Did NYC's coastal green infrastructure protect property during Hurricane Sandy? A case study of three coastal communities

March, 2016

THE TRUST FOR PUBLIC LAND

Did NYC's coastal green infrastructure protect property during Hurricane Sandy? A case study of three coastal communities was prepared for The Trust for Public Land by Drexel University with funding support from National Oceanic and Atmospheric Administration.

This report was co-authored by:

Jad Daley, Holly Bostrom and Marc Matsil,
The Trust for Public Land

Cover: Clark Jones

Foreword

The extreme devastation wrought on New York City's waterfront communities by Superstorm Sandy followed significant damage inflicted by Hurricane Irene just a year earlier. These events have created heartbreaking images of the storm's devastating impact on people's lives, and illustrated the vulnerability of New York City's homes, businesses, transportation networks, sewer systems, power grid, and natural resources in its low-lying areas. More events like this are likely to occur. Based on the effects of sea level rise projections alone, what is now a 1-in-100 year flood is anticipated to occur five times as often by the 2050s.[1, 2] Through this partnership, The Trust for Public Land, the City of New York ("the City"), Columbia University's Center for Climate Systems Research ("Columbia CCSR"), and the Consortium for Climate Risk in the Urban Northeast (CCRUN) – including CCRUN-affiliated researchers from Columbia University and Drexel University – joined together to research, plan, and create protective green infrastructure along the City's waterfront. This new green infrastructure, ranging from natural systems like wetlands to new waterfront parks that integrate creative storm protection features, will help absorb the brunt of sea level rise and storms to protect New Yorkers for generations to come.

The Trust for Public Land's Climate-Smart Cities™ initiative helps cities mitigate and adapt to climate change through conservation and design along four strategies:

> **CONNECT:** creating better bicycle and pedestrian networks helps people ditch driving, reducing carbon emissions and improving health.
>
> **COOL:** increasing green space such as parks, tree canopies, and gardens helps to cool the urban landscape, reducing the health impacts of heat waves for everyone, particularly older adults, low-income households, and other vulnerable residents.
>
> **ABSORB:** replacing pavement with permeable surfaces or swales helps to filter and absorb rainfall, reducing water treatment costs and preventing pollution.
>
> **PROTECT:** placing well-designed parks and green space where they can act as natural buffers to rising seas and storm surges protects surrounding neighborhoods while providing opportunities for people to get outdoors.

With support from the National Oceanographic and Atmospheric Administration, The Trust for Public Land's Climate-Smart Cities program commissioned research from Drexel University to assess the physical and social impact green infrastructure has on communities.

---

[1] Based on the high estimate for sea level rise.

[2] New York City Panel on Climate Change, 2013: Climate Risk Information 2013: Observations, Climate Change projections, and Maps. C. Rosenzweig and W. Solecki (Editors), NPCC2. Prepared for use by the City of New York Special Initiative on Climate Change.

Did NYC's Coastal GI Protect Property During Hurricane Sandy? A case study of three coastal communities

Authors: MILLER, Stephanie[1] (smm523@drexel.edu); GURIAN, Patrick[1] (plg28@drexel.edu); DALEY, Jad2 (Jad.Daley@tpl.org); BOSTROM, Holly[2] (Holly.Bostrom@tpl.org); MATSIL, Marc[2] (Marc.Matsil@tpl.org); MONTALTO, Franco[1,3] (fmontalto@coe.drexel.edu)

[1] Drexel University 3141 Chestnut Street Philadelphia, PA 19104

[2] Trust for Public Land 666 Broadway, 9th Floor New York, NY 10012

[3] eDesign Dynamics 402 West 40th Street New York, NY 10018

Corresponding Author: Franco Montalto

3141 Chestnut Street
251 Curtis
Philadelphia PA, 19104
fmontalto@coe.drexel.edu
Office: 215-895-1385

1. **Abstract**

New York City’s coastlines are a mosaic of remnant natural habitat, man-made wetlands, manicured parkland, and public beaches, intermixed with housing and industry, all of which are extremely vulnerable to flooding, storm surge, and damaging wave action. Risks are projected to increase overtime as sea levels rise, population grows, and the frequency and severity of extreme events increases. In order to protect its people and infrastructure, New York City will invest $20 billion into a coastal protection plan that re-imagines its shorelines as a hybrid of natural and man-made protective features. The purpose of this research was to investigate the role that green infrastructure can play at mitigating building damages during extreme coastal events. Hurricane Sandy was used as a case study to understand how the size and proximity of natural features can impact a property's odds of being damaged. In this paper we focus on building damages on Coney Island, Rockaway Peninsula, and the South Shore of Staten Island. Results suggest that proximity to different natural areas did play a measurable role in damage, though this role differed geographically. The impact of large natural features – for example wetlands, beaches, and parks – varied across the three study areas. At smaller scales, proximity to dunes and a dense tree canopy consistently protected buildings from surge and wind damage. Overall, results suggest that any coastal defense measure must be tailored to specific local conditions in order to be effective, with retreat perhaps offering the best protection against future extreme events.

2. **Introduction**

Hurricane Sandy made landfall in Brigantine, NJ on October 29, 2012. Although declassified to a tropical storm before landfall, hurricane-force wind gusts were reported in and around NYC (Blake, Kimberlain, Berg, Cangialosi, & Beven, 2013; Kiernan & Lenhardt, 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 (Blake et al., 2013; CCRUN, n.d.; Kiernan & Lenhardt, 2013; Office of the Mayor, 2012; Patrick, 2014; Spurlock, 2012; Tollefson, 2013). 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 (CCRUN, n.d.; NYC DCP, 2013). 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 in the tidal cycle. Modeling efforts by Colle et al. (2015) have shown that the storm surge and storm tides could have been at least 0.5 m higher (Colle et al., 2015).

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 (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. When asked how to best protect residents from these threats, more than 50% of experts surveyed by Miller et al. (2014) said to use natural ecosystems of some kind (Miller et al., 2014). Before leaving office the Bloomberg administration conceived a $20 billion coastal protection plan for NYC, including the use of "green" strategies to reduce coastal flood risks, such as beach nourishment, dune construction and stabilization, and the creation and maintenance of living shorelines, including wetlands (NYC DCP, 2011; NYC DCP, 2013). 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 flood risks while restoring, enhancing, or creating new forms of urban habitat and providing other valuable ecosystem services (NYS SLR Task Force, 2010; Temmerman et al., 2014; Wilks, 2011). 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 (Catalano de Sousa, Miller, Dorsch, & Montalto, 2013; NYS SLR Task Force, 2010).

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. Some observers have suggested that some of the existing dunes or marshlands may have played a role at reducing property damage during Hurricane Sandy (The Nature Conservancy, 2015). However, there is little scientific evidence to support these conclusions.

