Evaluation of NYC's Coastal Vulnerability and Potential Adaptation Strategies in the Wake of Hurricane Sandy

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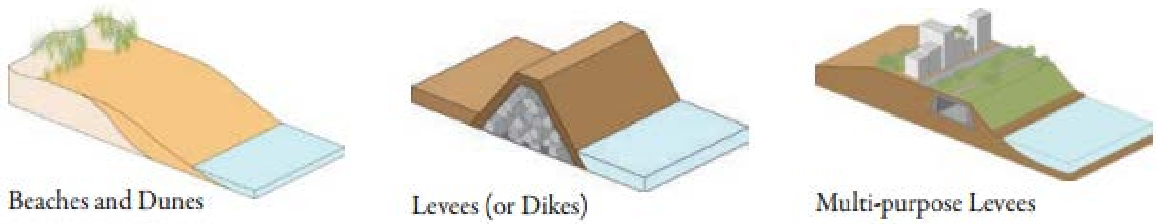
Introduction

Hurricane Sandy made landfall in Brigantine, NJ on October 29, 2012 (Blake et al. 2013). Although declassified to a tropical storm, hurricane-force wind gusts were reported in and around NYC (Kiernan and Lenhardt 2013, Blake et al. 2013). Moving approximately 37 km/h before landfall, Sandy slowed dramatically as it moved across the region (Blake et al. 2013). The storm's extraordinary size, slow progress, and track resulted in record-high surges, killed 43 people, caused more than 600,000 homes to lose power, left 20,000 people homeless, closed 40 schools for the remainder of the year, flooded 17% of the city's total land mass, and damaged $19 billion worth of public and private property in NYC (Office of the Mayor 2012, Spurlock 2012, Kiernan and Lenhardt 2013, NYC 2013, Tollefson 2013, Blake et al. 2013, Patrick 2014, CCRUN). On Staten Island, the peak surge was 2.91 m above normal and the combined surge and astronomical tide peaked at 4.44 m above the mean lower low water at Bergen Point West Reach (Blake et al. 2013). On top of the storm surge, waves upwards of 10 m battered the coastline (NYC 2013, CCRUN). The most heavily damaged area of NYC was Staten Island, where 21 people died, primarily as a result of heavy winds, and thousands of homes were destroyed, primarily due to the surge and waves. While damages from Hurricane Sandy were significant, the storm could have been significantly worse if it had made landfall at another time. Modeling efforts by Colle et al. (2015) have shown that storm surge and storm tides could have been at least 0.5 m higher.

After Hurricane Sandy experts and residents alike agreed that sea level rise, coastal flooding and storm surges, and extreme events pose the greatest threats to NYC in the coming decades (NYC 2013, Miller et al. 2014). In many ways, Sandy served as a call to action to revitalize and reimagine NYC's coastlines to be more sustainable and more resilient to these threats. Over the last few years many ideas have been proposed regarding how to best protect the city's coastlines. Before leaving office the Bloomberg administration conceived a $20 billion coastal protection plan for NYC (NYC 2013). The plan includes "hard", "green", and "hybrid" strategies for reducing coastal flood risks (NYC 2013, NYC DCP 2013, Tollefson 2013, Miller et al. 2014, Spalding et al. 2014). "Hard" engineering solutions include construction of storm surge barriers, levees, sea walls, groins, bulkheads, tide gates, and armored stone barriers (NYC 2013, NYC DCP 2013) (Figure 1). Although costly to build and maintain, previous research has shown that they can be effective at reducing wave damage, keeping out storm surges and protecting coastlines from imminent sea level rise (Coch 2012, NYC 2013, NYC DCP 2013). The “green” strategies included in NYC’s coastal protection plan include beach nourishment, dune construction and stabilization, and the creation and maintenance of living shorelines, including wetlands (NYC 2013, NYC DCP 2013) (Figure 1). Jointly referred to here as green infrastructure (GI), these strategies utilize soil and vegetation to mimic natural functions and processes, facilitating infiltration, detention, or other benign redirections of water. These strategies are believed to be able to mitigate coastal risks while restoring, enhancing, or creating new forms of urban habitat and providing other valuable ecosystem services (Montalto and Steenhuis 2002, Wilks 2011, Temmerman et al. 2014, Spalding et al. 2014). GI systems are also believed to be useful in managing stormwater, creating recreational opportunities, and mitigating the urban heat island effect. They are considered by some to be more cost-effective than equivalent hard engineering approaches to the same problems (Gedan et al. 2011, Spalding et al. 2014, Barbier 2015). “Hybrid” solutions combine the physical barriers of “hard” engineering with the aesthetic and

Figure 1: Examples of "green," "hard," and "hybrid" coastal engineering features. Source: NYC DCP 2013



habitat features from “green” solutions (Figure 1).

Prior to Hurricane Sandy the NYC coastline was already dotted with a number of GI sites. Parks, wetlands, beaches, and maritime forests lined the shores, though these habitats were non-uniform and not continuous over the entire coastline. Qualitative evidence has suggested that some of the existing dunes or marshlands may have played a role at reducing property damage during Hurricane Sandy (TNC 2015a, TNC 2015b). However, there is little scientific research validating these conclusions.

Studies quantifying the protective value of coastal GI for reducing property damage during Sandy-type events is limited, especially in urban areas. Along the Gulf Coast averted damages during individual storms are estimated between $23 and > $400,000 per hectare of wetland, with an average of $5,000 per hectare (Barbier 2015). The US Army Corps of Engineers (ACE) reports that every 2.7 miles of wetlands can reduce storm surges by one foot, although in urban areas finding such large, undisturbed tracks of wetlands are rare (ACE 1963). It generally appears that the storm protection services of wetlands are variable and highly dependent upon wind speed, storm forcing, elevation, the surrounding coastal landscape, waterbody connectivity, and vegetation (Barbier et al. 2008, Resio and Westerick 2008, Loder et al. 2009, Ebersole et al. 2010, Wamsley et al. 2010, Gedan et al. 2011, Acreman and Holden 2013, Barbier and Enchelmeyera 2014, Spalding et al. 2014, Hu et al. 2015). During slow moving storms with high winds, research has shown that surge can actually be higher over wetlands than in surrounding areas (Resio and Westerink 2008, Wamsley et al. 2010, Hu et al. 2015). Others report that the relationship between wetlands and flooding depends on wetland type and location. Upland wetlands offer the most flood protection during heavy rainstorms, while lowland wetlands are more useful for coastal protection (Acreman and Holden 2013). Vegetation is also a key factor, with surge and wave reduction both increasing as stem height and stem density increase (Loder et al. 2009, Spalding et al. 2014, Hu et al. 2015). The one fact that is consistent throughout the literature is that wetlands and natural areas are capable of reducing wave damage (Gedan et al. 2011, Loder et al. 2009, Spalding et al. 2014, Barbier and Enchelmeyera 2014). The degree of wave attenuation is primarily determined by continuity and surface roughness, not overall hectares or hectares traversed. As such, even small natural areas are capable of providing significant wave attenuation during storms (Barbier et al. 2008, Loder et al. 2009, Gedan et al. 2011, Barbier and Enchelmeyera 2014, Fagherazzi 2014).

