# ABSTRACT

ANALYSIS OF INFRASTRUCTURE DAMAGE AFTER SUPERSTORM SANDY:
A CASE STUDY OF LONG BEACH, NY

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Although much is known about the geomorphology of barrier islands and how barrier islands respond to storm events, no research has considered the implications of dense development on storm damage patterns. This research examines how anthropogenic attributes of a barrier island related to the infrastructural damage patterns incurred from Superstorm Sandy. Specifically, infrastructural damage was unrelated to development density and road orientation but closely related to depth of storm surge and conditions of the beach.

# ANALYSIS OF INFRASTRUCTURE DAMAGE AFTER SUPERSTORM SANDY:

# A CASE STUDY OF LONG BEACH, NY

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# Analysis of Infrastructure Damage Following Superstorm Sandy:
## A Case Study of Long Beach, NY

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# Chapter 1: Introduction

Much of the southern shore of Long Island, NY, was devastated by Superstorm Sandy in October 2012. As planning and rebuilding efforts occur, the affected communities are seeking solutions to make themselves more resilient to future storms and less susceptible to coastal hazards. Planning is a tremendous challenge for Long Island because communities are so densely populated that risk and damage costs are magnified and coastal retreat for such a large population is not a viable option. Many of these communities are located on barrier islands, which were totally inundated by storm surge during the event. On one barrier island, there are four towns of similar socioeconomic characteristics which suffered extensive devastation: Atlantic Beach, Long Beach, Lido Beach, and Point Lookout. Long Beach was chosen as the study area for this analysis of infrastructure damage patterns primarily because it is the most densely populated of these communities.

This research analyzes patterns of damage to infrastructure along both the bay and ocean sides of this barrier island, comparing and correlating areas with high levels of damage relative to the pre-storm presence of coastal structures (groins and seawalls) and to the geomorphological characteristics of the coastline (such as beach and dune shape, dune size, dune width, dune height, beach width, elevation, offshore characteristics, and vegetation). An enhanced understanding of factors compounding to generate damage to infrastructure in a major storm event is beneficial to planners on Long Island as well as to coastal planners in developed coastal communities around the world. This is especially important as coastal populations continue to increase. Understanding how infrastructure damage varies at a local scale may better equip and prepare decision-makers in scenarios where evacuation may be necessary, aid communities and developers in identifying suitability of locations for development, and provide useful information about the effectiveness of coastal engineering structures and natural and artificial dunes in areas with different levels of development.

A number of factors are expected to affect the degree and type of damage that properties on developed shorelines incur from a storm event. These factors include the hydrodynamic nature of the storm, morphological characteristics of the area affected, and the anthropogenic characteristics of the community. It is reasonable to expect that most infrastructure damage would occur along the ocean where major waves could batter the properties and wind would be strongest as it blew unobstructed across the water with a fetch of up to a thousand miles (Sobel, 2014). Many advocate for maintaining beaches in their natural state for protection of the natural system and also of properties behind dunes (Gares, 1990; Coch, 1994a; Coch, 1994b; Pethick & Crooks, 2002; Debaine & Robin, 2012), and it is further argued that removal and alteration of dunes may have adverse effects on the geomorphology of the island and the island's response to storm events (Coch, 1994a; Hamilton et al.,2008; Houser, 2009; Van de Graaff, 2009; Houser, 2013), so inhabitants nearby would likely be affected by this removal as well. Therefore, it is hypothesized that buildings located landward of well-developed dunes may incur lower levels of damage than those where dunes have been lowered, narrowed, or removed. At the same time, elements of the built environment are likely to have an impact on damage patterns. Relationships between property damage and debris from the storm are unclear but one might predict that more densely developed areas would lead to softening of the currents and turbulence of the surge as it engulfed the island, lessening impacts to all properties. Further, roads oriented in a north-south direction might act as conduits for surge between the ocean and bay, basically funneling surge across the barrier at an expedited rate and therefore properties along roads oriented north-south would suffer more damage than those along the roads oriented east-west.

