The limited role salt marshes may have in buffering extreme storm surge events: Case Study on the Jersey Shore

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Abstract

The hybrid hurricane and storm event dubbed "SuperStorm Sandy" of October 2012 was the most costly natural disaster to hit the US Atlantic coast, and the second most costly to affect the United States. This extreme weather event presented an excellent opportunity to assess the effectiveness of tidal salt marshes and maritime forests in buffering adjacent development from storm-related damage. To address this question of how well did or under what conditions did coastal ecosystems buffer adjacent human development, we undertook to quantify the incremental monetary value that a hectare or linear extent of fronting salt marsh and/or maritime forest had on protecting the built environment of the back-bay communities in the Barnegat Bay region of New Jersey, USA. Statistical modelling was used to estimate the relationship between the spatial extent and characteristics of fronting coastal wetlands with the various damage metrics derived from the Federal Emergency Management Agency National Flood Insurance Program payout and Preliminary Property Modeling Task Force damage data at the scale of the individual housing unit. While salt marshes may be effective in diminishing wave energies and buffering adjacent development under normal conditions, in the case of SuperStorm Sandy, we find no evidence that New Jersey's extensive coastal marshes significantly buffered and thereby reduced NFIP payouts on the majority of back-bay residential properties. The extreme conditions of this storm event with storm surges upwards of 2 meters, effectively flooded these marshes diminishing their protective capacity. The bulk of the residential properties damaged in our study area were located in lagoonal communities that are built directly adjacent to tidal water and are thereby highly vulnerable to storm surge-related flooding whether or not they are buffered by adjacent marshes. The results of this study should not be misconstrued in concluding that salt marshes do not have a positive value in protecting coastal properties; rather, their protective buffering capacity for extreme storm events is limited and that lagoonal-style developments remain highly vulnerable to sea level rise and future storms.

1. Introduction

Coastal ecosystems have been identified as serving a critical role in reducing the vulnerability of coastal communities to sea level rise and storm hazards (Duarte et al., 2013; Spalding et al, 2013). This *regulating* service often goes under the term, natural or green infrastructure. Tidal salt marshes are a characteristic landscape feature of Mid-Atlantic coastal bays, fringing both the back side of the barrier islands, as well as the mainland. Several reviews (Gedan et al., 2011; Shepard et al., 2011) have found that salt marshes have a moderating influence on attenuating storm surge and waves and a moderately positive role in shoreline stabilization. The potential of salt marshes to reduce storm surge has been typically expressed by empirically-determined attenuation rates, though this can be misleading because it does not account for the complex dynamics of individual storm events as well as the local bathymetry/topography (Resio and Westerink, 2008). For example, a surge attenuation rate of approximately 3 inches (vertical) for every linear mile of marsh was measured in the Louisiana Gulf Coast (Louisiana Coastal Wetlands Task Force, 1998). In comparison to mangrove wetlands, the attenuating effect of temperate maritime forests has not been extensively studied.

Complementing the physical studies, there have also been limited monetary accounting of the disturbance regulating services that coastal marsh systems potentially provide. Based on a limited meta-analysis, Liu et al. (2011) assigned New Jersey's coastal marshes a value of only \$1 acre^{-1} yr^{-1} for the ecosystem service of disturbance regulation. Several studies have directly attempted to directly quantify the buffering effect of coastal wetlands to the built environment. Farber (1987) estimated the value of coastal wetlands as protection of property against hurricane wind damage. Costanza et al. (2008) using a coarse scale regression model approach, found that a loss of 1 hectare of wetland corresponded to an average of USD 33,000 increase in hurricane damage. Barbier (2015) employed an expected damage function (EDF) method, which requires modeling the production of this protection service of estuarine and coastal ecosystems and estimating their value in terms of reducing the expected damages or deaths avoided by coastal communities. At a comparatively coarse 1km^2 scale, Arkema et al. (2014) modelled the number of people and total value of property highly exposed to hazards with and without natural coastal habitats for the entire US coastline. They evaluated the reduction in risk of damages provided by natural coastal habitats to current storm intensities and five scenarios of current and future sea level. Landry and Hindsley (2011) using a hedonic property model note the influence of ocean beaches and dunes on coastal property value beyond a 300 m buffer was insignificant.

Several approaches have been used to monetize the buffering effects of salt marsh. Boutwell and Westra (2015) estimated an ordinary least squares damage function at the county/parish level for 24 storms occurring over a 13-year period along the Northern Gulf of Mexico in the U.S. Controlling for population (as an indicator of risk) and storm severity (wind), they estimated a net present value of between \$2,600 and \$3,578 per hectare of wetland. Similarly, Costanza et al. (2008) used regression analysis to estimate the monetary value of the damage protection provided by wetlands during 34 hurricanes in the U.S. beginning in 1980, with controls for economic risk (gross domestic product) and wind speed. They found a mean estimate of \$8,240 per hectare per year (\$3,230 median) for the U.S., and an average value of \$1,084 per hectare per year for New Jersey. Barbier et al. (2013) used a two-step approach to estimate the value of storm protection for the Gulf Coast in Louisiana. They derived measures of wetland continuity (wetland-to-water ratio) and roughness (amount of vegetation) and used simulated storms to measure the surge attenuation effects associated with these variables. These variables were then used in an expected damage function across 315 geographic units ("sub-planning units" of approximately 1,780 households) to determine marginal values of increasing roughness and continuity. Their findings suggest that marginal increases in wetland continuity could lower residential damages by between $592,000 and $792,000 and marginal increases in vegetation roughness could lower damages by between $141,000 and $258,000 per sub-planning unit, respectively.

