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A SPATIAL ANALYSIS OF STORM CAUSED WATER LEVELS IN AN URBAN ESTUARY, RARITAN BAY, NEW JERSEY: SOME PRELIMINARY OBSERVATIONS

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ABSTRACT: *The spatial variability of coastal flooding along the New Jersey shoreline of Raritan Bay, an urban estuary, is determined using linear regression analysis. Water levels from six tide gages, installed in 1976 and 1977, are correlated to a tide gage at Sandy Hook, NJ. Peak water levels for the most severe storm in the past 30 years, occurring December 11-13, 1992, are derived at the six gage locations from the actual water level at Sandy Hook and regression equations. Storm surge is determined by subtracting the predicted tides from the derived water levels. Predicted tides in Raritan Bay increase westward from Sandy Hook by 1% to 9%. The statistically derived water levels and storm surge for the December 1992 storm do not follow a trend of steady increase westward. An embayment in the middle of the bay and sheltered from northeast winds has the highest derived water level, 1.82m above mean high water, and storm surge, 1.54m. Consequently, flood mitigation strategies must consider both broad and local scale factors and the site-specific nature of the variables that contribute to peak water levels throughout the bay.*

INTRODUCTION

Urban estuaries along the US East Coast are vulnerable to coastal flooding caused by two types of storms, extra-tropical cyclones and tropical cyclones. Raritan Bay is important because a large population lives in close proximity to the bay waters and the bay axis is perpendicular to the ocean thus maximizing potential water levels due to easterly winds resulting from the counterclockwise circulation around cyclones moving along the coast (Figure 1). Extra-tropical cyclones (northeasters), low-pressure disturbances that develop along cold fronts, occur frequently along the New Jersey coast. The intensity and classification of northeasters is based on the duration of the storm (Halsey, 1986; Dolan and Davis, 1992). The most intense northeasters occur between October and March. Tropical cyclones (hurricanes), 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 exceptionally dangerous. Peak hurricane season is between August and September.

The purpose of this paper is to quantify the spatial variability of coastal flooding in an urbanized estuary. Coastal flooding is caused primarily by storm surge. Storm surge can be defined as exceptionally high tides caused by wind stress and/or low pressure resulting from the passage of a coastal storm (Coch, 1994; Dolan and Davis, 1994). Storm surge can be quantified as the difference between actual water levels and predicted water levels (Dendrou et al.,1985). On the open coast, storm surge due to hurricanes can exceed five meters, while in a northeaster the storm surge is usually less than two meters (Dolan and Davis, 1994). In an estuary, storm surge is a function of the water made available on the open coast and the redistribution of that water within the estuary by local winds (Miller, 1988). Statistical methods are employed to determine the spatial variability of peak water levels in Raritan Bay. Site-specific water levels will be derived from regression equations and storm surge will be calculated by subtracting the predicted tidal levels from the derived water levels.

Models exist that explain water levels and storm surge in estuaries (Miller, 1988; National Oceanic and Atmospheric Administration (NOAA), 1992b; Coch, 1994). Tide tables for predicting water levels in Raritan Bay are based on astronomical data and do not account for daily meteorological conditions (NOAA, 1992b). Theoretical models that consider meteorological conditions suggest that in Raritan Bay, the dominant wind direction to supply water on the open coast is northeast, with local onshore winds producing the maximum surge at specific sites along the NJ shoreline of the bay (Miller, 1988). Field observations at Sandy Hook, NJ and Fire Island, NY, do not completely support this theory. High water levels at these specific sites have not been conclusively correlated to periods of onshore winds (Nordstrom, 1992; Nordstrom et al., 1996). Storm surge in estuaries depends on basin morphology, shoreline characteristics and ocean surge along with storm characteristics (Nordstrom et al, 1996).