Although the ability of urban coastal GI to reduce coastal risks has not been well studied and related studies often offer contradictory conclusions, the government has committed to greening NYC shorelines for coastal protection (Schuster and Doerr 2015). The ACE has initiated significant dune and beach restoration projects along large sections of coast (Gardner 2013). On Rockaway Beach, the ACE effort will ultimately replace more than 2.6 million cubic meters of sand to reduce risks from future storms (Gardner 2013). This volume includes sand lost during Hurricane Sandy, as well as sand lost to wind and wave erosion since the last re-nourishment project during 2004 (Gardner 2013). The DeBlasio Administration committed $12 million of the city’s money to the restoration of city-owned wetlands in Staten Island (Office of the Mayor 2014) and the US Environmental Protection

Agency (EPA) has provided grants to assist with NYC's Parks and Recreation Department's (NYC Parks) efforts to protect, restore, and monitor salt marshes, including new designs for Jamaica Bay (EPA 2014). Additional efforts call for the restoration and creation of living shorelines, oyster beds, and marsh islands (TNC 2015b, Schuster and Doerr 2015).

The purpose of this study is to investigate what role NYC coastal GI played in building damages during Sandy. Specifically, we wish to determine whether damages can be adequately predicted using only discrete physical relationships, such as topographic, distance to the coast, or proximity to a green space. We are also interested in which green features of NYC's coast were most strongly related to damages, and specifically in what way. This study looks at three case study sites – Coney Island, Brooklyn; Rockaway, Queens; and the South Shore of Staten Island. At all three sites we hypothesize that predicting damages without including a property's relationship to GI will be insufficient. We also hypothesize that NYC's coastal GI, despite being small and fragmented in many places, offered some protection to people and property during Hurricane Sandy.

To test both theories we will generate two models for damage prediction. Model 1 will try to predict damages using only geographic and architectural information. Model 2 will also include each property's physical relationship to GI. ANOVA testing will be used to compare whether there are significant differences between models. Results from the best model for the data will then be used to explain which features of the coast are most strongly linked to damages and which offered the most protection from Hurricane Sandy.

Materials and Methods

Data Available

To conduct this analysis we gathered a variety of datasets pertaining to NYC's green infrastructure, physical and social characteristics, climatic risks, and damages that occurred during Hurricane Sandy. The majority of these datasets were shapefiles or raster images; many were available for public download while others were acquired through a data sharing agreement between Drexel University, the Trust of Public Land (TPL), and the City of NY. The statistical tests are presented on only a small subset of the total database. The datasets chosen for analysis were based on the researchers understanding of what factors might have contributed to making a property more or less vulnerable to the effects of Hurricane Sandy and are described briefly in Table 1.

Table 1: Summary of datasets used in analytical and statistical analysis.

Layer	Description	Source	Other Notes
Elevation	Approximate elevation above sea level for all of NYC.	Raster file derived from 1-foot contours; available through data-sharing agreement	Original 1-foot contours derived from calibrated LIDAR and clipped at the shoreline.
Coastline	Polygon file showing the location of streams, rivers, and coastal waterbodies	Derived from 2010 CUGIR ; supplied by TPL	Used to calculate distance from the coast
Soil Survey	The soil name, permeability, type (natural, fill, mixed, etc.) for all of NYC	USDA 2005 Reconnaissance Urban Soil Survey	Field work conducted between 1996-1999; polygons derived from 1984-1985 field sheets
Surface Type	Raster file dictating permeable (tree canopy, grass / shrub, bare soil, water) and impermeable surface types (buildings, road / railroads, other)	University of Vermont Spatial Analysis Laboratory and New York City Urban Field Station	3 foot resolution; derived from 2010 LIDAR and 2008 4-band orthoimagery. Overall accuracy 96%
CAP Damages	Damages to housing units, as measured by aerial photography taken by the civil air patrol between 10-29-2012 and 11-8-2012	Civil Air Patrol (CAP)	Houses provided with two separate values: 0 (flooded), 1 (not flooded), which the Drexel team determined by intersecting the data with FEMA's SLOSH model of the Sandy SUrge; and a damage estimate on a scale from 0 – 4 (Not damaged → destroyed), which the CAP estimated from analysis of their aerial photography. The combination of these scores determined the total Damage Combination Value
Wetlands	Location of all NYC wetlands	Derived from 2010 CUGIR ; available through data sharing agreement	
Parkland	Location of all parkland in NYC (doesn't distinguish between waterfront / not waterfront)	Supplied by DPR	
Waterfront Parkland	Location of all waterfront parkland	NYC Department of City Planning	Any parkland separated from the water by a road is excluded (even if it is part of the same park)
FEMA Inspection	Summary of the number of houses inspected and offered aid by FEMA for each zip code. Dataset also provides the total assistance and average assistance per household. Available at the zip code scale.	FEMA	Values representative only for those houses who requested assistance above and beyond what was covered by private insurance.

For this analysis it was important to have a measure for property damage sustained during Hurricane Sandy. Unfortunately, only coarse information on building damages was made available by the Federal Emergency Management Agency (FEMA) and the Civil Air Patrol (CAP). The former consisted of average damage and assistance estimates for households whose repairs were not completely covered through private insurance; in other words, the FEMA dataset only represents damage costs for those properties which requested FEMA assistance. Additionally, this dataset was only available at the Zip Code level. The CAP damage data, developed by aerial photography, consisted of a categorical characterization of damages from 0 (not damaged) to 4 (destroyed) (Table 2). This categorization was not available for every parcel within the city, nor was the dataset uniformly distributed; the greatest concentration of CAP assessments were available along the coastlines most heavily impacted by the storm. Due to its more direct relationship to property damage, the CAP dataset, and not the FEMA estimates, was the primary indicator of damage severity used in this study. It should be noted that NYC's Department of Buildings has a quantitative, parcel-based damage dataset that was not available to the researchers due to confidentiality concerns.

Table 2: Description of CAP categorization of damages.

CAP Rating		**Description of Damages**
Not Damaged	0	No noticeable damage to buildings; may be some displacement of light structures
	1	Generally superficial damage to structures (loss of tiles or roof shingles) and / or displacement.
Damaged	2	Solid structures sustain significant exterior damage (e.g. missing roofs or roof segments).
	3	Some solid structures are destroyed and / or partially collapsed; most sustain exterior and interior damage (roofs missing, interior walls exposed).
	4	Most structures destroyed or washed away by surge effects.

Study Boundaries

While most datasets were available for all of NYC, this study was restricted to three of the most heavily damaged areas – Coney Island in Brooklyn, the Rockaway Peninsula in Queens, and the South Shore of Staten Island (Figure 1). Total and average FEMA assistance were highest in these areas. CAP damage assessments were also plentiful in these regions, with 7,237 points from Coney Island, 6,756 on the Rockaways, and 4,168 along the South Shore. Within the Rockaway dataset, the 132 houses that were destroyed or severely damaged by an electrical fire in Breezy Point during the midst of Hurricane Sandy were removed from this analysis, since fire damage was a secondary impact of the storm.