The hybrid hurricane and storm event dubbed “Superstorm Sandy” of October 2012 was the most costly natural disaster to hit the Atlantic coast, and the second most costly to affect the United States. Sandy produced higher peak storm-tide elevations and caused more damage along the northern coast of New Jersey than any other coastal storm in the 20th century (Suro et al., 2016). Sandy revealed serious challenges to the resilience and sustainability of coastal systems in a densely populated region, battering and inundating major cities and the string of a few large towns and many small, ocean- and bay-front communities along what is fondly known as the New Jersey Shore, the locus of this study. This extreme weather event presented an excellent opportunity to assess the effectiveness of salt marshes and maritime forests in buffering adjacent development from storm-related damage. How well did or under what conditions did these ecosystems buffer adjacent human development (i.e., serve as green infrastructure)? To address this question, we undertook to quantify the incremental monetary value that a linear extent of fronting salt marsh and/or maritime forest had on protecting the built environment. What is novel about this study is that the analysis was conducted using National Flood Insurance Program monetary payout data and the linear marsh/forest buffer distance acquired at the scale of the individual housing unit, rather than aggregated over census tracts or municipalities. The study focused on the mainland communities that fronted Barnegat and Great Bays in Ocean County, New Jersey, USA (Figure 1).

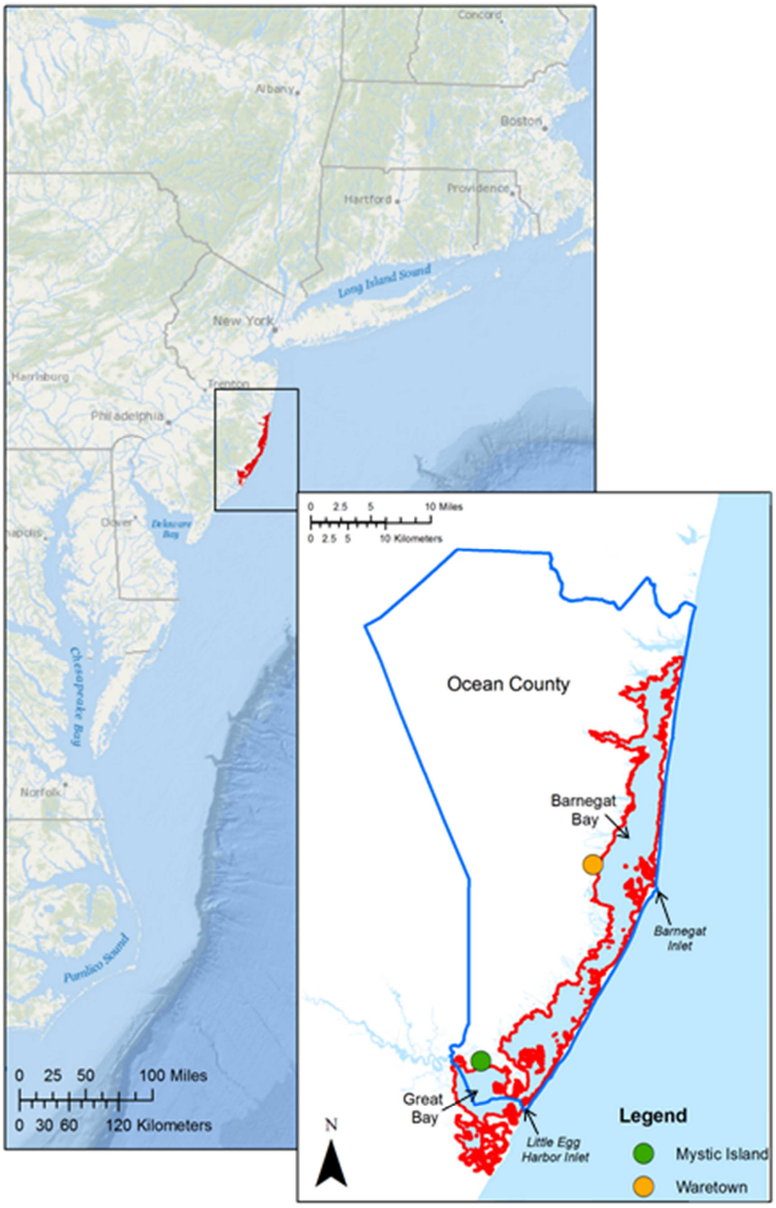

Figure 1. Map showing location of Barnegat-Great Bay study area, New Jersey, USA. Background base map source credit: ESRI.