## Research Questions

This research seeks to answer questions about whether and how physical land characteristics (dune width, beach width, vegetation, roughness, shoreline movement, barrier width, and surge depth), coastal engineering structures (the boardwalk and groins), and anthropogenic characteristics (the orientation of roads, density of houses, and presence of canals) during Superstorm Sandy may have influenced damage patterns on both the beach and bay sides of Long Beach Barrier Island. The specific research questions are:

**Research Question 1:** What trends can be seen in patterns of infrastructure damage on Long Beach?

**Research Question 2:** What physical characteristics of the barrier island are related to infrastructure damage?

**A:** How did the geomorphology along the beach change and by what measure? Is there a spatial relationship between beach changes and the patterns of property damage exhibited?

**B:** To what extent is elevation related to severity of infrastructure damage? Is depth of surge related to infrastructure damage to the same extent as elevation?

**C:** Is there a relationship between infrastructure damage and location on the barrier (North-to-South), and width of the barrier island?

**Research Question 3:** How do damage patterns differ between areas where properties are abutting dunes as compared to areas where dunes are absent?

**Research Question 4:** To what extent did characteristics of the built environment influence damage patterns?

**A:** What is the relationship between density of development and the severity of infrastructure damage?

**B:** What is the relationship between road orientation and severity of infrastructure damage?

**Research Question 5:** For individual properties, what were the compounding factors that put them most at risk for higher levels of damage?

# Chapter 2: Literature Review

## Introduction

It has been a recurring theme in geography over time that human aspects of the field do not coincide with the physical; occasionally this has polarized the discipline (Johnston, 2005). As a result, little research has been published that combines elements of human geography (i.e., planning and management) with the physical studies of geomorphology and land characteristics, despite many recognizing the need for more literature on the (Gares et al., 1994; Nordstrom, 1994; Jackson & Nordstrom, 2011). Just like the need for literature combining geomorphology and human geography, there is no research that has married storm damage disparities on a developed barrier island with morphologic characteristics and anthropogenic characteristics of the island. At present, minimal literature has been published considering the many different factors that combine to influence storm-incurred damages. Nothing has been published considering the factors that affect a single community's losses from a storm event. However, much of the material published regarding coastal research can be applied to study community interaction with the beach and reduction of vulnerability, often following major storm (Gares, 1987; Leatherman, 1987; Nordstrom, 1987; Coch, 1994; Gares et al., 1994; Boruff et al., 2005; Houser, 2009; Ewing et all., 2010; McFadden, 2010; McLaughlin & Cooper, 2010; Bernatchez, et al., 2011; Debaine and Robin, 2012; Arkema et al., 2013; Newton & Weichselgartner, 2013; Spalding et al., 2013).

Effects of storms on barrier island systems following a storm event, especially on undeveloped islands is well established. It is important to research developed barrier islands because developed coasts are vital to the well-being of local, state, and even federal economies. Researching heavily developed coasts while considering damages to human structures is advantageous to the millions of people living on developed coastlines as well as the planning agencies, coastal zone managers, and local governments, aiding them in evacuation and land use decisions and enabling them to better prepare areas of higher susceptibility to the hazard.

## Geomorphology of Barrier Islands

Many studies have taken place over a region of eighty-three miles on the southeastern shore of Long Island dubbed "FIMP," Fire Island to Montauk Point, (Nordstrom & McCluskey, 1985; Bocamazo et al., 2011; Lentz & Hapke, 2011; Lent, et al., 2013). In 1995, the US Army Corps of Engineers began a comprehensive study to evaluate storm damage measures and responses to breaches resulting from storms in the region (U.S. Army Corps of Engineers, 1996). This stretch of land is federally regulated and also developed by humans, so engineering structures such as groins and seawalls and beach nourishment are commonplace and affect the people on the developed barrier island. FIMP has similar geomorphology to Long Beach Island, given its proximity to the study area and comparable orientation. The FIMP region experiences alongshore drift transporting sediment from east to west with accretion taking place on the western portion of the island, thus Long Beach receives and transmits the same sediment drifting from East to West. Lentz and Hapke (2011) attribute volumetric changes in sediment between the two ends of the FIMP barrier to inner shelf geology and offshore characteristics. The sediment migration and behavior of Long Beach is comparably tied to offshore bathymetry.