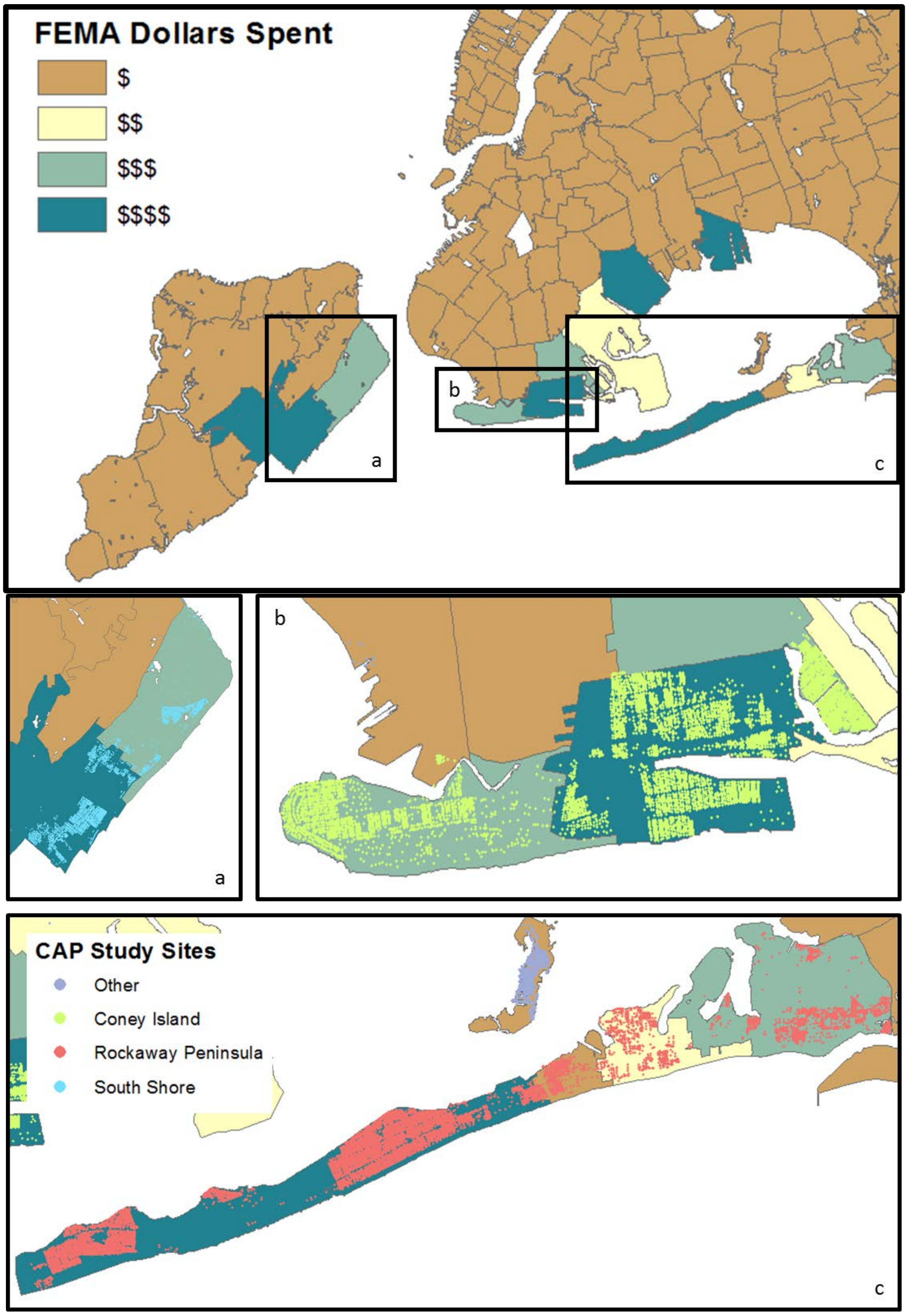


Figure 2: Location of the three study areas - Coney Island, Brooklyn; Rockaway Peninsula, Queens; and South Shore, Staten Island

Regressions

Two binomial logistic regressions were run for each study site to explore the relationship between damage severity (measured on a scale form 0-4) and various physical features. For both regressions the CAP data was divided into two categories – “damaged” and “not damaged.” Any house which had been rated a 0 or 1 by CAP was included in the “not damaged” category, while any house that had received a CAP rating of 2 or more was marked as “damaged” (Table 2). Each logistic regression attempted to determine whether a parcel was damaged based on the physical features of the property. Regressions were trained on 80% of the data for each study site and then tested on the remaining 20%. Receiver Operating Characteristic curves (ROC curves) were used to evaluate the predictive capacity of each logistic model. ROC curves plot how well the regressions separated CAP points into houses with and without damage; accuracy is measured by the area under the ROC curve (AUROC), with an area of 1.00 representing a perfect fit and 0.50 indicating the model is no better than random guessing (Tape). McFadden’s pseudo-R^2 values were also used to evaluate the goodness of fit for each model, to compare their performance. Pseudo R^2 tend to be low for logistic regressions; for our purposes any values greater than 0.20 indicate the model is an excellent fit for the data (McFadden 1979).

Table 3: Description of the variables in models 1 & 2.

Independent Variables	Model 1	Model 2
Elevation	X	X
Distance to the Coast	X	X
Building Area	X	X
Building Height	X	X
Soil Permeability		X
% Tree Canopy		X
% Grass		X
% Bare Earth		X
Distance to the Nearest Natural Area		X
Size of the Nearest Natural Area		X

Model 1 sought to predict damages at each study site using only a property’s elevation above sea level, distance from the coast, building area, and building height (Table 3). The rationale behind Model 1 is that damages are primarily a result of exposure to the storm. Hurricane Sandy was a storm characterized by a large storm surge so we expect that the properties with the greatest odds of being damages were those with the greatest exposure to this surge. In other words, we expected the results of Model 1 to show that small, short houses close to the shore and at low elevations had the greatest odds of being damaged.

Model 2 predicts damages using all the factors in Model 1, plus the property's relationship to various GI elements (Table 3). These GI elements include soil permeability, which was represented on a scale from 0-5; distance to the nearest natural area, which includes parks, wetlands, beaches, and other nature-based coastal GI; and the amount and types of pervious surfaces near the property. Pervious surface coverage is measured as the percentages of a 50mX50m square, centered on the property, that is occupied by either tree canopy, grass, or bare earth. Bare earth is a proxy for sand, and therefore beaches (Table 3).

Within each study area ANOVA testing revealed whether Model 1 and 2 were statistically different or not. A p value ≥ 0.05 indicated that Model 1 was sufficient for estimating damages in that study area, while a p value ≤ 0.05 indicated that the models were significantly different from one another and that model 2 provided more information. Differences in McFadden's R^2 values were then used to pick the better of the two models, while AUROC was used to estimate each model's predictive capacity, regardless of goodness of fit. Using the best model for each study area a thorough examination of how factors influenced the odds of being damages was conducted. Significance, standardized coefficients (β values), and the change in odds were all used to characterize and to explain the relationship between each predictor and property damage, using the best model for each study area. Any variable with a p value < 0.05 was considered a significant predictor. β values revealed the magnitude and sign of the relationship between each variable and damages. Standardization of the β values allows all variables to be compared to one another, despite their differing units. The change in odds was calculated from the odds-ratios and represent the impact that a one unit change in the independent variable would have on the odds of a property being damaged. Both the β values and change in odds represent a variable's influence on damage while holding all other variables constant. Also, negative β values and changes in odds indicated that a variable is negatively correlated to damages; in other words, as that variable increases the odds of a property being damage decrease.

Results and Discussion

ANOVA Results

ANOVA results reveal that Model 1 and Model 2 are statistically, significantly different at all three study sites, with p values less than 0.001 (Table 4). McFadden's R^2 values were used to determine which model was the better fit for the data at each study site. At all three study sites Model 2 had higher McFadden's pseudo-R^2 values, suggesting that the relationship of a property to local GI mattered (Table 4). All three Model 2s also have ROCS values of at least 0.80, also suggesting that the GI information is important (Table 4) (Tape). On Coney Island the McFadden's pseudo-R^2 value improves by 0.07 points between Models 1 and 2; the difference is 0.17 and 0.14 for the Rockaway and South Shore models, respectively (Table 4). Comparison of all three Model 2s suggests that the regression on the Rockaway dataset has the best overall fit, with a McFadden's R^2 value of 0.20 (Table 4) (McFadden 1979). Because Model 2 was an improvement over Model 1, a detailed examination of the Model 2 results for each of the three study sites is presented below.

Table 4: Comparison of Model 1 and Model 2 for the Coney Island, Rockaway, and South Shore study sites.