1.1 Background

SuperStorm Sandy hit the New Jersey coast on October 29 into October 30, 2012. Meteorological and hydrological data collected at the Waretown, NJ station (midway down Barnegat Bay on the mainland side) of the Davidson Laboratory's Urban Ocean Observatory provided insight into the physical conditions during the event (Figure 2). The wind direction was approximately 30^{o} as the storm approached, then switched to 165^{o} after the eye crossed inland around 6 pm on the 29^{th}. Wave heights were highest as the storm approached, then calmed as the eye crossed and then picked up again briefly. The following reconstruction is based on Blumberg et al. (2014). At the oceanfront, Sandy's peak surge occurs at 20:00 EDT on October 29th, coinciding with the astronomical spring high tide there. Water levels reached an elevation of 8.25ft NAVD88 on the oceanfront and 1.75ft NAVD88 in the upper Bay. Peak water levels in the upper Bay occur 7 hours after the peak surge on the oceanfront, and reach an elevation of 7.25ft NAVD88 with widespread flooding along the entire Barnegat Bay shoreline. Water levels in the Bay slowly receded over the day on October 30th but were still above flood level by midnight on October 31st.

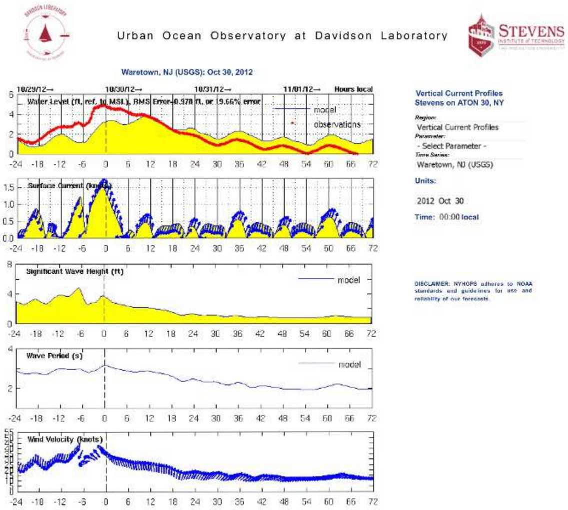

Figure 2. Meteorological and hydrological data collected at the Waretown, NJ station of the Davidson Laboratory's Urban Ocean Observatory**.**

2. Methods:

2.1 Individual parcel database

Individual housing unit parcels were used as the geographic unit of analysis. Data from nine municipalities that were on the mainland (i.e., rather than on the barrier island) and fronted either Barnegat or Great Bays was used. The municipalities included: Barnegat, Berkeley, Brick, Toms River, Eagleswood, Lacey, Little Egg Harbor, Ocean, and Stafford Townships. A parcel Geographic information system (GIS) database was developed that matched property value data from the New Jersey Mod-IV property tax database to Sandy-related flood and payout data from the National Flood Insurance Program (NFIP) administered by the Federal Emergency Management Agency (FEMA) for each individual parcel. The NFIP offers flood insurance coverage for residential structures of up to $250,000 (or in some cases up to $500,000 for larger structures) and up to $100,000 in coverage for damage to contents in communities that adopt floodplain management ordinances and practices outlined by FEMA. Discounted premiums are available in communities that undertake measures that exceed these minimum requirements. In total, over 144,000 NFIP claims for over $8.1 billion in flood damage were paid for properties affected by Hurricane Sandy in October 2012.[1] In New Jersey, of 75,000 claims filed, NFIP had paid a total of $3.9 billion to 58,055 policy holders as of January 2015.[2] The researchers on the project were given access to the FEMA NFIP Payout data for SuperStorm Sandy for research purposes with certain restrictions to protect individual homeowner confidentiality. In addition, we also examined the FEMA Preliminary Property Modeling Task Force (MOTF) damage assessment data (FEMA, 2012). The data sets were address-matched and quality checked for locational accuracy to tie the damage records to the parcels.

Additional information was derived as to the physical characteristics of each parcel. For example, parcels with higher elevations might be expected to suffer less physical damage as the result of flooding, holding all else constant. Elevation mean and standard deviations were derived from the USGS digital elevation model (1 meter DEM available through the National Enhanced Elevation Assessment https://nationalmap.gov/3DEP/documents/enhanced_elevation_data.pdf). FEMA Preliminary Flood Insurance Rate (FIRM) maps include information on flood zones and base flood elevation (BFE). FEMA defines BFE as "computed elevation to which floodwater is anticipated to rise during the base (100 year) flood." It is "the regulatory requirement for the elevation or floodproofing of structures"[3] and is expected to be positively associated with flood damage. BFE and Floodzone values were derived from the P-FIRMs and the majority value observed for each parcel was determined and assigned to each parcel. While BFE is a numeric value, it is treated as nominal in this analysis.

2.2 Quantify Disturbance Buffering Effect on built infrastructure

Based on the storm surge and wave/current modeling outputs from the New York Harbor Observing and Prediction System (NYHOPS, Urban Ocean Observatory; http://hudson.dl.stevens-tech.edu/SSWS/)) for the date of SuperStorm Sandy landfall on October 29, 2012 (described above and in Figure 2), three separate buffer analyses were conducted (Figure 3):

1) perpendicular distance (in feet) from the main body of Barnegat Bay-Little Egg Harbor;

2) 30° from North (as the storm approached); and,

3) 165° from North (after the storm made landfall).