Studies quantifying the protective value of coastal GI for reducing property damage during Sandy-type events is limited, especially in urban areas. Most of the research that has been conducted concerns wetlands. Costanza et al. (2008) estimate the average value of New York State's coastal wetlands for hurricane protection at more than USD 50,000 ha^{-1} yr^{-1} (Costanza et al., 2008). The actual storm protection services of individual wetlands are, however, variable and highly dependent upon wind speed, storm forcing, elevation, the surrounding coastal landscape, waterbody connectivity, and vegetation (Acreman & Holden, 2013; Barbier & Enchelmeyer, 2014; Gedan, Kirwa, & Wolanski, 2011; Hu, Chen, & Wang, 2015; Loder, Irish, Cialone, & Wamsley, 2009; Resio & Westerick, 2008; Wamsley, Cialone, Smith, Atkinson, & Rosati, 2010). Wamsley et al. (2010) estimate surge attenuation is anywhere between 1m per 60km of wetlands traversed to 1m per 4km, based on observed data (Wamsley et al., 2010). Researchers consistently report that coastal GI has the ability to reduce wave damage (Barbier & Enchelmeyer, 2014; Gedan et al., 2011; Loder et al., 2009; Moller et al., 2014; Spalding et al., 2014). The degree of wave attenuation is primarily determined by continuity and surface roughness, however, and not overall hectares or distance traversed. As such, even small urban GI may be capable of providing significant wave attenuation during storms.

After Hurricane Sandy, various levels of government committed to greening NYC shorelines for coastal protection. In 2010 the New York State Sea Level Rise Task Force recommended the construction and maintenance of non-structural, natural protection features along the coast to protect against sea level rise and the threat of future storm surges (NYS SLR Task Force, 2010). Since Hurricane Sandy, the Army Corps of Engineers (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 to the restoration of City-owned wetlands in Staten Island (Office of the Mayor, 2014) and the US Environmental Protection Agency has provided grants to assist the NYC's Department of Parks and Recreation (NYC DPR) in its efforts to protect, restore, and monitor salt marshes, including new marshes in Jamaica Bay (Newsroom, EPA, 2014). NYC DPR also plans to restore over 86 acres of maritime forests in Brooklyn and Queens (NYC DCP, 2011). Additional efforts call for the restoration and creation of living shorelines, oyster beds, eelgrass beds, and marsh islands (The Nature Conservancy, 2015; NYC DCP, 2011; Schuster & Doerr, 2015).

This study investigates whether NYC's coastal GI played a role in mitigating building damages during Hurricane Sandy. Specifically, we studied whether building damages could be predicted reasonably with topographic elevation, distance to the coast, proximity to green space, and other physical characteristics of the building site. We were interested in which natural features of NYC's coast were most strongly correlated to building damages, and in what way. The research focused on three discreet study sites – Coney Island, Brooklyn; Rockaway, Queens; and the South Shore of Staten Island. The overarching hypothesis was that for all three sites, predictive models that do not explicitly consider a property's various physical relationships to local GI would poorly predict damages. More explicitly, we hypothesized that NYC's coastal GI, despite being small and fragmented, provided some protective services for nearby coastal properties during this particular extreme event.

To test this hypothesis, we generated two models. Model 1 predicts damages using only geographic and architectural information. Model 2 includes those variables, as well as information on each property's physical relationship to GI. Chi-square (χ^2) difference tests compared whether there were significant differences in the predictive ability of both models. The statistical results were then used to explain which coastal features were most strongly linked to building damages, and which, if any, offered protection from Hurricane Sandy's extreme force.

3. Materials and Methods

3.1 Data Available

The analysis utilized a variety of datasets pertaining to NYC's green and grey infrastructure, physical and social characteristics, climate 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 XXXXX, the Trust of Public Land (TPL), and the City of NY. The specific datasets utilized in the 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. The analysis and statistical tests are thus based on only a small subset of the total database.

To undertake the analysis, a quantifiable measure for building damage sustained during Hurricane Sandy was needed. Though NYC's Department of Buildings has a comprehensive database of building damages developed from post-hurricane surveys, this data was not available to the research team due to confidentiality concerns. Less comprehensive data sets published by the Federal Emergency Management Agency (FEMA) and the Civil Air Patrol (CAP) were, however, made available. The FEMA data, published at the zip code level, consisted of average damage and assistance estimates for households whose repairs were not completely covered through private insurance, i.e. only damage costs for those properties that requested assistance from FEMA. The CAP data, developed using 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 performed along the coastlines most heavily impacted by the storm. The CAP dataset was chosen as the primary indicator of building damage severity for this study because it was available at the lot level and covered a large portion of the impacted area of the City.

3.2 Study Boundaries

The study focused on three of the most heavily damaged areas of the City – 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 properties assessed in Coney Island, 6,756 on the Rockaways, and 4,168 along the South Shore. Within the Rockaway dataset, 132 properties that were destroyed or severely damaged by an electrical fire in Breezy Point during the midst of Hurricane Sandy were removed from the analysis since the fire was considered a secondary impact of the storm.

3.3 Model Building

Two binomial logistic regression models were developed for each study site to explore the relationship between damage severity (measured on a scale from 0-4) and the location of various physical features. Each logistic regression model attempted to predict whether a building was damaged based on the physical features and location of the property. In the analysis, the CAP damage data was recoded into two categories – “damaged” and “not damaged.” Any building that had been rated a 0 or 1 by CAP was included in the “not damaged” category, while any building that had received a CAP rating of 2 or more was marked as “damaged” (Table 2).

Model 1 sought to predict damages at each study site using only a building’s elevation above sea level, distance from the coast, area, and height (Table 3). Hurricane Sandy produced a large storm surge and it could be reasonably expected that buildings with the greatest odds of damage were those with the greatest exposure to this surge. The expectation was that Model 1 would show that small, short buildings, located close to the shore and at low elevations had the greatest odds of being damaged.

By contrast, Model 2 assumed that building damages would be better predicted if, in addition to all the independent variables in Model 1, the building's relationship to various GI elements were considered (Table 3). These GI elements included soil permeability, represented on a scale from 0 (impermeable) to 5 (highly permeable); distance to the nearest natural area, including all parks, wetlands, beaches, and other natural systems; size of the nearest natural area; and the amount and types of pervious surfaces near the building. Pervious surface coverage is measured as the percentages of a 50m by 50m square, centered on the property, that is occupied by either tree canopy, grass, or bare earth (which includes sand) (Table 3). Model 2 was designed to test whether a property's relationship to GI had any significant impact on CAP damage level.