		Coney Island, Brooklyn	**Rockaway, Queens**	**South Shore, Staten Island**
Model 1	AUROC	0.80	0.64	0.70
	McFadden's pseudo-R^2	0.11	0.03	0.04
Model 2	AUROC	0.85	0.82	0.82
	McFadden's pseudo-R^2	0.18	0.20	0.18
	ANOVA (chi-square)	**$p < 0.001$**	**$p < 0.001$**	**$p < 0.001$**

Coney Island, Brooklyn

Results of the Coney Island logistic regression are shown in Table 5. Elevation, distance to the coast, the amount of bare earth around a property, building area, and the size of the nearest natural area are the only significant predictors in the model (Table 5). Model fit is estimated by the AUROC, which is 0.85, and McFadden's pseudo R^2, which is 0.18 (Table 4). Both values suggest that the logistic regression is a good fit for the data.

Table 5: Results of the Coney Island logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and each variables impact on the odds of being damaged.

Coney Island Model 2	Mean	Standard Deviation	Standardized (β) Coefficient	Significance*	Change in Odds of Being Damaged
Soil Permeability	3.37	0.91	4.58	*	83.38
Elevation (ft)	8.12	1.73	2.50	*	18.69
Distance to the Coast (m)	1016	776.2	-13.10	***	-0.20
% Tree Canopy	14.45	11.22	1.71	.	1.83
% Grass	9.97	7.89	-0.30		-0.45
% Bare Earth	0.22	2.43	0.81	*	3.99
Building Area (ft^2)	2665	2827	2.84	***	0.01
Building Height (floors)	1.975	0.93	-1.08		-18.69
Distance to the Nearest Natural Area (m)	630.8	362.9	1.22		0.04
Size of the Nearest Natural Area (acre)	270.6	354.5	10.30	***	0.35
*p value = '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 0					

The Coney Island logistic regression confirms some intuitive relationships – namely that houses close to the beach had the greatest odds of being damaged during Hurricane Sandy. This is supported by the fact that the odds of being damage decrease by 0.20% for every 1 unit (1 meter) increase in distance from the shore (Table 5). Similarly, the more bare earth that can be found around a property, the greater the odds of being damaged (Table 5). For every 1% increase in the amount of bare earth within the 2,500m^2 of land surrounding a property, the odds of being damage increased by nearly 4% (Table 5). Together, these results suggest that houses closest to the beach had the greatest odds of being damaged. This is further corroborated by the role of natural areas at predicting damage odds. Houses nearer to large natural areas were at greater risk of being damage (Table 5). Around Coney Island the two biggest natural areas are the beach and Marine Park, both of which are adjacent to the shorelien.

One relationship which appears counterintuitive is the relationship between elevation and damage. One would initially expect that if houses closest to the beach were more damaged, elevation would also be directly proportional to damage. In fact, Model 2 suggests that a one unit increase in elevation actually increases the odds of being damaged by 18.69% (Table 5). The topography of Coney Island provides one possible explanation (Figure 3). Elevation is actually higher nearest the beach and close to the shore. The analysis presented here cannot explain how these three variables (elevation, distance to the coast, and bare earth) interacted with one another, but the results clearly indicate that buildings subject to the triple threat of surge, wave damage, and severe winds were more likely to be damaged than those further inland. Future studies are needed to confirm whether these buildings actually protected houses further inland from the worst of the storm.

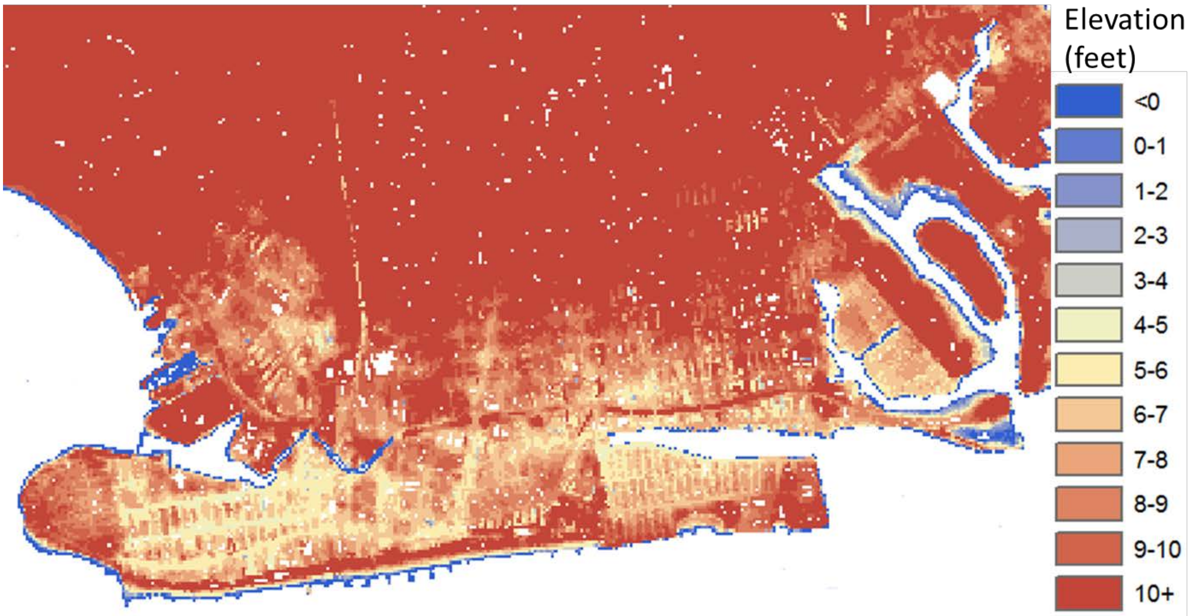


Figure 3: Elevation map of the Coney Island study area.

Another relationship that is significant on Coney Island is the impact of building area. The model suggests that an increase in building area increased the odds of being damaged. This is only relevant for large changes in building area, as small increases do not significantly affect the odds of being damaged at all (odds ratio = 0.01) (Table 5). This result likely stems from the high number of high-rise apartment buildings found along the boardwalk of Coney Island and the proximity of Kingsborough Community College buildings to the shore (Berke 2012). These buildings have a larger total area than more traditional single-family or multi-family homes, exposing more of their ground floors to damage from surge, plus their height and proximity to the shore would have exposed them to the worst of the wind.

The last very important predictor of damages on Coney Island is soil permeability. Soil permeability is measured on a scale from 0-5, with 0 representing very slow permeability and 5 very fast. The regression suggests that houses with higher permeability were more likely to be damaged than those with lower permeability. A one unit increase in soil permeability increased a property's odds of being damaged by more than 80% (Table 5). The soil permeability map for Coney Island reveals that the most permeable soils are found right along the coast, near beaches and parkland, with a large concentrations of high permeability sand (Figure 4).

Figure 4: Map of soil permeability for the Coney Island study area.

All in all, the picture from the Coney Island Model 2 is clear – houses near to the coast had the greatest odds of being damaged. Any protection that might have been offered by elevation gains was probably negated by proximity to the coast.

Rockaway Peninsula, Queens

Results from the Rockaway Peninsula logistic regression are shown in Table 6. The factors found to be significant are soil permeability, distance to the coast, the amount of tree canopy around a property, the amount of bare earth around a property, building area, building height, distance to a natural area, and size of the nearest natural area (Table 6). Elevation was not found to be significantly related to damage (Table 6). The model fit can be estimated by the AUROC curve, which is 0.82, and McFadden's pseudo R^2, which is 0.20 (Table 4). These values suggest that the model is an excellent fit for the data.

Table 6: Results of the Rockaways logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and each variables impact on the odds of being damaged.