Spatial analysis techniques in ESRI ArcMap were used to generate directional distance buffers to the closest coastal water along the three trajectories. High spatial resolution land use/land cover data derived from the NJ Land Use/Land Cover 2012 GIS data set (NJDEP, 2015) provided information on the spatial extent of salt marsh and maritime forest. The

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[1] "The Flood Insurance Claims Process in Communities after Sandy: Lessons Learned and Potential Improvements," Statement of FEMA Administrator Craig Fugate before the U.S. Senate Committee on Banking, Housing and Urban Affairs, July 30, 2014.

[2] Gurian, Scott, "Explainer: Why Many Sandy Victims are Frustrated with their Insurance Companies," *njspotlight.com*, January 20, 2015.

[3] https://www.fema.gov/base-flood-elevation

[3] http://www.state.nj.us/treasury/taxation/lpt/TaxListSearchPublicWebpage.shtml

separate and cumulative linear extent of marsh, forest, and urban land separating the property from the coastline was then determined (in feet) for each parcel centroid (Figure 3).

The cross-bay wind fetch distances along the 30 and 165 degree trajectories (i.e., distance across the bay at the specified angle to the start of each distance buffer along the shoreline) were also recorded for each parcel**.** Wind fetch was determined using the "SPM" method as listed in the USACE 'Shore Protection Manual.' In contrast to a single wind direction, the SPM method produces a wind fetch that is the arithmetic mean of nine radial measurements of 3-degree increments around the target wind direction (Rohweder et al., 2008).

In addition, perpendicular distance was measured from any tidal water body (i.e., any tidal creek or lagoon as well as the main body of the bay). Lagoonal communities (i.e., areas where the marsh and upland had been dredged to create boat access to the main body of the bay via a lagoon and the dredge spoil dumped to form long fingers of land that were subsequently developed into residential housing) were identified on recent aerial photography and there boundaries digitized. In many lagoonal communities, a parcel might be relatively distant from the main body of the bay but directly adjacent to tidal water.

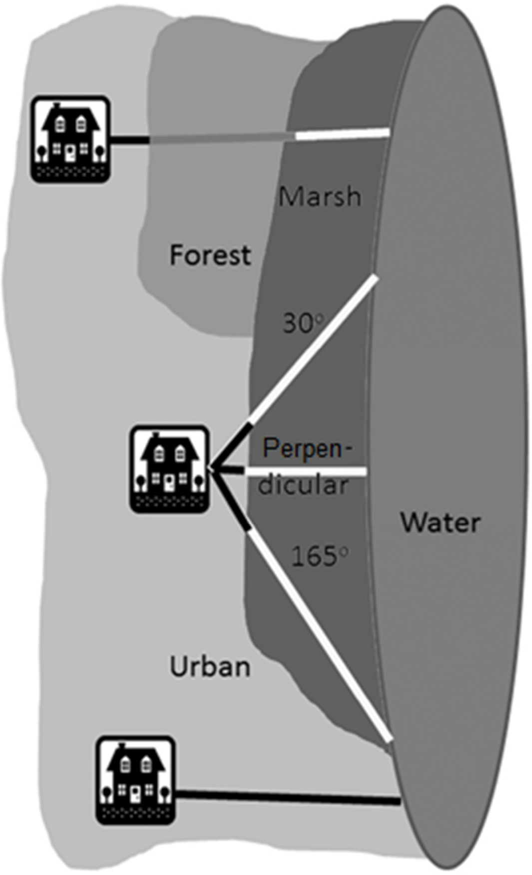

Figure 3. Graphic illustrating the three distance buffer trajectories: 30^o, 165^o and perpendicular. Note that only the perpendicular buffers are shown for the combined marsh-forest-urban and urban-only examples.

2.3 Statistical Methodology

Statistical modelling was used to estimate the relationship between the spatial extent and characteristics of fronting coastal wetlands with the various damage metrics (i.e., NFIP payout and MOTF damage data) to the adjacent built environment to quantify the level of ecosystem services related to buffering storm-related disturbance.

Similar to Boutwell and Westra (2015b), the initial baseline model is an ordinary least squares model, of the form

$$NFIP_i = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + e_i$$

where $NFIP_i$ is monetary damage sustained by a parcel as measured by National Flood Insurance Program payouts, x_1 is the average elevation of the parcel in feet, x_2 is the base flood elevation (BFE) for the majority of the parcel, x_3 is the distance in linear feet of marsh buffer measured from the shoreline adjacent to the parcel, x_4 is the distance in linear feet of forested land between the shoreline and the parcel, x_5 is the distance in linear feet of urban land cover between the shoreline and the parcel, x_6 is the assessed value of the structure on the land in 2012 (the year of the storm)[4], x_7 is a residualized form of the maximum flood depth measured at the parcel[5], and x_8 is a count variable controlling for parcels containing more than one property that may have sustained damage. A set of binary variables for the nine municipalities was included to capture variation across municipalities that is not captured in the variables measuring individual property characteristics. Inclusion of these binary variables mitigates effects of omitted variable bias that may result in biased coefficients. Additional models add a vector of binary variables for property type, a squared marsh term, buffer distances (marsh, forest and urban) along the selected major storm directions (i.e., 30^o and 165^o), a measure of wind fetch distance in these same selected storm directions, and a comparison of inside vs. outside lagoonal communities.