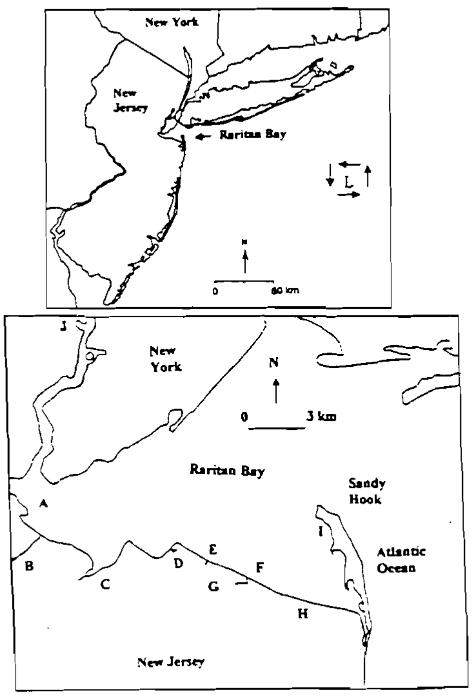

FIGURE 1: Study site: A. South Amboy B. Cheesequake Creek C. Keyport D. Keansburg E. Pews Creek F. Compton Creek G. Port Monmouth H. Atlantic Highlands I. Gage at Sandy Hook J. Newark International Airport "L" refers to a low pressure disturbance. The arrows represent circulation patterns around the low.

In general, both the site-specific and general research needed to predict coastal storm flood elevations and erosion rates on both local and national levels is lacking (Wood, 1990). Post storm reconnaissance observations have been made for Raritan Bay following two catastrophic events, Hurricane Donna in 1960 and a December 1992 storm (US Army Corps of Engineers (USACE), 1960, 1993). Although comprehensive, a spatial distribution of water levels can not be obtained from these reports because of the qualitative nature of the observations.

Some reaches within Raritan Bay are included in the New Jersey Hazard Mitigation Plan, a plan that includes both ocean and bay shorelines (NJ Department of Environmental Protection, 1985). The scale and the classification system used in the plan do not adequately account for the variability of coastal flooding in the bay. Coastal flooding along estuarine shorelines is not controlled by the same variables that cause coastal flooding along ocean shorelines. Ocean side processes have limited application to bayside processes (Nordstrom, 1980).

Reduction of flooding hazard in Raritan Bay is the responsibility of the Federal Emergency Management Agency (FEMA). FEMA's Flood Insurance Rate Maps are based on the proximity of land elevations to 100-year and 500-year flood water levels. Government efforts apply principles on scales that do not adequately address the fine spatial characteristics of estuarine shorelines and the level of damage that can be caused by storms much smaller than 100-year or 500-year storms. The spatial variability of coastal flooding in Raritan Bay results from processes that current studies and models do not address. The statistical methods used here begin to address the need for a quantitative analysis of estuarine coastal flooding.

METHODOLOGY

A continuous record of hourly water levels exists for Sandy Hook since 1910. Hourly water levels are available for six additional gages in the bay for various months between January 1976 and May 1977. Equations are developed using least-squares regression analysis of the 1976-1977 gage data and the Sandy Hook data. Water levels at the gage locations (y in the equation) can be derived for any storm since 1910, using water levels recorded at the Sandy Hook gage (x in the equation). Correlation coefficients, standard error of the slope and y-intercept, standard error of estimate (scatter) and Durbin-Watson test statistics are calculated to provide levels of confidence and to test for autocorrelation.

Water levels selected for use in the regression analysis met the following two criteria: (1) Winds from the north to east with a minimum speed of five m/s, and (2) An hourly water level above local mean high water for the site. Wind directions and speeds are determined from 3-hour observations at Newark International Airport, approximately 20 kilometers north of Raritan Bay (NOAA, 1992a). Although these records may not reflect the exact wind speed and direction at each site in the bay, they do reflect the general wind patterns that would cause elevated water levels in the bay. Water levels are determined from National Ocean Service (NOAA) records. Between January 1, 1976 and May 31, 1977, 73 hourly water level measurements satisfied both criteria for Sandy Hook. The sporadic operation of the other gages prohibited using 73 measurements in the analysis for each gage. Therefore, the number of hourly water levels (n) used for statistical analysis ranged from 16 to 56.