In conjunction with the development of Models 1 and 2, exploratory modeling was performed considering alternative covariates. The purpose of this exploratory modeling was to investigate whether general correlations between building damages and each variable included in Models 1 and 2, respectively, varied with distance from the nearest natural feature. The goal was to search for non-linearity in the effects of distance from GI in an attempt to find the model with the best possible fit for each study site, regardless of the theoretical significance of each factor. In addition to the variables included in Models 1 and 2, distance to the nearest wetland, distance to the nearest park, size of the nearest wetland, size of the nearest park, and distance to waterbodies (which include land-locked waterways, small streams, and major coastlines) were also included in this analysis. Akaike Information Criterion (AIC) scores were used to quantitatively compare the predictive skill of these exploratory models with one another as well as with the hypothesis-driven Models 1 and 2. Factor combinations included in these exploratory models necessarily varied across study area due to differing physical factors. For this reason the significance of associations found by this effort was not considered rigorous, and the emphasis was placed on presenting the results of Models 1 and 2.

3.4 Statistical testing

Each model was trained on 80% of the data within each study area and then validated on the remaining 20%. The Variance Inflation Factor (VIF) was used to test for multi-collinearity. A VIF value of 5 was set as the threshold for acceptable correlation; any factor with a VIF greater than 5 was removed from the model. 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, n.d.). McFadden's pseudo-R^2 values were also used to evaluate the goodness of fit for each model and to compare their performance. Pseudo R^2 tend to be low for binary logistic regressions; for our purposes any values greater than 0.20 indicate the model is an excellent fit for the data (McFadden, 1979).

Within each study area, a χ^2 difference test was used to assess whether Models 1 and 2 had statistically different predictive ability. Specifically, the χ^2 difference test determined whether the inclusion of more covariates in Model 2 was justified based on a significant increase in predictive capacity. For this comparison, 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 Model 2 was the better fit.

McFadden’s psuedo-R^2 values and AUROC values were 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 the different variables influenced the odds of being damaged 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 variable and property damage. 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 and ranges of variability. 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.

4. Results

4.1 General

The χ^2 difference tests reveal that Model 1 and Model 2 are statistically, and significantly different from one another at all three study sites, with p values less than 0.001 (Table 4). In other words, the addition of covariates, all of which have to do with a property’s physical relationship to GI, significantly improves the prediction of damage odds. At all three study sites, Model 2 had higher McFadden’s pseudo-R^2 values (Table 4), indicating a superior predictive ability to Model

1. 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). All three Model 2s also have AUROCS values of at least 0.80 (Table 4). Comparison of the Model 2 results at all three sites suggests that the regression on the Rockaway dataset has the best overall fit, with a McFadden's pseudo-R^2 value of 0.20 (Table 4) (McFadden, 1979). Because Model 2 was found to be better than Model 1, a detailed examination of the Model 2 results in each study area is presented below. We note that many of the trends observed in the exploratory models mentioned at the end of the methods section were consistent with the results from Model 2.

4.2 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). VIF values for all factors were less than 2, suggesting that multi-collinearity was not a concern. The AUROC value was 0.85 and the McFadden's pseudo-R^2 was 0.18 (Table 4), both indicating a good fit of the model to the data.

4.3 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). VIF values for all factors were less than 2, suggesting that multi-collinearity was not a concern. The AUROC value was 0.82

and the McFadden's pseudo-R^2 was 0.20 (Table 4), both indicating an excellent fit of the model to the data.

4.4 South Shore, Staten Island:

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 50m by 50m (Table 7). VIF values for all factors were less than 2, suggesting that multi-collinearity was not a concern. 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).

5. Discussion

5.1 General

Results of the χ^2 difference test, and the fact that the McFadden's pseudo-R^2 and AUROC values were found to be higher for Model 2 at all three study areas, suggests that a building's physical relationship to local GI matters. More specifically, damages cannot be adequately characterized without considering the role of local GI. In all three study areas, GI played a significant role in determining which buildings were damaged by this storm. However, the factors that mattered most, and whether they were associated with increased or decreased risk of damage, differed across the three study sites. The mathematical form of the Model 2 logistic regression equations were distinct, indicating that a unique combination of factors were the significant predictors of damage at each study area. This finding generally suggests the role that GI played in altering building damage levels varied spatially. A more detailed analysis of each study area is presented below through an analysis of the Model 2 results.

5.2 Coney Island, Brooklyn

The Coney Island Model 2 logistic regression results are useful in exploring several physical hypotheses regarding the causes of building damages. The first is that buildings closest to the coast had the greatest odds of being damaged during Hurricane Sandy. This finding is supported by the fact that the odds of being damage decrease by 0.20% for every one unit (1 meter) increase in distance from the shore (Table 5). Similarly, the more bare earth around a property, the greater the odds of being damaged (Table 5). For every 1% increase in the amount of bare earth within the 50m by 50m surrounding a property, the odds of being damage increased by nearly 4% (Table 5). 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 damaged (Table 5). On Coney Island the two biggest natural areas are the beach and Marine Park, both of which are adjacent to the shoreline.

A second physical relationship that initially appeared counterintuitive pertained to the relationship between topographic elevation and damage. Since, as described in the previous paragraph, buildings closest to the shore were more likely to be damaged, it might be expected that elevation would also be inversely 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). Two possible explanations are offered. The first is that when controlling for distance from the coast, buildings at higher elevations were more vulnerable to wind-related damage. The second stems from the fact that topographic elevation on Coney Island does not increase with distance from the shore (Figure 2). Elevation is actually highest near the beach and close to the shore. Though this analysis did not systematically examine interactions among the three variables described thus far (elevation, distance to the coast, and bare earth), the results would suggest 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 coastal buildings actually protected houses further inland from the worst of the storm.

A third physical relationship that was significant on Coney Island was the relationship between building damages and building area. The model suggests that an increase in building area increased the odds of being damaged. This finding was only relevant for large changes in building area; small increases did not significantly affect the odds of being damaged at all (odds ratio = 0.01) (Table 5). One possible explanation is that there are a large number of high-rise apartment buildings along the boardwalk of Coney Island, and the coastline also includes the relatively large buildings of the Kingsborough Community College campus (Szulman, 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. Their height and proximity to the shore would also have exposed them to the worst of the wind.

The last very important physical relationship that can be explored on Coney Island regards soil permeability. Soil permeability was measured on a scale from 0-5, with 0 representing very low permeability and 5 very high. 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 and near beaches and parkland, two areas that have already been correlated with greater odds of damage (Figure 3).

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. Properties that were near to natural areas along the coast had even greater odds. Any protection that might have been offered by elevation gains was probably negated by proximity to the coast and/or increased exposure to wind.

5.3 Rockaways, Queens

Like on Coney Island, buildings on the Rockaway peninsula that were surrounded by a lot bare earth (including sand) were at greatest risk during Hurricane Sandy. A 1% increase in the amount of bare earth surrounding a property increased that building's odds of being damaged by 8.20% (Table 6). This finding might initially suggest that, once again, properties near the coast were most vulnerable. However, unlike on Coney Island, on the Rockaways the closer a property was to the coast the *less* likely it was to be damaged (Table 6). The most probable explanation is that flooding on the Rockaways came primarily from Jamaica Bay, and not from the ocean. The southern half of the Rockaway peninsula is generally at higher elevation that the northern half bordering on Jamaica Bay. The latter may be partially attributed to dunes created and maintained by the ACE along the southern coast (Gardner, 2013) (Figure 4). Anecdotal and visual evidence suggests that buildings behind the dunes were better protected than buildings without dunes (NYC DCP, 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; instead the worst flooding on the Rockaways came from Jamaica Bay (Figure 5)Figure . 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 buildings, many far from either coast, to significant flooding and associated damages.