We tested a series of ordinary least squares models to measure monetary damages for parcels that received NFIP payouts as a function of marsh buffer, other geographic features, property value, storm severity and whether the parcel was a part of a lagoonal development (i.e., where the marsh or upland was dredged to create a series of finger canals/lagoons with the intervening space developed with housing). We applied VIF (variance inflation factor) analysis to every regression to reduce collinearity. Adjusted VIF for each variable was under 3 (target threshold < 5) with the vast majority being <2.

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[4] Because land value is largely a function of proximity to the shoreline, this variable would be expected to control for much of the same variation as is already captured in the urban and forest distance variables. As such, the land value was excluded from the analysis.

[5] Flood depth, calculated by the FEMA Modeling Task Force (MOTF) measures “the depth in feet of inundation at each structure point relative to the ground surface.” This variable is included in order to capture any influence of flood depth not detected by the other independent variables. Because this variable may also be a function of other predictors in the model, a residualized form of the variable was used.

3. Results

The resulting dataset contained 30,224 parcels, of which 12,964 received NFIP payouts (some of these were excluded from the modeling due to missing data). The 30,224 parcels and the 12,964 with payouts are shown in Figure 4. Based on further quality control, plots that failed internal logic tests (i.e., plots where the payout > parcel property value) were excluded, leaving a total of 9,706 parcels. There were 8015 lagoonal community parcels vs. 1691 non-lagoonal community parcels. Exploratory data analysis shows that while the majority of lagoonal community parcels had less than 1000’ marsh buffer, a sizeable number had marsh buffer distances of 1000 to 7000’ (Figures 5a,b). The inclusion of Forest buffer distance did not increase the overall buffer distance substantially (Figure 5b)

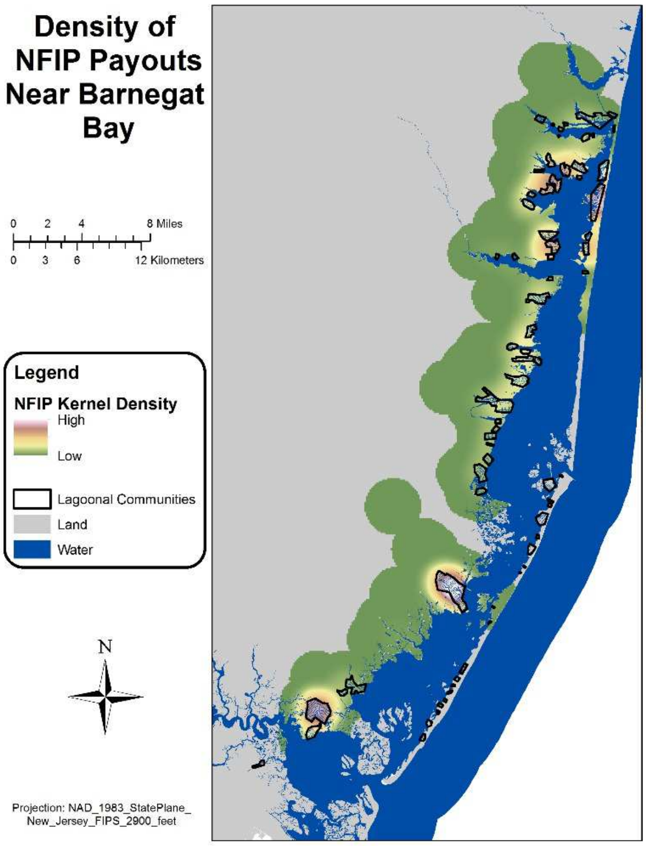

Figure 4. Kernel density map of NFIP Payouts.

