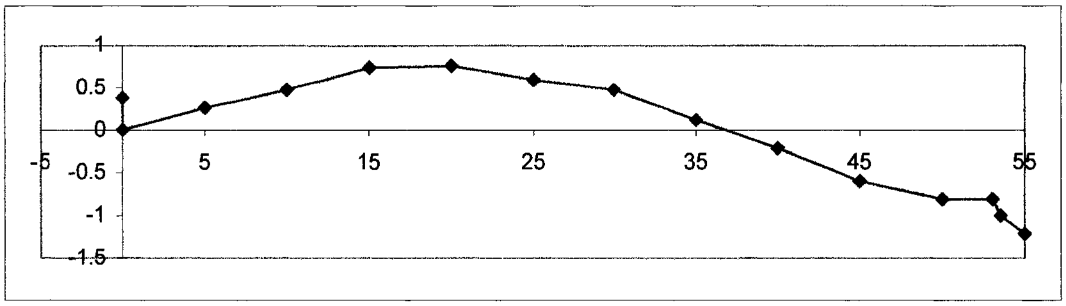
Site 41 stake subdatum=0=1.639m NGVD grassy knobs 50 m east of creek



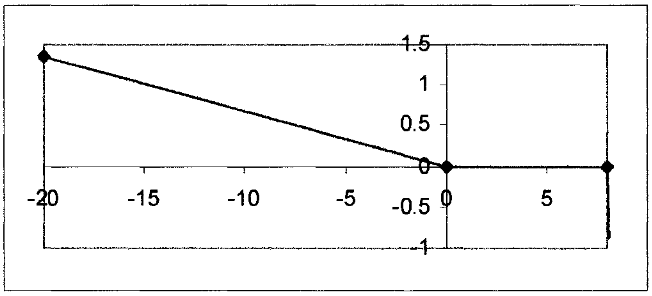
Site 42 transect=311 0=1.135m NGVD 1929 grassy/overwash stake



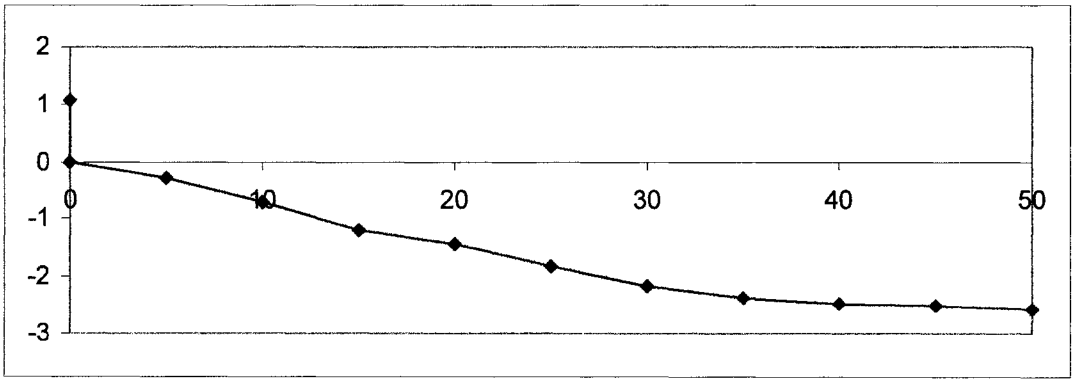
Site 43 transect =9 Conaskonk pt overwash 0= 1.252 m NGVD stake



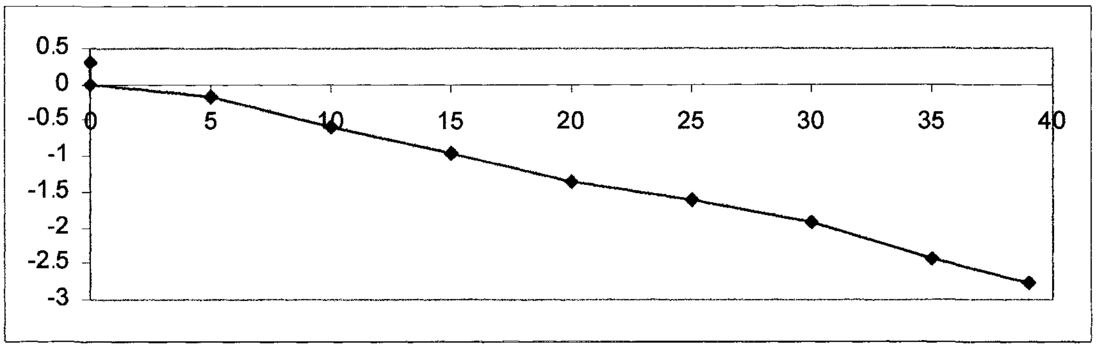
Site 44 bulkhead at 1.961m NGVD base .887 Grassy with overwash