Soil permeability was another important predictor of damages on the Rockaways. The regression suggests that buildings in regions of lower soil permeability were more likely to be damaged than those in higher permeability regions. A one-unit decrease in soil permeability increased a building’s odds of being damaged by almost 70% (Table 6). This trend is exactly opposite to that observed on Coney Island. One possible explanation may be related to the fact that on the Rockaways, the most permeable soils are typically found on the ocean-side (Figure 6). The presence of clay on East Rockaway and along Jamaica Bay, likely due to the filling of historic wetlands, results in decreased permeability in those regions. It is possible that damages were exacerbated in regions of poor permeability since ponded water would have been slower to infiltrate during and after the storm. It is, however, also possible that flooding happened to be more severe, and to create more damage, in the portions of the peninsula that coincidentally had less permeable soils. A detailed investigation into the types of damage found on the bayside of the island might be able to help disentangle whether damage in those regions was immediate or due to prolonged flooding. The data that would have been required to perform such an analysis was, however, not available to the research team.

The relationship between building damages and natural areas on the Rockaways was found to be complex. Model 2 suggests that buildings farther from natural areas were at a greater risk of being damaged (Table 6). This observation may be because properties nearer to the ocean-side beach, one of the largest natural areas on the Rockaways, were less exposed to Sandy’s surge due to the ACE dune construction projects previously implemented there. Buildings on the bay side of the peninsula suffered the worst damages. Buildings nearest to the ocean-side beach were also situated on sandy, more permeable soils, an attribute that was negatively correlated with damages on the Rockaways as described above (Table 6, Figure 6). However, Model 2 also suggests that buildings nearest to *large* natural areas were more likely to be damaged. Although the beach is one of the largest natural areas on the Rockaways, there are also very large tracts of wetlands on the bayside of the peninsula, particularly to the east. These areas are associated with low soil permeability which, as mentioned previously increased the odds of being damaged. These areas are also closer to the bay, where Sandy's flooding was worst. Previous studies in other areas have shown that coastal GI, particularly wetlands, can actually exacerbate storm surges over natural areas, and help to convey surges further inland under the right conditions (Ebersole, Westerink, Bunya, Dietrich, & Cialone, 2010; Loder et al., 2009; Resio & Westerink, 2008). Additional research is necessary to confirm whether such a phenomenon occurred over the back-bay wetlands of the Rockaways.

The last interesting relationship noted on the Rockaways was between tree canopy and building damages. As the amount of tree canopy surrounding a property increased, the odds of that property being damage decreased by 3.41% (Table 6). One possible explanation is that trees mitigated wind damage. Buildings surrounded by a dense tree canopy may have been better protected from wind gusts. A dense tree canopy may also have served as a net for flying debris, including any tree branches or limbs that might have come loose. Additional testing is needed to further explore the relationship between tree canopy coverage and building damage. Before advocating trees as a form of natural protection, a separate and related investigation, outside the scope of the present study, would explore the relationship between tree canopy density and damage to other kinds of infrastructure, such as power lines.

In summary, like on Coney Island, the Rockaway investigation suggests that proximity to beaches and wetlands increased the odds of being damaged. At a minimum, more protection appears necessary for buildings on the bayside to reduce inundation from Jamaica Bay, while dune restoration on the ocean side appears to have been effective at mitigating damages. Additionally, the peninsula's tree canopy may have served to protect buildings against wind and flying debris, though more research is necessary to investigate the role of trees in other kinds of damages. Nonetheless, the findings of this study suggest that on the Rockways two forms of GI, dunes and trees, may have provided protection to buildings during Sandy.

5.4 South Shore, Staten Island

Tree canopy was also found to be a significant predictor of damages on the South Shore of Staten Island. Like on the Rockaways, the more tree canopy around a building, the lower its odds of being damaged (Table 7). On Staten Island, a 1% increase in the amount of surrounding tree canopy decreased a building's odds of being damaged by 1.84% (Table 7). As stated previously, this finding may indicate a protective role that trees provide against wind and flying debris.

However, and in contrast to the findings in Brooklyn or Queens, on the South Shore of Staten Island the area of grass surrounding a building was also a significant predictor of damage (Table 7). As the area of grass increased, so too did the odds of building damages (Table 7). This finding may be an artifact of the data coding; natural areas, such as parks or wetlands were classified as "grass" in the surface type data layer, and as mentioned previously, under certain sets of conditions, natural areas can serve to propagate surges further inland (Table 1) (Ebersole et al., 2010; Loder et al., 2009; Resio & Westerink, 2008). However, an alternative explanation could be related to the lower density, suburban-style density of development patterns found on Staten Island. To the extent that areas classified as "grass" also include lawns, it could be that buildings surrounded by lawns presented greater fetch areas, subjecting the building to more wind, flying debris, and direct exposure to surge and waves. Buildings surrounded by lawns would have received less protection from wind and flying debris compared to those surrounded by trees or other buildings. Buildings surrounded by lawns may also have been more vulnerable to flooding. A close-up view of a sampling of damaged buildings suggests this alternative explanation may have merit (Figure 7). The damaged houses tend to border grassy areas while row houses tended to have less damage (Figure 7). Further supporting the theory that buildings surrounded by lawns were more vulnerable is the fact that on Staten Island properties closer to natural areas (which would have primarily been classified as grassy surfaces) were more likely to be damaged (Table 7).

All in all, the results suggest that a close proximity to natural areas and lower density development on the South Shore of Staten Island greatly increased the risk of property damage during Hurricane Sandy. The South Shore analysis presents a different picture of Sandy vulnerability when compared to the other two study areas. Elevation, distance to the coast, and permeability were insignificant predictors of damage. Instead tree and grass coverage mattered more. The more surrounding trees, the lower the odds of being damaged, while the more grass, including parks, wetlands, and natural areas, the greater the odds of being damaged.

6. Conclusions

This study is limited in several ways. First, we examined building damages associated with Hurricane Sandy only, a storm that generated high wind, waves, and a storm surge in New York City. The conclusions developed from this research are thus unique and do not necessarily apply to the impacts of other storms such as Hurricane Irene, which deposited much higher amounts of precipitation on the City when it occurred in 2011. 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.