The northeaster storm of December 11-13, 1992 is used for this study because it was the most devastating storm in the last 30 years at Raritan Bay with damages exceeding two million dollars (USACE, 1993). The storm is depicted by plotting wind speeds and directions based on three hour observations at Newark International Airport and hourly water levels recorded at Sandy Hook.. The peak hourly water level at Sandy Hook is used to derive the peak water level at each of the six gage locations based on the regression equations. The derived peak water levels are corrected to local mean high water for each location using the 1960-1978 tidal epoch. The tidal epoch is the length of record used to calculate a tidal datum. Mean high water is used because it is the maximum water level caused by the tides. Water levels above mean high water indicate storm contributions.

NOAA Tide Tables provide constants for predicting water heights at Sandy Hook and the six gage locations in Raritan Bay. Predicted high tide on December 11, 1992 was 0.26 m above mean high water and occurred at 8:18 am. The predicted tides at six locations are calculated from the Sandy Hook prediction using the following constants: South Amboy (*1.06), Cheesequake Creek (*1.09), Keyport (*1.07), Keansburg (*1.05), Port Monmouth (*1.03), and Atlantic Highlands (*1.01). The time lag of the tide from Sandy Hook to the most westerly location, South Amboy, is minimal. Five of the six tide prediction locations are exactly the same as the locations of the 1976-1977 gages. The exception is Keansburg, where the gage data is for Pews Creek, while the prediction location is to the west at Waackaack Creek. Data from Waackaack Creek did not correlate well with the data from Sandy Hook and was therefore excluded in results. Storm surge is calculated for the six gage locations and the Sandy Hook gage by subtracting the predicted tide from the corrected water level.

RESULTS

The standard error of estimate (scatter), standard error of the slope (SE of slope) and y-intercept (SE of y-inter), and R^2 values provide measures of confidence in the equations and results. The R^2 values ranged from 0.882 to 0.968, excluding the relatively poor correlation for South Amboy (Table 1). The equations for South Amboy and Compton Creek have the highest errors. The other four gages have low errors and high correlation with the highest standard error of estimate at Cheesequake Creek, 0.0474m, and the highest standard error of the slope and y-intercept at Atlantic Highlands, 0.078 and 0.1950m, respectively (Table 1).

Water levels collected over time may be autocorrelated in that the level of response from one period affects the level of response in the next period (Younger, 1979). If the water levels are autocorrelated, they can not be reliably analyzed using simple linear regression. The Durbin-Watson d-statistic (d-stat) is derived from an analysis of the residuals and can determine if the degree of autocorrelation in the data set is significant. Values of the d-statistic around two usually indicate that no autocorrelation exists (Younger 1979). The values for Cheesequake Creek, Keyport, Pews Creek and the Atlantic Highlands indicate that autocorrelation is unlikely. The value for Compton Creek is inconclusive while the South Amboy value indicates autocorrelation is likely (Table 1).

Data from four of the six gages provide equations that are highly correlated and are statistical significant. The differences between the coefficients in equations are likely due to the elevation at which each gage was established relative to mean high water at the site. Weighted regression was used to rectify the errors in the equations for South Amboy and Compton Creek but did not conclusively eliminate the possibility of autocorrelation or significantly reduce the standard errors. Therefore, the original equations are kept with the understanding that the results be viewed with caution.

From December 11-13, 1992, strong winds persisted from the north and northeast peaking at 17 m/s (Figure 2). Storm-caused water levels are superimposed on the semi-diurnal nature of the tides at Sandy Hook (Figure 3). Water levels were consistently elevated on December 11 with Sandy Hook recording a peak of 3.7m that equates to 1.53m above mean high water. The predicted tide at Sandy Hook is 0.26m above mean high water, yielding a storm surge value of 1.27m (Table 2). Water levels derived using the Sandy Hook value of 3.7m, the regression equations, and corrected to local mean high water, ranged from 1.37m to 1.81m (Table 2). Subtracting the predicted tides for each location produces storm surge values from 1.09m to 1.54m (Table 2). The standard errors in the analysis were approximately 0.1m suggesting that the derived water levels are significant.