Rockaways Model 2	Mean	Standard Deviation	Standardized (β) Coefficient	Significance*	Change in Odds of Being Damaged
Soil Permeability	4.62	0.79	-3.77	***	-71.22
Elevation (ft)	7.30	1.62	0.02		0.29
Distance to the Coast (m)	785.6	423.8	2.73	***	0.17
% Tree Canopy	10.94	8.89	-1.19	***	-3.41
% Grass	11.37	8.84	-0.12		-0.35
% Bare Earth	0.47	3.56	1.06	***	8.20
Building Area (ft^2)	2021	2505	0.07		0.00
Building Height (floors)	1.68	0.68	0.54	.	22.73
Distance to the Nearest Natural Area (m)	804.7	505.9	-3.36	***	0.17
Size of the Nearest Natural Area (acre)	95.37	155.1	1.65	***	0.28
*p value = '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 0					

Like on Coney Island, Rockaway properties surrounded by a lot bare earth (including sand) were at greatest risks during Hurricane Sandy. A 1% increase in the amount of bare earth surrounding a property increased that house's odds of being damaged by 8.20% (Table 6). This finding might initially suggest that, once again, properties near the coast were more vulnerable. However, unlike on Coney Island, on the Rockaways the closer a property was to the coast the *less* likely that property was to be damaged (Table 6). The most probable explanation of this contrasting results is that flooding on the Rockaways came primarily from Jamaica Bay, not the ocean. The middle of the Rockaways serves as a low point that stretches back into Jamaica bay, with higher elevations on the ocean-side that may be at least partially attributed to dunes created and maintained by the ACE (Gardner 2013) (Figure 4). Anecdotal and visual evidence suggests that houses behind the dunes were significantly more protected than houses without dunes (NYC 2013). These dunes, however, were not themselves immune to damages, with an average loss of 1.4m of vertical erosion across the city (USGS 2014).

Where dunes protected the seaward coast, some neighborhoods were not inundated at all (Figure 6). The worst flooding on the Rockaways came from Jamaica Bay. Storm forcing on the deep, dredged channels of the Bay pushed large quantities of water over the back of the barrier island. The wide, bayside floodplain then exposed a number of houses, many far from either coast, to significant flooding and associated damages.

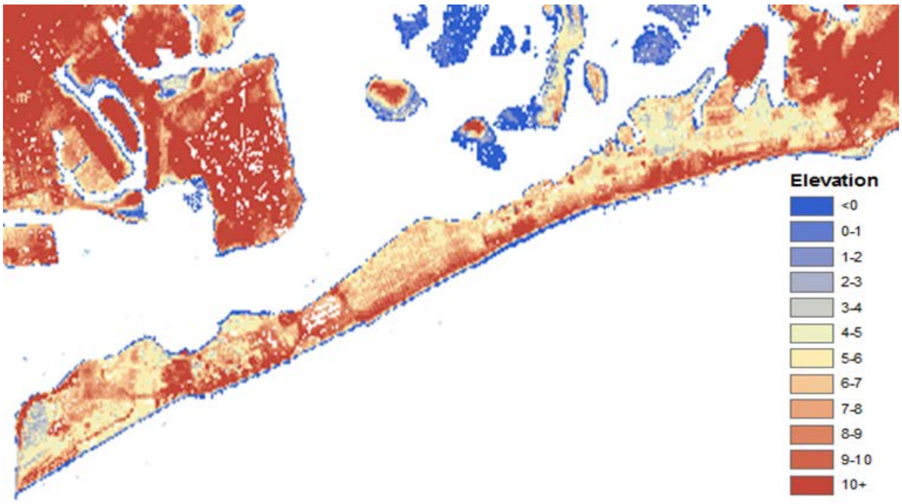


Figure 5: Elevation map of Rockaway Peninsula.

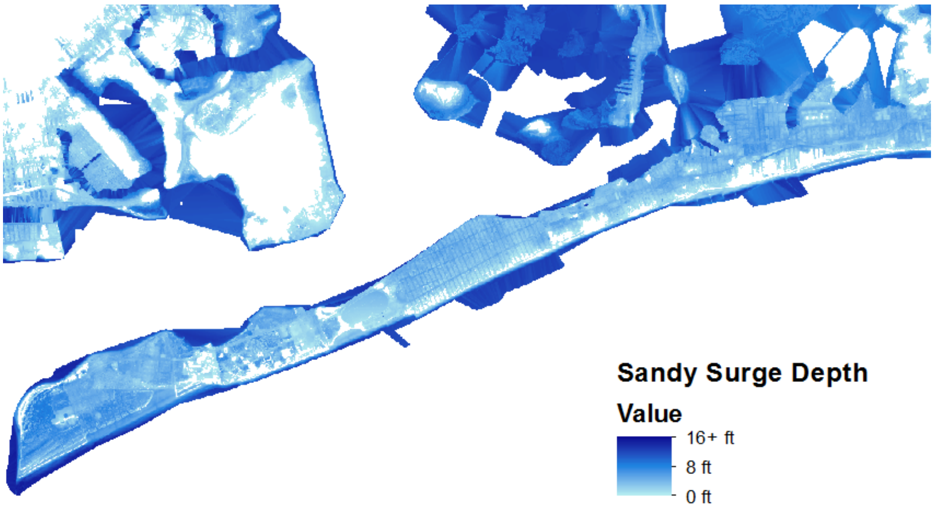


Figure 6: Map of surge depth on the Rockaway Peninsula during Hurricane Sandy.

Another factor that was an important predictor of damages was soil permeability. The regression suggests that houses with lower soil permeability were more likely to be damaged than those with higher permeability. A one unit decrease in soil permeability increased a property's odds of being damaged by almost 70% (Table 6). This is exactly the opposite trend to what occurred on Coney Island. A possible explanation is that in the Rockaways, the most permeable soils are typically found on the ocean-side, (Figure 7). On East Rockaway and near Jamaica bay, soil permeability is decreased due to the presence of clay, likely due to the filling of historic wetlands in these regions. It is possible that the poor permeability of the island's bayside contributed to the damage in that region since these soils would have constrained the rate that ponded water could have infiltrated post-Sandy. It is, however, also possible that this finding is merely coincidental. In other words, the flooding happened to be more severe, and to create more damage, in the portions of the island that just happened to have less permeable soil. A detailed investigation into the nature of the types of damage found on the bayside of the island might be able to help untangle whether damage was immediate or due to prolonged flooding.

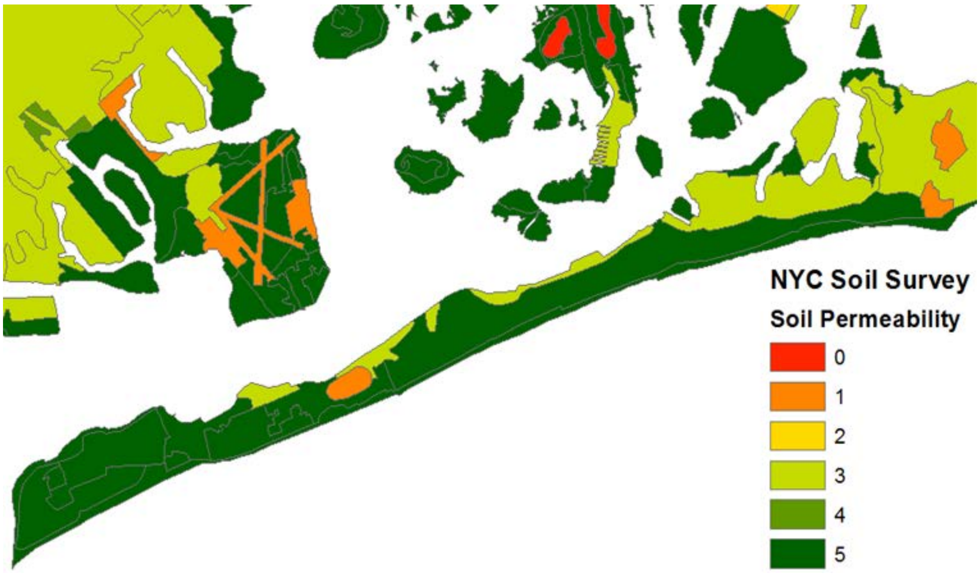


Figure 7: Map of soil permeability on Rockaway Peninsula.