Site 45 transect=61 0=2.086m NGVD 1929 subdatum-telepole

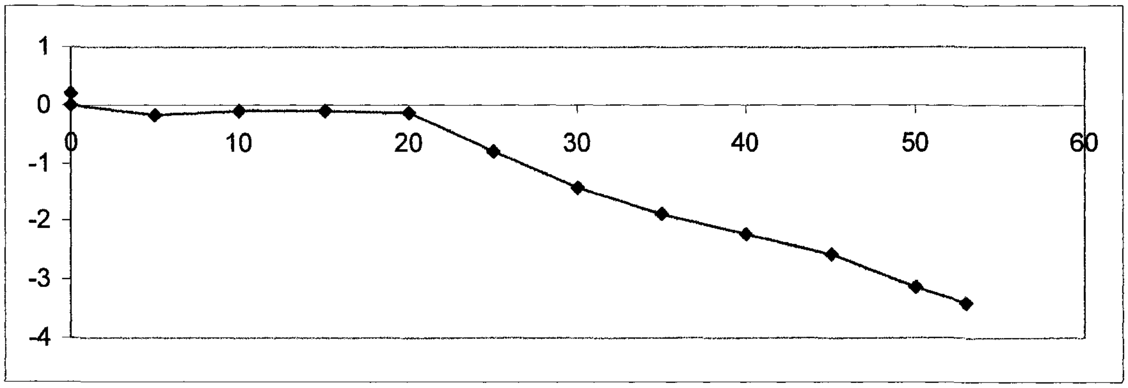


Site 46 transect=59 open lot subdatum lower square post 0=2.742m NGVD



Subdatum-25th bulkhead from walk
3.658m NGVD 1929

Site 47 Beach project 0=3.464m NGVD 1929



Site 48 Fire Hydrant 3.544m NGVD Top of Bulkhead 3.413 m NGVDElevation of rocks 2.613

Benchmarks

Benchmarks are used for determining standard reference elevations to compare water levels at different sites throughout Raritan Bay. Forty-nine sites were surveyed from the Cheesequake creek jetty to a bulkhead at Union Beach using a Topcon Autolevel and Mertic Rod. Four benchmarks were located and used to standarize all profile elevations to National Geodetic Vertical Datum 1929 (NGVD 1929). Sites 1-10, located between the jetty at Cheeseqauke creek and terminating at a creek separating Laurence Harbor from Siedler beach in Aberdeen, were tied in to a benchmark on a bridge crossing over Cheesequake Creek. The error based on tie back calculations for these sites is 0.128 meters. This is the highest error of all the locations and can be attributed to the heavy traffic and movements along Route 35 on which the bridge is situated. The elevation of the benchmark on the bridge is 12.88 meters NGVD.

Sites 11-27 are located in Aberdeen Township. A large seawall was constructed in the late 1970's at an approximate height of 12 feet (3.66 meters) NGVD. The US Army Corps of Engineers has recently placed benchmarks on the seawall. Benchmark 140 on the western end of the seawall at Cliffwood Beach is at an elevation of 12.14 feet (3.700 meters) NGVD and is used to determine the profile elevations for Sites 11-27. The error for sites west of the seawall based on tie back calculations is 0.019 meters. The error for sites east of the seawall based on tie back calculations is 0.044 meters.

Sites 28- 36 are located in the town of Keyport. A benchmark is located at the end of Cedar Street and front the bay waters at an elevation of 2.774 meters NGVD. Sites southwest of the benchmark have a tie back error of 0.059 meters and sites to the northeast have a tie back error of 0.076 meters.

Sites 37-44 are located along the marsh at Conaskonk Point. Elevations for these sites are tied into each other with an error of 0.018 and to a post at the east end of the marsh (Site 44). The post is tied into a benchmark in Union Beach. A bulkhead and artificial beach was recently built in Union Beach. The US Army Corps of Engineers has surveyed locations around the project. A pk plate (HV5412) embedded in the intersection of Front and Florence Avenues is used to establish the elevation of the post in the marsh. The elevation of the pk plate (HV5412) is 2.919 meters NGVD. The elevation of the post at Site 44 in the marsh based on the pk plate is 1.961 meters NGVD. The error for this tie in is 0.068 meters.

Sites 45-48 are located along Front Street in Union Beach. The elevations are tied into pk plate Hv5412 with an error of 0.001 meters. The accuracy of the field surveys and the standardization of all elevations to NGVD allows for the comparison of water levels throughout the study site.

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