The study also did not consider damages to properties other than buildings, nor did it consider secondary impacts associated with Sandy. Many secondary impacts, such as the electrical fire that devastated over 100 homes in Breezy Point during the middle of the storm were quite significant (Barr, 2013; Colangelo, Morales, & Connor, 2012; Kleinfield, 2012). The hurricane prevented firefighters from traveling to the scene of the blaze, and the storm's heavy winds helped to fuel and spread the flames until the fire eventually burned out on its own (Barr, 2013; Colangelo et al., 2012; Kleinfield, 2012). Less obvious, but no less severe of a secondary impact, were the regional wastewater treatment plants, including Bay Park Sewage Treatment Plant in East Rockaway, N.Y., that were flooded during the storm, releasing billions of gallons of raw sewage into the water in the days and weeks after the storm (Kenward, Yawitz, & Raja, 2013). In New Jersey containment areas flooded and fuel tanks experienced significant leaks after exposure to Sandy's surge (Hutchins, 2012). The water helped to quickly spread the fuel, oil, and other pollutants, resulting in the worst oil spill in New Jersey in more than a decade (Hutchins, 2012). Although neither spill resulted in the immediate loss of lives or property, the environmental toll is high and will be felt for years to come. Though beyond the scope of this study, the relationship between Hurricane Sandy and these secondary impacts warrants further investigation.

Our ability to isolate the effects of specific variables was also limited by the lack of uniformity in the development patterns of NYC's coastal communities. For example, 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. But it was impossible to test what would have happened to smaller buildings if they covered a larger area of Coney Island's beach front, since an extensive sampling of such buildings simply do not exist. Similar realities limited apply to our ability to isolate the effects of other variables.

Despite such limitations, in 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 building damage in the study sites. A detailed investigation into which natural features mattered most revealed significant geographic differences. Proximity to natural areas increased the odds of damage along the Rockaways and decreased the odds along the South Shore of Staten Island. Higher soil permeability was associated with greater damages in Coney Island and lesser damage in the Rockaways. Trees seem to be associated with lower damage levels on the Rockaways and the South Shore, but were not a significant predictor of damage on Coney Island. This analysis implies that Sandy interacted with the city's physical and natural infrastructure in complex, geographically specific ways, suggesting that investments in coastal protection must be planned strategically and tailored to unique, local conditions.

Although investments in the construction, enhancement, and protection of natural systems may restore a larger portfolio of ecosystem services than could ever be achieved by hard engineering measures, it may be difficult to claim unequivocally that, within the spatial constraints presented by the city, natural systems will be able to protect people and property from future storm surges alone. This study suggests that some natural areas did help to mitigate Sandy's destructive forces in at least some portions of the city. Dunes may have provided protection to ocean-side properties on the Rockaways. However, 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, suggesting that not all coastal GI could serve the same purpose. Tree canopy was beneficial possibly due to the protective nature trees can have against wind and flying debris, but this finding was not consistent across all three study sites, perhaps because trees would have offered limited protection against storm surge.

The lack of consistent results across all of the coastal areas examined in this study does not allow us to claim that GI, in its current coverage and configuration, unequivocally reduced the vulnerability of buildings to damages from Sandy. While some forms of GI in some places likely provided some protection, the only sure-fire way of reducing coastal risks associated with storms like Hurricane Sandy may be retreat. This same conclusion was made two years before Sandy by the New York State Sea Level Rise Task Force (2010), based solely upon the projected impacts of sea level rise and climate change on the city's coastal flooding risks (NYS SLR Task Force, 2010). However, even if the protective services provided by GI are 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. Indeed, when less heavily impacted by development, coastal ecosystems provide a wide range regulating, supporting, provisioning, and cultural ecosystem services.

Acknowledgements

The authors would like to thank Ziwen Yu and Romano Foti, both of Drexel University, for their assistance with data management. This research was funded in part by the Trust for Public Land's Climate-Smart Cities Program through support from NOAA's Coastal Resilience Networks Grant and the National Oceanic and Atmospheric Administration's grant NA15OAR4310147 to the Center for Climate Risk in the Urban Northeast.

References

Acreman, M., & Holden, J. (2013). How Wetlands Affect Floods. Wetlands, 33, 773-786. doi - 10.1007/s13157-013-0473-2

Barbier, E.B., & 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

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

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

Catalano de Sousa, M.R., Miller, S.M., Dorsch, M., & Montalto, F.A. (in press). Green Infrastructure as a Climate Change Resiliency Strategy in Jamaica Bay, NY. In E. Sanderson, W. Solecki, J. Waldman, & A. Parris (Eds.), *Prospects for Resilience: Loss, Recovery and the Future of New York City's Jamaica Bay*. New York: Island Press.

Colangelo, L.L., Morales, M., & Connor, T. (2012, October 30). Hurricane Sandy: Fire in Breezy Point burns down more than 80 homes, residents devastated. *Daily News*. Retrieved from: http://www.nydailynews.com/new-york/queens/breezy-point-devastated-80-homes-burn-article-1.1194973

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

Consortium for Climate Risks in the Urban Northeast (CCRUN) (n.d.). Hurricane Sandy. Retrieved from http://ccrun.org/Sandy_home

Costanza, R., Perez-Maqueo, O., Martinez, M.L., Sutton, P., Anderson, S.J., & Mulder, K. (2008). The Value of Coastal Wetlands for Hurricane Protection. *Journal of the Human Environment*, 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.

Gardner, C. (2013, October 28). *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

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

Hutchins, R. (2012, November 14). *Oil spills, other Hurricane Sandy damage present N.J. with potential pollution headaches*. Retrieved from http://www.nj.com/news/index.ssf/2012/11/hurricane_sandy_oil_spills.html

Kenward, A., Yawitz, D., & Raja, U. (2013, April 30). *Sewage Overflows from Hurricane Sandy*. Retrieved from http://www.climatecentral.org/pdfs/Sewage.pdf

Kiernan, M.K. & Lenhardt, M.F. (2013). What’s in a name(d) storm? What Sandy has taught us about flood, storm surge, and FEMA flood zones. *FDCC Quarterly*, 63(4), 318-399.

Kleinfield, N.R. (2012, December 24). Battered Seaside Haven Recalls Its Trial by Fire. *NY Times*. Retrieved from: http://www.nytimes.com/2012/12/25/nyregion/breezy-point-battered-seaside-haven-recalls-its-trial-by-fire.html?_r=0

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 Analyzing Travel Behavior of Individuals: Some Recent Developments. In Hensher, D. & Stopher, P. (Eds.): *Behavioural travel modelling* (pp 279-318). London: Croom Helm

Miller, S., Kidd, G., Montalto, F., Gurian, P., Worrall, C., & Lewis, R. (2014). Contrasting Perspectives Regarding Climate Risks and Adaptation Strategies in the New York Metropolitan Area after Superstorm Sandy. *Journal of Extreme Events*, 1(1), 1-22. doi - 10.1142/S2345737614500055

Moller, I., Kudella, M., Rupprecht, F., Spencer, T., Maike, P., van Wesenbeeck, B.K.,…Schimmels, S. (2014). Wave Attenuation Over Coastal Salt Marshes Under Storm Surge Conditions. *Nature Geoscience*, 7(10), 727-731.