The influence of natural areas on damages on the Rockaways is clear from Model 2. Houses closer to natural areas, particularly large natural areas, were at greater risk of being damaged (Table 6). This finding makes sense for a few reasons. Like on Coney Island, one of the largest natural areas on the Rockaways is its large ocean-side beach. Houses nearest to the beach would have generally had a higher percentage of bare earth nearby, an attribute that is positively correlated with damages (Table 6). However, there are also very large wetlands found on the bayside, particularly to the east. These areas are associated with low soil permeability, which increases the odds of being damaged, and sit nearer to the bay, where flooding was worst. Previous studies have shown that natural areas, particularly wetlands, can actually exacerbate storm surge under the right conditions (Resio and Westerink 2008, Wamsley et al. 2010, Hu et al. 2015). These studies suggest that slow moving storms lead to higher surges over natural areas compared to impervious surfaces. This was the case during

Hurricane Sandy and may explain why close proximity to large natural areas may have been positively corrected to greater odds of damage. Additional testing is needed to determine whether the relationship between property damage and natural areas is strictly linear, or if beyond a certain distance, perhaps associated with wave damage, they provide a protective role.

The last feature of note in the Rockaways is the relationship between tree canopy and damages. As the amount of tree canopy surrounding a property increases, the odds of that property being damage decrease by 3.41% (Table 6). This might observation could be related to wind damage. Houses surrounded by a dense tree canopy might have been better protected from wing gusts. Similarly, the dense tree canopy could have served as a net for flying debris, including their own branches or limbs that might have come loose.

Like on Coney Island, the Rockaway analysis suggests that proximity to beaches and wetlands around the island increased the odds of being damaged. At a minimum, more protection appears needed on the bayside to reduce inundation from Jamaica Bay., while dune restoration on the ocean side appears to be an effective strategy. Additionally the islands defense of tree canopy may have served to protect buildigns against wind and flying debris. Together, these preliminary findings suggest a potential protective role provided by two forms of GI, dunes and trees.

South Shore, Staten Island

Table 7: Results of the South Shore logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and each variables impact on the odds of being damaged.

South Shore Model 2	Mean	Standard Deviation	Standardized (β) Coefficient	Significance*	Change in Odds of Being Damaged
Soil Permeability	2.81	0.72	0.37	.	14.02
Elevation (ft)	9.64	9.29	-0.24		-0.69
Distance to the Coast (m)	2243	1324	0.24		0.00
% Tree Canopy	12.79	9.81	-0.72	*	-1.84
% Grass	19.40	10.69	1.32	***	3.18
% Bare Earth	0.03	0.62	-55.80		≈ -100%
Building Area (ft^2)	1692	1379	-0.04		0.00
Building Height (floors)	1.81	0.63	-0.30		-11.35

Distance to the Nearest Natural Area (m)	492.3	488.4	-10.22	***	-0.54
Size of the Nearest Natural Area (acre)	128.3	171.0	-0.20		-0.03
*p value = '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 0					

Results of the South Shore analysis are shown in Table 7. Elevation and distance to the coast were not found to be significantly related to damage (Table 7). The only factors which are significant predictors of damage are distance to the nearest natural feature and the amount of tree canopy and grass in the surrounding 50mX50m (Table 7). The AUROC is 0.82 and McFadden's pseudo R^2 is 0.18, suggesting the model is a good fit for the data (Table 4).

Like on the Rockaways, tree canopy is again a significant predictor of damages. The results are consistent with those emerging from the Rockaways analysis, name that the less tree canopy around a property, the greater its odds of being damaged (Table 7). This time a 1% increase in the amount of surrounding tree canopy decreases a property's odds of being damaged by 1.84% (Table 7). As stated previously, we suspect this finding is indicative of a protective role that trees are performing against wind and flying debris.

Unlike either of the other study areas, on the Staten Island the amount of grass around a property is also a significant predictor of damage (Table 7). As the amount of grass increases so do the odds of being damaged (Table 7). This finding may indicate the impact of natural areas, such as parks or wetlands, on damages, since most coastal GI is represented as "grass" in the surface type data layer and, as has been mentioned previously, surge can be higher on natural areas under certain conditions (Table 1) (Resio and Westerink 2008, Wamsley et al. 2010, Hu et al. 2015). However, an alternative explanation could be due to the lower density of development patterns found on Staten Island. To the extent that "grass" is indicative of lawns, it could be that stand alone buildings, surrounded by lawns, presented greater fetch areas, subjecting the building to more wind and flying debris. Such buildings would have received less wind and debris protection from trees and also from other buildings, which might also have been able to provide a physical barrier to flood water. A close-up view of damaged houses suggests this alternative explanation may have merit (Figure 8). The damaged houses tend to border grassy areas while houses surrounded by other houses tended have less damage (Figure 8). Further supporting this theory is that properties closer to natural areas were more likely to be damaged (Table 7). All in all, the results suggest that a close proximity to natural areas and lawns on the South Shore of Staten Island greatly increased the risk of property damage during Hurricane Sandy.

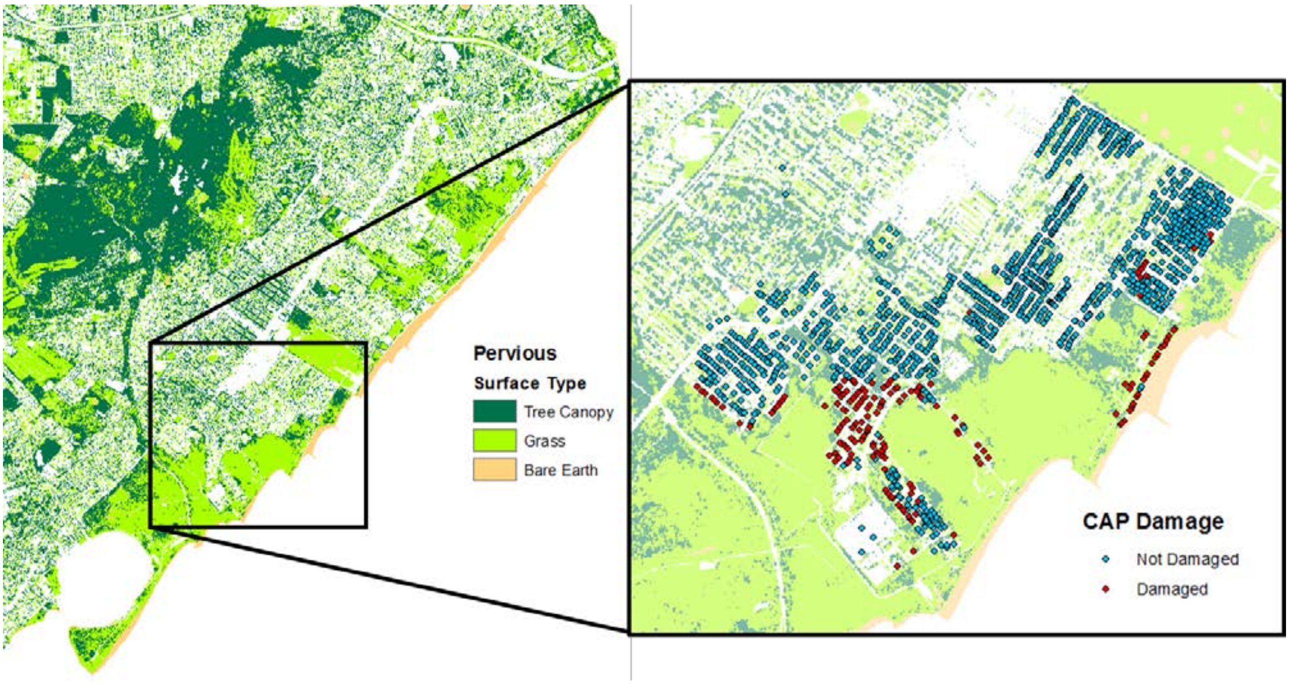


Figure 8: Map of tree canopy, grass, and bare earth coverage on the South Shore, Staten Island. In-set shows CAP damage classifications (damaged or not damaged) for houses in the South Shore study area.