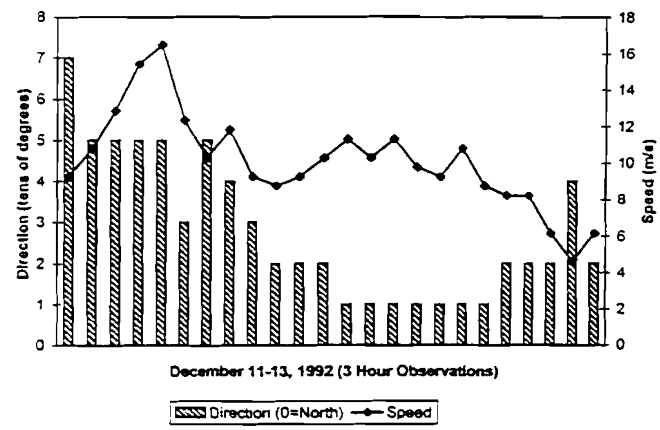

FIGURE 2: Wind data from Newark International Airport, Newark, NJ for the December 1992 storm.

Table 1. Statistical analysis for six tide gages

Location	Equation*	SE of slope	SE of y-inter*	Scatter*	R^2	d-stat	n
Atlantic Hghlds	y=1.087x-0.6491	0.078	0.1950	0.0450	0.902	1.869	23
Compton Creek	y=1.103x+2.273	0.108	0.26	0.0640	0.882	0.855	16
Pews Creek	y=0.919x+1.111	0.045	0.1090	0.0266	0.968	1.225	16
Keyport	y=1.120x-0.1882	0.042	0.1035	0.0416	0.951	1.546	45
Cheesequake Cr	y=0.884x+0.3089	0.053	0.1311	0.0474	0.911	2.078	29
South Amboy	y=0.887x+0.0078	0.095	0.2368	0.1134	0.617	0.951	56

* meters

Table 2. Derived water levels and storm surge for December 11, 1992

Derived Location	Correction gage record	Corrected water to local mhw	Predicted level (mhw)	Storm tide (mhw)	surge
Sandy Hook	3.70[1]	2.17	1.53	0.26	1.27
Atlantic Highlands	3.37	1.71	1.66	0.263	1.40
Compton Creek	6.35	4.62	1.73	0.268[2]	1.46
Pews Creek	4.51	3.09	1.42	0.273[3]	1.15
Keyport	4.29	2.47	1.82	0.278	1.54
Cheesequake Creek	3.58	2.21	1.37	0.283	1.09
South Amboy	3.29	1.92	1.37	0.276	1.10

Water levels in meters, mhw-mean high water

[1] Actual gage recording

[2] Prediction at Port Monmouth

[3] Prediction at Keansburg

This analysis is somewhat problematic because the December 1992 water level at Sandy Hook is greater than the range of the 1976-1977 data. An assumption is made that a linear relationship exists outside the data set, an assumption that may or may not be valid. Confidence for making this assumption is grounded in the fact that the data used in the analysis

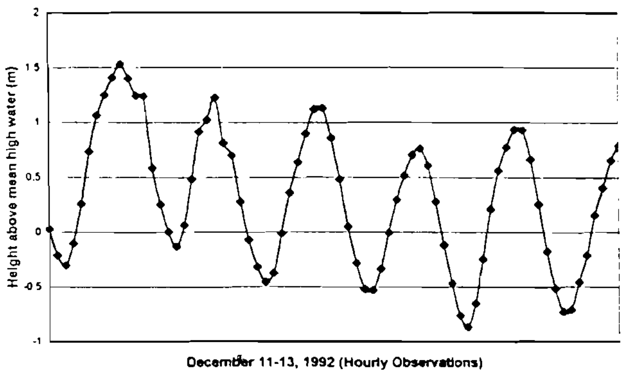

FIGURE 3: Actual water levels at Sandy Hook, NJ for the December 1992 storm.

consisted only of higher than normal water levels, consequently water levels slightly outside the data set could be determined. Furthermore, the USACE report indicates a flood level for the December 1992 storm of approximately 1.8 m above mean high water at Keyport corresponding strongly with the statistically derived water level of 1.82m.