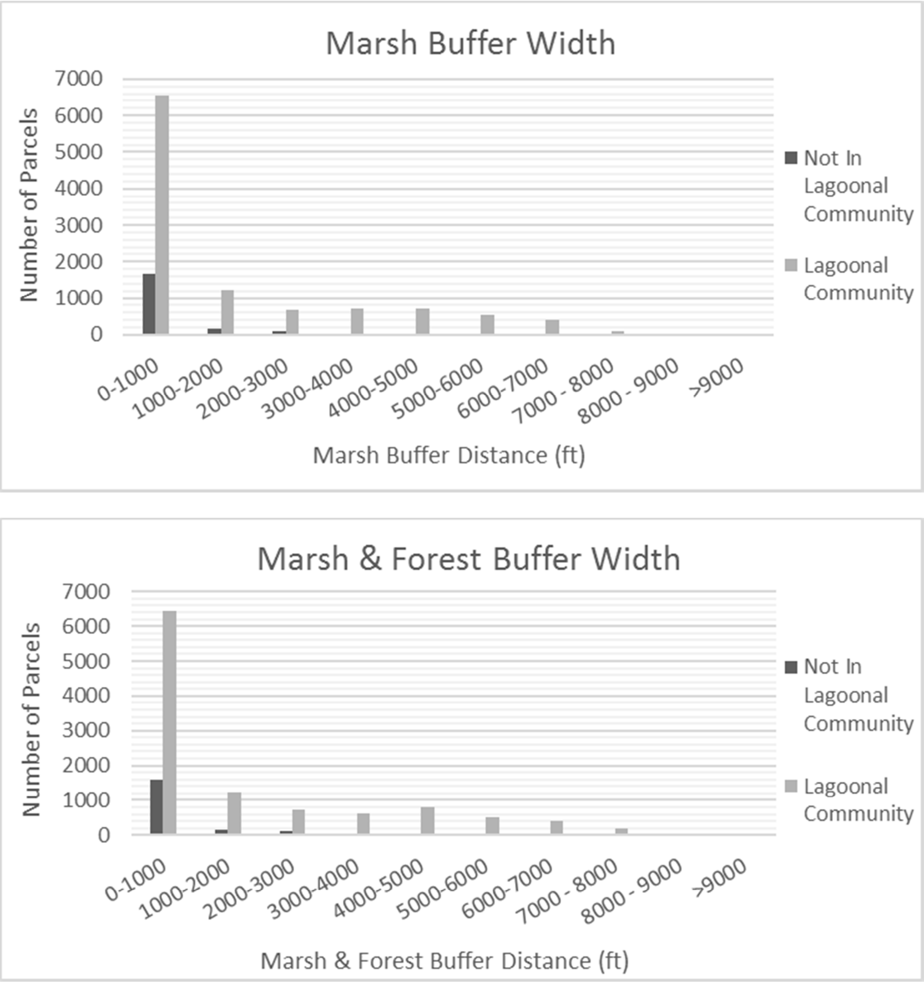

Figure 5. Histogram of number of parcels vs. buffer width for parcels within vs. outside of lagoonal communities: A) marsh only; b) marsh + forest.

Overall, there is a very weak relationship (R^2 of 0.184) between NFIP Payout and the multiple variables regression analysis (Table 1). NFIP Count, which is a measure of the number of buildings on a parcel, and Building Assessed Value (as of 2012) were highly significant (Table 2). Parcel elevation, and BFE Depth were highly significant (with Pr(>|t|) of 2.25E-82 and 6.19E-15 respectively). As expected as elevation gets higher, NFIP Payouts decrease and vice versa for BFE depth. Whether a parcel was within a lagoonal community was highly significant (with Pr(>|t|) of 1.52E-11). Distance to Tidal Water was significant (Pr(>|t|) < 0.05) 3.99E-05) with the expected negative sign (i.e., as a parcel gets further from tidal water NFIP payouts decrease). While Marsh and Urban Buffer Distance were significant (with Pr(>|t|) of 8.66E-33 and 0.00015, respectively), the coefficients were positive (i.e., NFIP payouts increased with increasing Marsh Buffer distance). Forest Buffer Distance was not significant (i.e., Pr(>|t|) < 0.05) as were the Directional Fetch Distance variables (FetchDistance30Degrees and FetchDistance165Degrees) and MOTF Flood Depth.

Table 1. Results of Econometric Analysis

Sample Size	F(19, 9686)	Prob > F	R-Squared	Adj-R2
9706	108.91	0	0.184	0.182

Table 2. Significance level of individual parameters.

Variables	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	**-22516**	**8822.65**	**-2.55**	**0.011**
NFIP count (#Buildings on parcel)	**32715.92**	**1518.279**	**21.55**	**0.000**
Elevation (Parcel mean)	**-28758.9**	**1482.63**	**-19.4**	**0.000**
Forest buffer distance	-1.79108	1.851617	-0.97	0.333
Marsh buffer distance	**4.054442**	**0.3333607**	**12.16**	**0.000**
Urban buffer distance	**3.557629**	**0.8117531**	**4.38**	**0.000**
BFE (Parcel majority)	**6038.491**	**885.856**	**6.82**	**0.000**
Building_assessment_2012	**0.022506**	**0.0023297**	**9.66**	**0.000**
Fetch distance 30degrees	0.045846	0.0441911	1.04	0.300
Fetch distance 165degrees	-0.01831	0.0548869	-0.33	0.739
Distance to tidalwater	**-13.0167**	**2.673717**	**-4.87**	**0.000**
Lagoonal community**	**6596.054**	**1499.236**	**4.4**	**0.000**
MOTF flood depth	-15.5969	454.7523	-0.03	0.973

*Bold variables have significant coefficients.

** Dummy variable for a location in a lagoonal community (1=Y, 0=N).

Separate models were run for lagoonal and non-lagoonal communities. The overall R^2 for the lagoonal model was still quite weak (R^2 = 0.157). The variables of Elevation, BFEMajority, Marsh distance (positive), and Urban distance were significant. For non-lagoonal communities, the overall model had a stronger R^2 (R^2 of 0.423). In addition to NFIP Count and Building Assessed Value, Elevation and Marsh Buffer Distance were significant variables.