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

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

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

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

New York State Sea Level Rise (NYS SLR) Task Force (2010, December). *New York State Sea Level Rise Task Force Report to the Legislature*. Retrieved from http://www.dec.ny.gov/docs/administration_pdf/slrtffinalrep.pdf

Newsroom, Environmental Protection Agency (EPA). (2014). *EPA Provides a Quarter Million Dollars to Protect Wetlands in New York* [Press release]. Retrieved from https://yosemite.epa.gov/opa/admpress.nsf/0/A0548608EDDECF9085257DAF005DD60C

Office of the Mayor, New York City. (2012). *Mayor Bloomberg Releases Hurricane Sandy Federal Aid 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, New York City. (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*. Retrieved from https://www.climate.gov/news-features/featured-images/future-flood-zones-new-york-city

Resio, D.T., & Westerink, J.J. (2008). Modeling the Physics of Storm Surges. *Physics Today*, 61(9), 33-38. doi - 10.1063/1.2982120

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

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

Szulman, J. (2012, November). Kingborough Post-Sandy. *Scepter*, pp. 1, 4

Tape. (n.d.). *Thomas G. Interpreting Diagnostic Tests*. Retrieved from - http://gim.unmc.edu/dxtests/Default.html

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.

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

United States Geological Survey (USGS). (2014, October 21). Hurricane Sandy Response – Storm Impacts and Vulnerability of Coastal Beaches. 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 wetlands in reducing storm surge. *Ocean Engineering*, 37, 59-68.

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

List of Tables

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, bays, and all other waterbodies	Derived from 2010 CUGIR ; supplied by TPL	Used to calculate distance from the nearest major coastline (ocean, bay, river)
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 damage estimates on a scale from 0 – 4 (Not damaged → destroyed), which the CAP estimated from analysis of their aerial photography.
Wetlands	Location of all NYC wetlands	Derived from 2010 CUGIR; available through data sharing agreement	
Parkland	Location of all parkland in NYC	Supplied by DPR	Include waterfront parks
Waterfront Parkland	Location of only waterfront parkland	NYC Department of City Planning	Any parkland or parkland segment separated from the water by a road or other barrier 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.	Federal Emergency Management Agency (FEMA)	Values representative only for those houses who requested assistance above and beyond what was covered by private insurance.

Table 2: Description of CAP damage categories.

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.

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

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-R2	0.11	0.03	0.04
Model 2	AUROC	0.85	0.82	0.82
	McFadden's pseudo-R2	0.18	0.20	0.18
	χ^2 difference	$p < 0.001$	$p < 0.001$	$p < 0.001$

Table 5: Results of the Coney Island logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and how a one unit increase in each variable changes 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 (ft2)	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					

Table 6: Results of the Rockaways logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and how a one unit increase in each variable changes 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 (ft2)	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					

Table 7: Results of the South Shore logistic regression (Model 2). Includes mean and standard deviation for each variable, beta values, significance, and how a one unit increase in each variable changes 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					

List of Figures

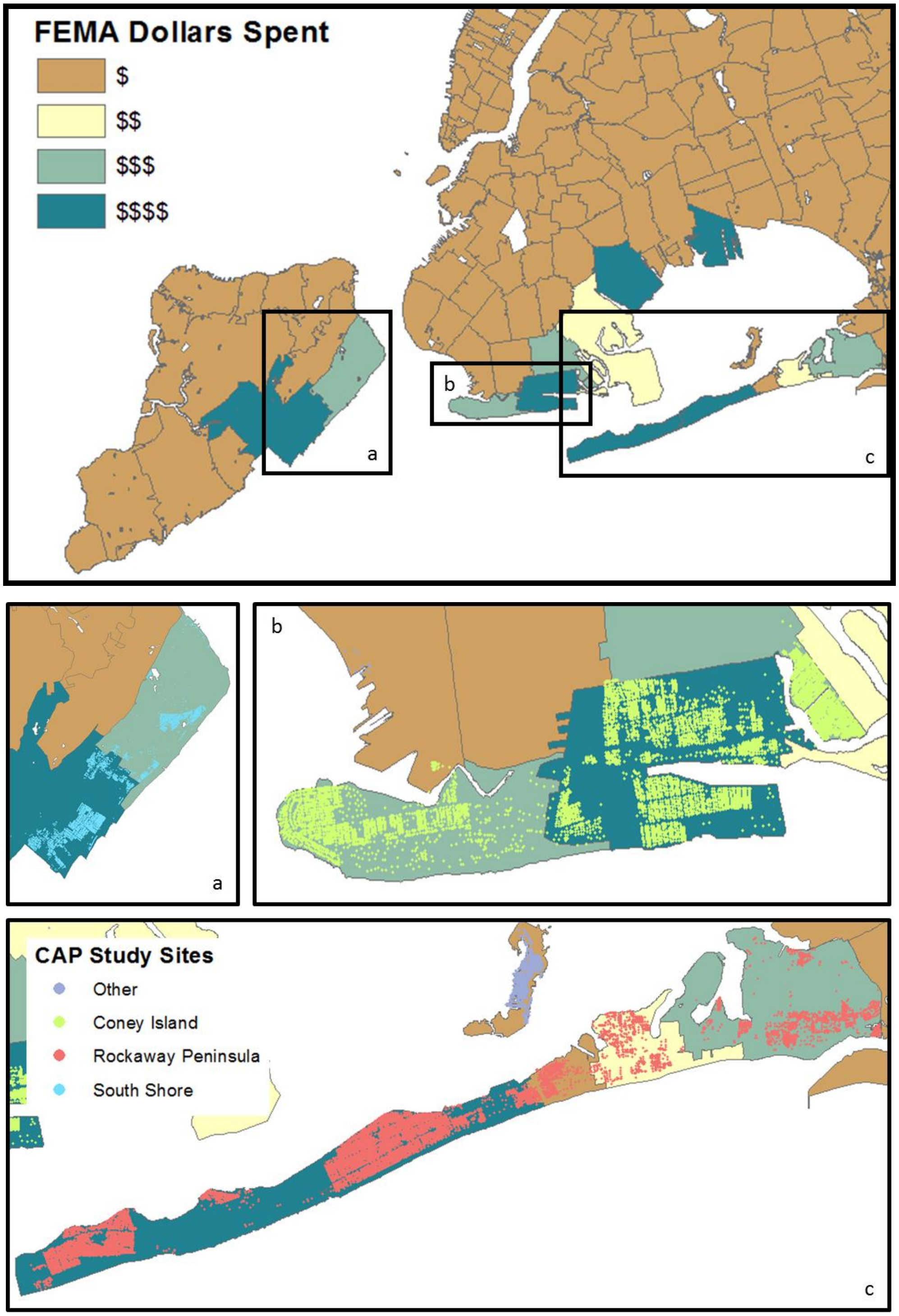

Figure 1: Location of the three study areas - Coney Island, Brooklyn; Rockaway Peninsula, Queens; and South Shore, Staten Island