Overall the Staten Island analysis presents a different picture of Sandy vulnerability. Elevation, distance to the coast, and permeability were insignificant predictors of damage. Instead trees and grass seem to matter. The more trees, the lower the odds of being damaged, while the more grass, the greater the odds of being damaged. As stated above, proximity to "grass" includes proximity to parks, wetlands, and other natural areas. Most natural areas fall close to the shoreline on Staten Island and, although distance to the coast was not a significant predictor, it may be that the surge in those areas was greater; fetch distances and exposure to flying debris may also have been greater.

Conclusions

For all three study sites, Model 2 better predicted damages compared to Model 1. This finding suggests that natural features played a key role in Sandy damages and significantly impacted the odds of damages in the three areas. However, a detailed investigation into which natural features mattered most revealed significant geographic differences. While trees seem to be associated with lower damage levels in the Rockaways and Staten Island, proximity to natural areas increased the odds of damage in all three locations. Higher soil permeability was associated with greater damages in Coney Island and lesser damage in the Rockaways. Houses at higher elevation were more damaged on Staten Island, though no significant topographic differences in damage odds were found in either of the other two study areas.

Though some of these relationships can be at least partially justified by differences in the geography and development patterns of the study areas, the lack of uniformity of NYC's coastal communities limited our ability to isolate the effects of independent variables in each location. The fact that the largest buildings on Coney Island are near the beach may explain the positive association between building area and damages at the location, for example. However, because we are unable to test what would have happened to smaller buildings if they covered a larger area of Coney Island's beach front, our ability to extrapolate these findings is limited. Similar limitations apply to our understanding of the other variables associated with damages.

This analysis confirms that Sandy interacted with the city's physical and natural infrastructure in complex, geographically-specific ways. Overall the analysis suggests that investments in coastal protection must be planned strategically, considering both unique, local conditions and the potential generalizable value of natural features like dunes and trees, both of which appear to have helped to mitigate Sandy's destructive forces in some ports of the city. The study also suggests that there may be merit to coastal retreat. Though dunes may have provided protection to ocean-side properties on the Rockaways, greater proximity to bare earth (which is a proxy for sand), lesser distances to natural areas, and greater proximity to large natural areas regularly appeared as positively correlated to damage. The only GI that was negatively correlated to damages consistently was tree canopy, possibly due to the protective nature a dense tree canopy can have against wind damages and flying debris.

The results of this analysis need to be qualified by the uniqueness of Sandy as a storm. The literature suggests that the protective value of at least wetlands is highly variable and often specific to storm characteristics. Under other storm circumstances, might proximity to beaches, parks, wetlands, and other natural areas have demonstrated greater protective services? More research is needed to answer this question. Even if the protective services provided by GI is found to mirror those observed during Sandy, we underscore that this is only one of many ecosystem services provided by GI in the city. Filling or replacing these features with bulkheads or other "gray" infrastructure significantly diminishes the value of the coast during dry weather and less extreme conditions, where they provide climate regulating, habitat, and social services to the people and wildlife of NYC.

References

Acreman, M. and Holden, J. (2013). How Wetlands Affect Floods. *Wetlands* 33: 773-786. DOI 10.1007/s13157-013-0473-2

Aerts, J.C.J.H. and Botzen, W.J. W. (2011). Flood-resilient waterfront development in New York City: Bridging flood insurance, building codes, and flood zoning. *Ann. N.Y. Acad. Sci.* 1227:1-82 DOI: 10.1111/j.1749-6632.2011.06074.x

Barbier, E.B.; Koch, E.W.; Silliman, B.R.; Hacker, S.D.; Wolanski, E.; Primavera, J.H.; Granek, E.; et al. (2008). Coastal Ecosystem-based Management with Nonlinear Ecological Functions and Values. *Science* 319:321-323

Barbier, E.B. and Enchelmeyer, B.S. (2014). Valuing the storm surge protection service of US Gulf Coast wetlands. *Journal of Environmental Economics and Policy* 3(2):167-185 DOI: 10.1080/21606544.2013.876370

Barbier, E.B. (2015). Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosystem Services* 11:32-38

Barr, Meghan. (2013, August 9). Breezy point Sees Little Rebuilt After Devestating Superstorm Sandy Fire. *Huffington Post.* Retrieved from: http://www.huffingtonpost.com/2013/08/09/breezy-point-sandy-recovery-fire-hurricane-_n_3731178.html

Berke, Ned. (2012, November 15). Doused During Sandy, Kingsborough Community College Rises Like A Phoenix From Floodwaters. *Sheepshead Bites*. Retrieved from: http://www.sheepsheadbites.com/2012/11/doused-during-sandy-kingsborough-community-college-rises-like-a-phoenix-from-floodwaters/

Blake, E.S.; Kimberlain, T.B.; Berg, R.J.; Cangialosi, J.P.; Beven, J.L. *Tropical Cyclone Report: Hurricane Sandy (AL182012), 22-29 October 2012*; National Hurricane Center: Miami, FL, USA, 2013; pp 1-157.

CCRUN (n.d.). Hurricane Sandy. Retrieved from: http://ccrun.org/Sandy_home [Accessed August 14, 2015]

City of New York (NYC) (2013, June 11). *A Stronger, More Resilient New York*. New York City Special Initiative for Rebuilding and Resiliency. Retrieved from http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf

Clancy, T.; Kenneth, C.; Cortacans, H.P. New Jersey's EMS Response to Superstorm Sandy: A Case Study of the Emergency Management Assistance Compact. *Prehospital and Disaster Medicine* 29(3):326-329

Coch, N.K. (2012). Hurricane Flood Protection in NYC – Now Is Not the Time for Multiple Surge Barriers. Discussion of: Hill, D., 2012. The Lessons of Katrina, Learned and Unlearned. "Journal of Coastal Research", 28(2), 324-331. *Journal of Coastal Research* 28(5):1313-1315

Colle, B.A.; Bowman, M.J.; Roberts, K.J.; Bowman, M.H.; Flagg, C.N.; Kuang, J.; Went, Y.; Munsell, E.B.; Zhang, F. (2015). Exploring Water Level Sensitivity for Metropolitan New York During Sandy (2012) Using Ensemble Storm Surge Simulations. *J. of Marine Science and Engineering* 3:428-443

Corps of Engineers, US Army Engineer District, New Orleans, (USACE) 1963. Interim survey report, Morgan City, Louisiana and vicinity, Serial no. 63. US Army Engineer District, New Orleans, LA.