4. Discussion

Our study is the first to our knowledge that examined the NFIP payout data and coastal marsh and maritime forest buffers for a real storm event at the scale of the individual parcel. Examination of the Econometric analysis results (Table 1) suggests that while the overall model was weak (i.e., adjusted R^2 of 0.187). some of the variables examined were statistically significant. Higher NFIP payouts were found to be positively associated with #Buildings on Parcel, Building Assessment $ Value, BFE, Inside Lagoonal Community, and negatively associated with Parcel Elevation and Distance from Tidal Water. Counter to our original hypothesis, higher NFIP payouts were positively associated with greater Marsh and Urban Buffer distance (Forest Buffer Distance was not significant). Fetch Distance and MOTF Flood Depth were not significant. Elevation, Lagoonal Communities and BFE Majority had the biggest effect on NFIP Payouts with: Elevation (-$28,759); Lagoon (+$6,596) and BFE (+$6,038) (based on regression coefficient). The Elevation effect was stronger in Non-lagoonal communities.

Distance from Tidal Water has an effect in the composite and lagoonal-only models but no effect in the non-lagoonal regression model.

A key limitation of our analysis was that damage payout data were not available for properties with flood damage that were not compensated by NFIP payouts. It is not clear how much non-NFIP-covered flood damage may have occurred and these damages are not captured in the analysis. We did not have data on the existence of NFIP policies for properties that did not receive payouts for flood damage; for this reason, all properties that did not receive payouts – including possible NFIP-covered properties that did not suffer damages – were thus excluded from the analysis. This also limited our ability to implement models estimating or controlling for the probability of flood damage as measured by the presence of an NFIP claim or payout. On a different note, we did not have the actual location of the building footprints with the parcel boundaries. Thus we employed average attributes of parcels rather than the specific building itself; for example, the average elevation for the parcel rather than the elevation for the building proper. While having finer granular data would be useful, we don't believe it would have substantively changed the results.

Our expectation going into this study was that coastal marshes would serve to reduce the damage due to Superstorm Sandy related flooding. However, we found that Marsh and Urban Buffer Distance had a weak effect ($4.05 and $3.55/per foot distance) but in the wrong direction (i.e., in a counterintuitive positive fashion with increasing marsh buffer increasing the NFIP payouts). Taken at face value, one might conclude coastal marshes had no protective value; that increasing marsh buffers actually increase storm damage and NFIP payouts. Other studies conducted in the same geographic location for the same storm as our work found that marshes had a protective effect. Using risk industry-based flood models, Narayan et al. (2016) estimated that coastal wetlands saved more than US$ 625 million in avoided flood damages from Superstorm Sandy across the northeastern USA. For census tracts with wetlands, there was on average a 10% reduction in property damages across the region. To examine the benefits of wetlands beyond an individual hurricane, they estimated the effects of saltmarshes on annual flood losses to properties in Ocean County, New Jersey for 2000 storm events. Areas behind existing marshes were predicted to have an average of 20% less property losses than areas where marshes have been lost. However, it should be noted that this study analyzed coarser resolution damage data aggregated to the census tract or municipal level. Loerzel et al. (2017) combined coastal hydrodynamic and wave models (i.e., the Advanced Circulation (ADCIRC) and Simulating Waves Nearshore (SWAN) models) to estimate flood depth for both a "marsh present" and "marsh absent" (i.e., replaced with open water) scenarios. The study calculated the avoided residential property damages for individual structures under a given storm scenario based on the modeled floodwater depth and by the structure's property value (as derived from the parcel's tax valuation data). They estimated a storm reduction value of wetlands at approximately of $8.34 million for a SuperStorm Sandy-like event. The marsh was shown to be of highest value in the simulated 50-year storm ($13.1 million) in terms of absolute value and lower value for a 25-year storm ($9.8 million) suggesting a threshold effect for storm damage reduction benefits.

Thus it would appear that these two studies completely contradict what we observed. Upon further reflection, we explain our results this way, 1) we analyzed fine scale resolution of actual parcel-level monetary damage data; 2) we examined marsh/forest buffer distances for individual parcels; 3) while the intervening marsh buffers may have diminished wave energies and reduced damage, they were not sufficient to attenuate the storm-related surge; and 4) most importantly, a vast majority of the mainland parcels within the Barnegat-Great Bay study area that received NFIP payouts were located in lagoonal communities. By their very nature most lagoonal communities were built directly atop coastal marshes and are generally surrounded by marsh. As seen in Figure 4, the hotspots of NFIP payouts are largely found in lagoonal communities either along the mainland shore or the back-side of the barrier islands. As seen in Figure 5, the parcels within lagoonal communities show higher marsh buffer distances then most developed parcels outside lagoonal communities. Because these lagoonal communities sit at comparatively low elevation and are directly adjacent to tidal water, they are consequently highly vulnerable to storm surge damage. While high winds and waves were responsible for damage along the barrier island beaches, storm-surge related flooding after the storm had made landfall was responsible for most of the damage in these back-bay communities (Suro et al., 2016).