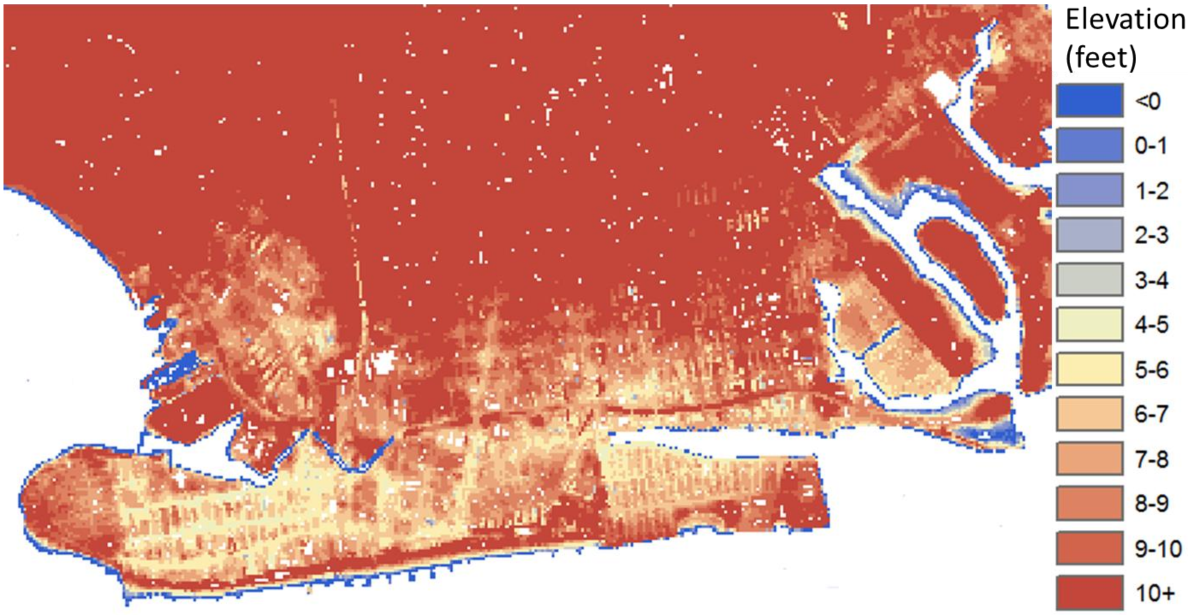

Figure 2: Elevation map of the Coney Island study area.

Figure 3: Map of soil permeability for the Coney Island study area.

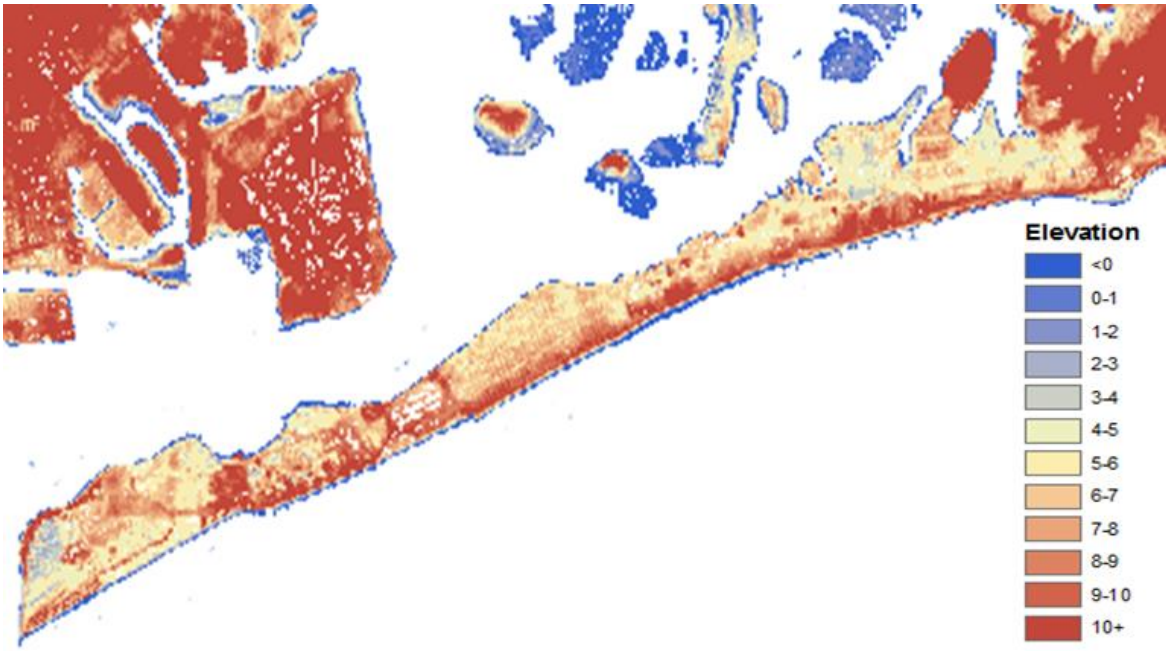

Figure 4: Elevation map of Rockaway Peninsula.

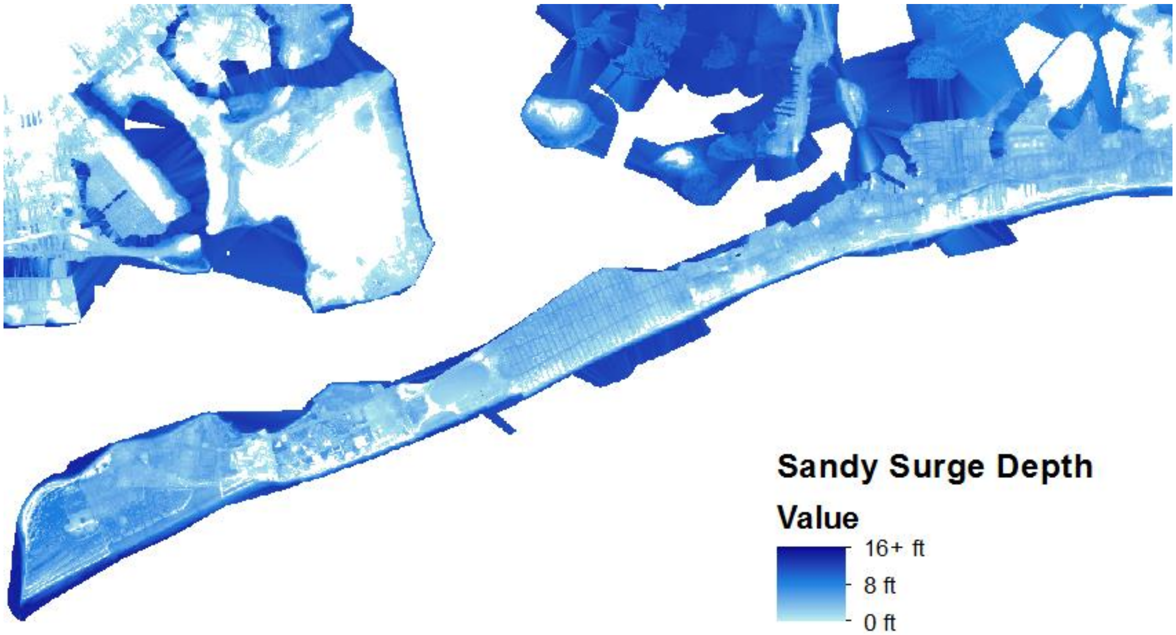

Figure 5: Map of surge depth on the Rockaway Peninsula during Hurricane Sandy.