DISCUSSION

Predicted water levels increase westward in the bay because of the tides (Figure 4). The derived water levels and storm surge values increase from Sandy Hook to Port Monmouth, decrease at Keansburg, peak at Keyport and then drop off markedly at Cheesequake Creek and South Amboy (Figure 4). Storm-caused water levels do not mimic the tides. Locations in the middle of the bay may have either high or low storm-caused water levels.

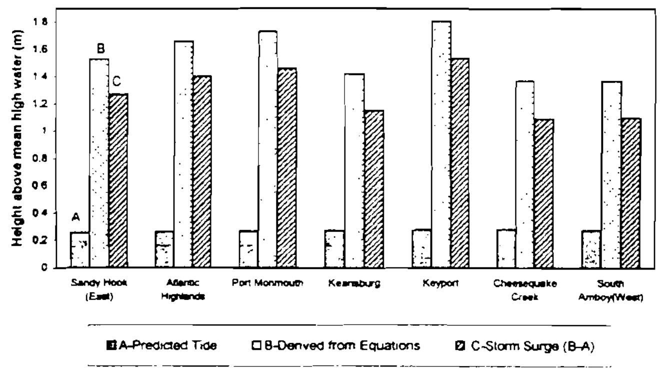

FIGURE 4. Comparison of predicted tides, derived water levels and storm surge for December 11, 1992.

The shorelines of Port Monmouth and Keansburg are exposed to the bay mouth therefore having long fetches for winds to blow over (Figure 1). Both sites sustained similar damage from the December 1992 storm. However, the derived water level and storm surge at Keansburg is relatively low. If storm surge propagated in concert with the tides, a value of between 1.46 and 1.54 would be expected at Keansburg. The low water level suggests that local controls affect storm surge at Keansburg. Site specific variables have a pronounced affect on winds, waves and water levels on estuarine shorelines (Jackson and Nordstrom, 1992). The variability observed between Keansburg and Port Monmouth may also be attributed to the affects of human modifications at and near Pews Creek and Compton Creek.

Keyport has the highest derived water level and storm surge. According to reconnaissance data from the US Army Corps of Engineers, Keyport also experienced the highest flood levels (USACE, 1993). Keyport is generally sheltered from northeast winds (Figure 1). A possible explanation for the extreme water levels is that while the peak winds were northeasterly, strong winds with a more northerly component were also persistent resulting in local onshore winds (Figure 3). A local onshore wind can maximize storm surge at a site (Miller, 1988). A northerly wind direction would maximize the fetch for storm surge and wave development at Keyport, whereas it has less significance for the shorelines oriented to northeast winds, such as Port Monmouth, Keansburg and Atlantic Highlands.

The orientation and configuration of Cheesequake Creek apparently enhances predicted tidal effects but restricts storm caused water levels. Cheesequake Creek has the highest predicted tide but the lowest derived water level and storm surge. High tides are expected at South Amboy due to its westward location in the bay. The derived water levels and storm surge at South Amboy are relatively low and likely influenced by the limited fetch in the north-northeast direction. The low levels for South Amboy may be attributed to errors in the regression analysis but the low levels at Cheesequake Creek are statistically significant.