A perfect illustration of the lagoonal community effect is the Mystic Island development (Figure 6). Even though this community is separated from Barnegat and Great Bays by extensive coastal marshes, the community was heavily damaged by SuperStorm Sandy with many parcels receiving NFIP payouts (Figure 4). In the case of SuperStorm Sandy, the storm surge of 2 meters completely submerged the fringing coastal marsh. Further, the finger canals (lagoons) are tidal with a direct connection to the estuary and thereby rise with the storm surge. As most of the homes built only several feet above MHHW and many not elevated on pilings, this development was highly vulnerable to flooding by SuperStorm Sandy's surge.

Figure 6. Natural color aerial image (acquired February 2017) of Mystic Island development, near Tuckerton, New Jersey.

In considering the protective value of coastal marshes, one must separate the effect of storm surge related flooding with wave height and energy reduction. Post-storm reconstruction of High Water Mark data, conclusively show that under the extreme conditions of SuperStorm Sandy these salt marshes flooded with water upwards of 2m in depth (Suro et al., 2016). No data are available on the role that these marshes may have had in reducing wave heights or dissipating wave energies. Modeling and empirical studies suggests that this may have been the case. Hydrodynamic modeling studies demonstrate that vegetation can have a damping effect on wave energies but that effect is lessened with increasing depth (Mendez et al., 1999). One set of experimental flume studies attributed a 60% reduction in wave height due to marsh vegetation even when flooded to a depth of 2m (Moller et al., 2014). While related, the role of coastal marshes in attenuating storm surge is also distinct. Based on prior work on the Louisiana Gulf Coast, it would take 14.5 km of marsh buffer to attenuate a storm surge of 1m (at a surge attenuation rate of approximately 7.6 cm (vertical) for every linear mile of marsh; Louisiana Coastal Wetlands Task Force, 1998). Wamsley et al. (2010) updated this earlier work on the potential of Louisiana's wetlands to reduce storm surge based on empirical data and modeling studies. They found the range of surge attenuation rates was 1m per 60km to 1m per 4km. They concluded that wetlands have the potential to reduce surges but that it is dependent on landscape and storm characteristics. Lawler et al. (2016) modeled a series of barrier island and back bay systems on the Virginia coast that are more similar to the Barnegat Bay situation than the Louisiana wetland studies. They found that strong storms like Sandy producing surges of 1m or more, may overwhelm the mitigating impact of other factors such as friction and attenuation effects contributed by back bay wetlands. Thus while it is very likely that the Barnegat-Great Bay salt marshes served to reduce Superstorm Sandy-related wave energies, they were of insufficient spatial extent to attenuate the storm surge. We should note that the greatest marsh buffer distance we measured in our study areas was on the order of 2.4 km (1.5 miles).

5.Conclusions

While salt marshes may be effective in diminishing wave energies and buffering adjacent development under normal conditions, in the case of SuperStorm Sandy, our study did not demonstrate significant effect on reducing surge-related flooding. We found no evidence that increasing marsh buffer distance reduced the $ amount of NFIP payouts for those properties that received NFIP payouts. These results run counter to our original hypothesis that increasing marsh (and or forest) buffer distance would serve as a protective buffer lowering NFIP damage payouts to storm-affected residential properties. The factor that appears to be critical in terms of explaining our results is that the bulk of the residential properties damaged in our study area were located in lagoonal communities. These lagoonal communities are built directly adjacent to tidal water and are thereby highly vulnerable to storm surge-related flooding whether or not they are buffered by adjacent marshes. The results of this study should not be misconstrued in concluding that salt marshes do not have a positive value as storm and flooding protection, as well as a host of other valuable ecological services. Rather, their protective buffering capacity for extreme storm events is limited and that lagoonal-style developments remain highly vulnerable to sea level rise and future storms. Thankfully, New Jersey banned this dredging, filling and development of coastal marshes in its pioneering Wetland Act of 1970, as well as the Coastal Area Facility Review Act of 1973 (CAFRA) (Fair, 2004). Unfortunately, the state is saddled with the legacy of these ill-advised development decisions in the form of thousands of acres and housing units located in lagoonal developments scattered all along its Atlantic coast. If these highly vulnerable communities are to be protected from future large storm events, then the feasibility of employing a hybrid approach that supplements the existing natural infrastructure with additional engineered structures such as removeable flood gates and/or moveable flood walls (Sutton-Grier et al., 2015) needs to be explored.

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Figure Captions

Figure 1. Map showing location of Barnegat-Great Bay study area, New Jersey, USA. Background base map source credit: ESRI.

Figure 2. Meteorological and hydrological data collected at the Waretown, NJ station of the Davidson Laboratory's Urban Ocean Observatory**.**

Figure 3. Graphic illustrating the three distance buffer trajectories: 30^o, 165^o and perpendicular. Note that only the perpendicular buffers are shown for the combined marsh-forest-urban and urban-only examples.

Figure 4. Kernel density map of NFIP payouts.

Figure 5. Histogram of number of parcels vs. buffer width for parcels within vs. outside of lagoonal communities: A) marsh only; b) marsh + forest.

Figure 6. Natural color aerial image of Mystic Island development, near Tuckerton, New Jersey.