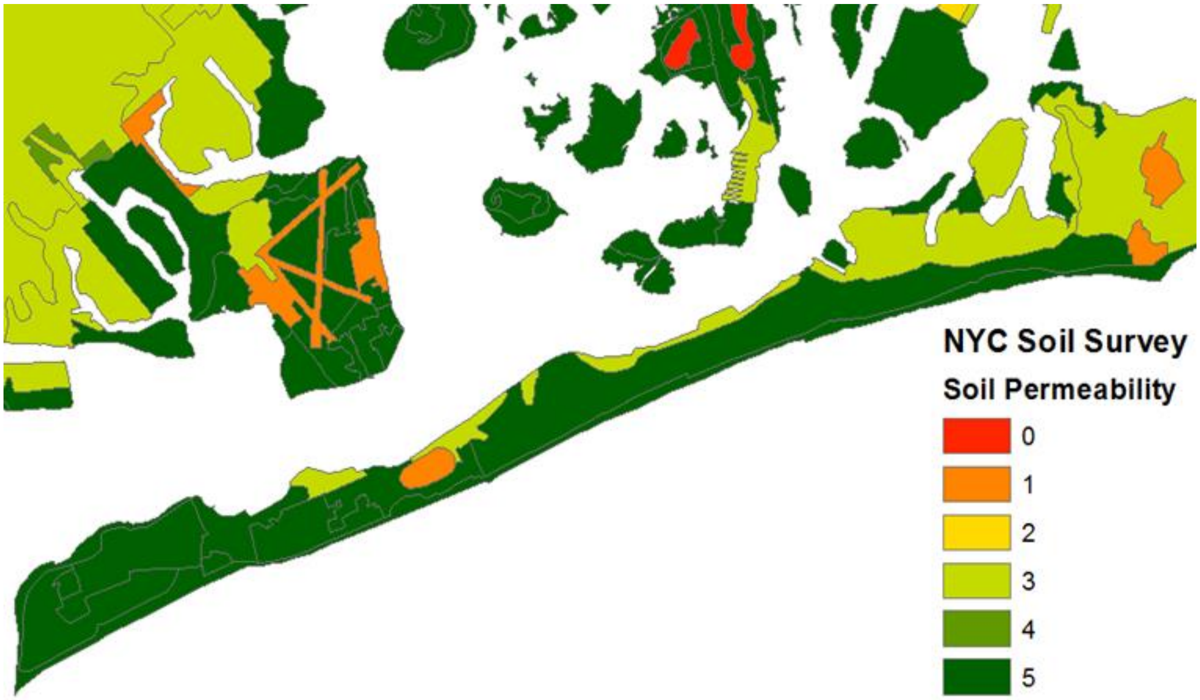

Figure 6: Map of soil permeability on Rockaway Peninsula.

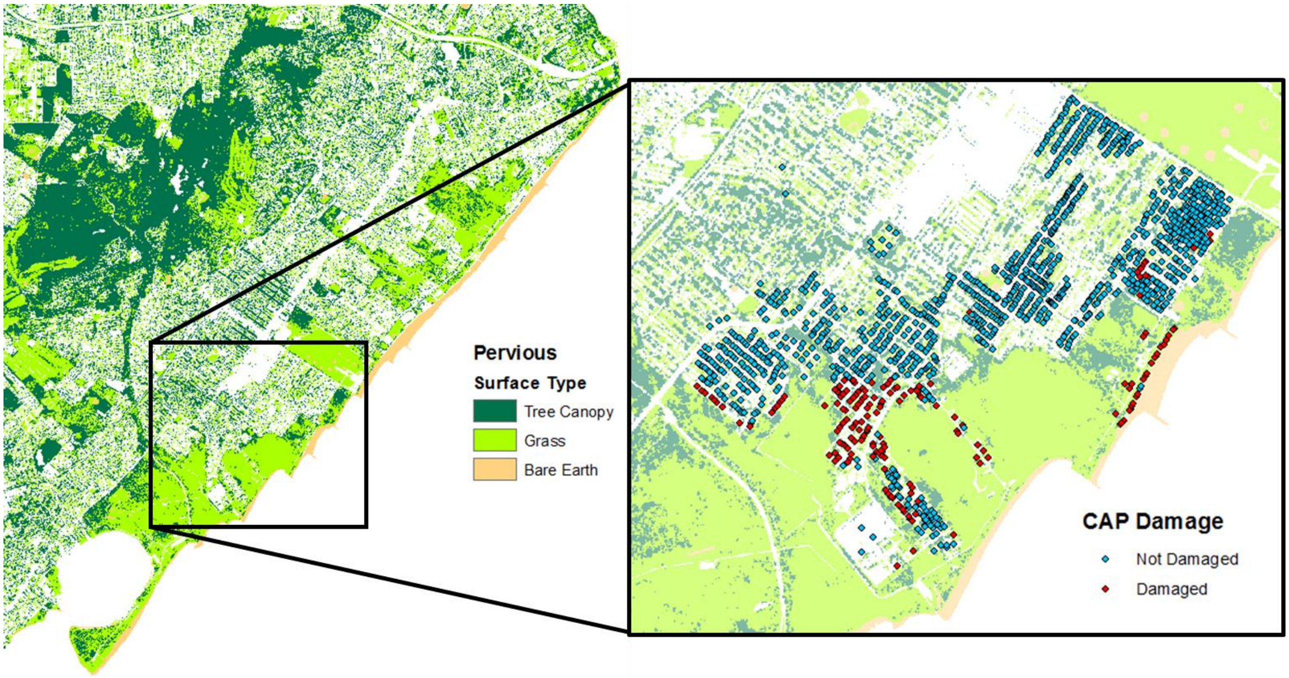

Figure 7: Map of tree canopy, grass, and bare earth coverage on the South Shore, Staten Island. In-set shows CAP damage classifications (damaged or not damaged) for houses in the South Shore study area.