Costanza, R.; Perez-Maqueo, O.; Martinez, M.L.; Sutton, P.; Anderson, S.J.; Mulder, K. (2008). The Value of Coastal Wetlands for Hurricane Protection. *J. of the Human Env.* 37(4):241-248

Ebersole, B.A.; Westerink, J.J.; Bunya, S.; Dietrich, J.C.; Cialone, M.A. (2010). Development of storm surge which led to flooding in St. Bernard Polder during Hurricane Katrina. *Ocean Engineering* 37:91-103

Environmental Protection Agency (EPA) (2014). United States: EPA Provides a Quarter Million Dollars to Protect Wetlands in New York. *MENA Report*. Retrieved from: http://search.proquest.com/docview/1636565389?accountid=10559

Fagherazzi, Sergio. (2014). Coastal Processes: Storm-proofing with Marshes. *Nature Geoscience*. 7(10): 701-702. DOI: 10.1038/ngeo2262

Gardner, C. (2013, October 28th). U.S. Army Corps of Engineers works after Sandy to repair and restore beaches in New York designed for coastal storm risk reduction. Retrieved from: http://www.nan.usace.army.mil/Media/NewsStories/StoryArticleView/tabid/5250/Article/488052/us-army-corps-of-engineers-works-after-sandy-to-repair-and-restore-beaches-in-n.aspx

Gedan, K.B.; Kirwa, M.L.; Wolanski, E. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change* 106:7-29 DOI 10.1007/s10584-010-0003-7

Lane, K.; Charles-Guzman, K.; Wheeler, K.; Abid, Z.; Graber, N.; Matter, T. (2013). Health Effects of Coastal Storms and Flooding in Urban Areas: A Review and Vulnerability Assessment. *J. of Env. And Public Health* 2013:913064 DOI: 10.1155/2013/913064

Hu, K.; Chen, Q.; Wang, H. (2015). A numerical study of vegetation impact on reducing storm surge by wetland sin a semi-enclosed estuary. *Coastal Engineering* 95:66-76

Jacob, K.; Gornitz, V.; Rosenzweig, C. (2006). Vulernability of the New York City Metropolitan Area to Coastal Hazards, Including Sea-Level Rise: Inferences for Urban Coastal Risk Management and Adaptation Policies In L. McFadden, R. Nicholls, and E. Penning-Roswell (Eds.), *Managing Coastal Vulnerability* (pp. 141-158). Oxford, U.K.: Elsevier Publishing.

Kensinger, Nathan. (2015, September 17). The Slow Resurgence of the Rockaway Bungalow. Retrieved from: http://ny.curbed.com/archives/2015/09/17/the_slow_resurgence_of_the_rockaway_bungalow.php

Loder, N.M.; Irish, J.L.; Cialone, M.A.; Wamsley, T.V. (2009). Sensitivity of hurricane surge to morphological parameters of coastal wetlands. *Estuarine, Coastal, and Shelf Science* 84:625-636.

McFadden, D.(1979): Quantitative methods for analysing travel behavior of individuals: Some recent developments. In: Hensher,D.& Stopher, P.(eds.): Behavioural travel modelling. London: Croom Helm

Michael, K.K. and Lenhardt, M.F. (2013). What's in a Name(d) Storm? What Sandy Has Taught Us About Flood, Storm Surge, and FEMA Flood Zones. *Risk Management* 63:318-339

Moller, I.; Kudella, M.; Rupprecht, F.; Spencer, T.; et al. (2014). Wave Attenuation Over Coastal Salt Marshes Under Storm Surge Conditions. *Nature Geoscience*. 7(10):727-731

National Register of Historic Places, Far Rockaway Beach Bungalow Historic District, Queens County, NY, 13000499

NYC Department of City Planning (NYC DCP). (2011). Vision 2020: New York City Comprehensive Waterfront Plan. Retrieved from http://www.nyc.gov/html/dcp/pdf/cwp/vision2020_nyc_cwp.pdf

NYC Department of City Planning (NYC DCP). (2013). Urban Waters Adaptive Strategies. Retrieved from: http://www1.nyc.gov/assets/planning/download/pdf/plans-studies/sustainable-communities/climate-resilience/urban_waterfront_print.pdf

NYC Department of City Planning (NYC DCP). (2014). Population: Current Population Estimates. Retrieved from http://www.nyc.gov/html/dcp/ [Accessed July 27, 2015]

Office of the Mayor (2012). Mayor Bloomberg Releases Hurricane Sandy Federal Air Request. [Press Release] Retrieved from: http://www.nyc.gov/portal/site/nycgov/menuitem.c0935b9a57bb4ef3daf2f1c701c789a0/index.jsp?pageID=mayor_press_release&catID=1194&doc_name=http://www.nyc.gov/html/om/html/2012b/pr443-12.html&cc=unused1978&rc=1194&ndi=1

Office of the Mayor. (2014). Mayor de Blasio Announces Key Resiliency Investments to Support Small Businesses and Jobs, Including New Business Resiliency Program and Major Upgrades Across Sandy-Impacted Neighborhoods [Press Release]. Retrieved from: http://www1.nyc.gov/office-of-the-mayor/news/568-14/mayor-de-blasio-key-resiliency-investments-support-small-businesses-jobs-

Patrick, L. (2014, March 18). Future Flood Zones for New York City. *Climate.gov*. Retrieved from https://www.climate.gov/news-features/featured-images/future-flood-zones-new-york-city [Accessed July 28, 2015]

Spalding, M.D.; Ruffo, S.; Lacambra, C.; Meliane, I.; Hale, L.Z.; Shepard, C.C.; Beck, M.W. (2014). The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. *Ocean & Coastal Management* 90:50-57

Spurlock, C. (2012, October 31). Hurricane Sandy New York City Power Outage Map: Thousands Without Electricity in Metro Area. *Huffington Post*. Retrieved from http://www.huffingtonpost.com/2012/10/31/hurricane-sandy-new-york-city-power-outage-map_n_2050380.html

Tape, Thomas G. Interpreting Diagnostic Tests. Retrieved from: http://gim.unmc.edu/dxtests/Default.htm

Temmerman, S.; Meire, P.; Bouma, T.J.; Herman, P.M.J.; Ysebaert, T.; De Vriend, H.J. (2013). Ecosystem-based Coastal Defense in the Face of Global Change. *Nature*. 504:79-83

The Nature Conservancy (TNC). (2015a). The Nature Conservancy Releases Innovative Urban Coastal Resilience Report on Protecting Cites from Climate Change Impacts [Press Release]. Retrieved from: http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newyork/newsroom/the-nature-conservancy-releases-innovative-urban-coastal-resilience-report-o.xml

The Nature Conservancy (TNC). (2015b). Urban Coastal Resilience: Valuing Nature's Role. Retrieved from: https://tnc.app.box.com/s/9awez618538tf24rnu5mv73fkfa668mr/1/4092107687/34093516459/1

Tollefson, J. (2013, February 14). New York vs. the sea: in the wake of Hurricane Sandy, scientists and officials are trying to protect the largest US city from future floods. *Nature*. Retrieved from: http://www.nature.com/news/natural-hazards-new-york-vs-the-sea-1.12419

Schuster, E. and Doerr, P. (2015). A Guide for incorporating Ecosystem Service Valuation into Coastal Restoration Projects. *The Nature Conservancy*. Retrieved from: http://www.nature.org/media/oceansandcoasts/ecosystem-service-valuation-coastal-restoration.pdf

United States Geological Survey (USGS). Hurricane Sandy Response – Storm Impacts and Vulnerability of Coastal Beaches. (2014, October 21). Retrieved from: http://coastal.er.usgs.gov/sandy-storm-impact-vulnerability/research/coastal-impacts.html

Wamsley, T.V.; Cialone, M.A.; Smith, J.M.; Atkinson, J.H.; Rosati, J.D. (2010). The potential of wetland sin reducing stomr surge. *Ocean Engineering* 37:59-68

Wilks, B. (2011). Marine Streets – A Living Marine Edge. *Ecological Restoration* 29(3):292-297