CONCLUSION

The strong correlation between the 6 gage locations in Raritan Bay and the long-term record at Sandy Hook allows for determining the spatial variability of water levels caused by a coastal storm. Statistically significant predictive equations are generated for 4 of the 6 gages with storm surge ranging from 1.09m to 1.54m and standard errors around 0.1m. Water levels that vary by 0.45m are significant because many homes are built at the mean high water level along estuarine shorelines. Evidence exists to substantiate the validity of at least one equation, Keyport, in predicting values outside the data range. Predicted tides can be used as an indicator of the dynamics of water levels in an estuary and for determining storm surge if actual or derived water levels exist. A comparison of the predicted tides to derived water levels and storm surge suggests that local factors may enhance or detract from the propagation of storm surge in an estuary. Tides tables and existing models can not explain the variability at all sites. Further research is warranted to investigate the local controls on the existing spatial variability in the derived water levels and storm surge. Quantitative water levels, rather than qualitative post storm data, are needed to verify the spatial variability in the derived water levels and storm surge. The next step is to identify and quantify the local controls that affect the coastal flooding. These controls include but are not limited to storm characteristics, elevation and slope, orientation of shoreline, proximity to creeks and the status of existing shore protection structures.

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REFERENCES

Coch, N. K. 1994. Hurricane Hazards Along the Northeastern Atlantic Coast of the United States. *Journal of Coastal Research* Special Issue 12:115-147.

Dendrou, S.A., Moore, C.I. and Myers, V.A. 1985. Application of Storm Surge Modeling to Coastal Flood RateDeterminations. *Marine Technological Society Journal* 19(2):42-50.

Dolan, R. and Davis, R. 1992. An Intensity Scale for Atlantic Coast Northeast Storms. *Journal of Coastal Research* 8(4):840-853.

Dolan, R. and Davis, R. 1994. Coastal Storm Hazards. *Journal of Coastal Research* Special Issue 12:103-114.

Halsey, S.D. 1986. Proposed Classification System for Major Northeast Storms: East Coast USA, Based on Extent of Damage. *Geological Society of America, Abstracts with Programs* (Northeastern Section) 18:21.

Jackson, N. and Nordstrom, K. 1992. Site Specific Controls on Wind and Wave Processes and Beach Mobility on Estuarine Beaches. Journal of Coastal Research 8(1):88-98.

Miller, C.D. 1988. Hydrodynamic Response of an Estuary to Storm Forcing. In *Hydraulic Engineering* pp. 720-726. ASCE: New York

National Oceanic and Atmospheric Administration 1992a. Local Climatological Data for Newark International Airport. National Climate Data Center, Asheville, NC.

National Oceanic and Atmospheric Administration 1992b. Tide Tables for East Coast of North and South America. National Ocean Service:US Department of Commerce.

New Jersey Department of Environmental Protection 1985. New Jersey Hazard Mitigation Plan Section 406 Plan.Trenton, NJ.

Nordstrom, K.F. 1980 Cyclic and Seasonal Beach Response A Comparison of Oceanside and Bayside Beaches. *Physical Geography* 1(2):171-196.

Nordstrom, K. F. 1992. *Estuarine Beaches*. London: Elsevier.

Nordstrom, K.F., Jackson, N.L., Allen, J.R. and Sherman, D.J. 1996. Wave and Current Processes and Beach Changes on a Microtidal Lagoonal Beach at Fire Island, NY, USA. In *Estuarine Shores:Evolution,Environments and Human Alterations*, eds. K.F. Nordstrom and C.T. Roman, pp.213-232. New York:Wiley.

U. S. Army Corps of Engineers, New York District 1960. Raritan Bay and Sandy Hook Bay, N.J.Cooperative Beach Erosion Control and Interim Hurricane Study. New York: U.S. Army Corps of Engineers.

U. S. Army Corps of Engineers, New York District. 1993. Raritan Bay and Sandy Hook Bay, N.J.Combined Flood Control and Shore Protection Reconnaissance Study. New York: U.S. Army Corps of Engineers.

Wood, W. 1990. Coastal Management Alternatives for Reducing Storm Impacts at a Coast. *Shore and Beach* 58: 72-74.

Younger, M.S. 1979. *Handbook for Linear Regression*. Belmont, CA : Duxbury Press.