Topographic surface roughness is a variable that characterizes and describes the land. There are various techniques in classifying topographic roughness (Grohmann et al., 2011); these techniques vary based on moving window size and the spatial scale of the features being studied. This research studies medium-scale features on a barrier island before and after a major storm event, Superstorm Sandy, to classify the changes in roughness of the land.

Roughness is frequently studied in alluvial fan deposits or in topographically diverse regions of the world such as Scotland (Frankel & Dolan, 2007; Grohmann et al., 2009; Grohmann et al., 2011) and these findings can be applied to beach morphology, specifically as a basis of comparison in beach morphology after a major event. Previous research conducted in the study area suggests that erosion of the beach was approximately 15.5 meters as a result of Sandy but the changes in topographic roughness of this barrier island have not been studied. It is useful to understand how much rougher or smoother the beach and dune became as a result of the storm because these characteristics may ultimately correlate with infrastructure damages nearby. It is hypothesized that Sandy moved sediment around and effectively flattened the beach and dune, filling in subtle sinks and variations in roughness and also removing any vegetation or larger items such as boulders, effectively decreasing roughness values throughout the beach.

## Storms and Geomorphology

In a storm event, there are a number of factors that heighten risk to structures and communities on developed barriers. Barrier islands are susceptible to coastal threats including shoreline erosion from a storm, shoreline retreat from gradual sea level rise and alongshore currents, in addition to threats unique to barriers in particular – overwash events are not uncommon during major storms and inlet breaching occurs after many hurricanes.

Bathymetry and the topography of the sea floor are easy to overlook when considering geomorphological changes of a barrier island or the effects a storm can inflict on such an island. The gentle slope of the continental shelf of barrier islands on the East Coast of the US, like Fire Island or Long Beach, puts these islands at increased risk to storm damage. The northeast, particularly Long Island, is extremely vulnerable to storm damage because of the east-to-west orientation of the coast, which enables many storms to strike head-on instead of obliquely to the shoreline (Coch, 1994). Although the notion of shoreline equilibrium is disputed and the definition is not agreed upon, it is clear that barrier islands are dynamic and constantly changing. Barrier islands of the Atlantic coast, in particular, are never in equilibrium because they are perched barriers sitting on top of older and eroding stratigraphic units and thus are constantly affected by waves and currents altered by the bathymetric shoal features of the inner shelf (Riggs et al., 1995).

In storm events, offshore bathymetry certainly plays a role in geomorphological changes, shoreline retreat and erosion, and may reduce or contribute to community vulnerability. Waves break upon nearshore bars and the transition between shallow water and deep water waves during a storm event determines how far offshore the waves are able to break and dissipate their energy before reaching the beach. A flat slope causes waves to break farther offshore and can alleviate the risk of inland flooding (Gares, 1990). Offshore bathymetry is also a factor of consideration when predicting overwash locations on a barrier island during a storm event (Lentz et al., 2013). Steep offshore profiles tend to concentrate storm energy through wave refraction and reduced attenuation; this potentially leads to erosional hotspots during a storm (Houser, 2009). A given barrier island may also undergo cyclic adjustment of the bathymetry offshore over time. This adjustment is characterized by a steepening phase where the shoreline position is stable and retreating slowly, followed by a stormy period of shoreline flattening and rapid landward migration (Leatherman, 1987). Sandy hit the coast of the study area at the end of the 2012 hurricane season, and Sandy was the only hurricane to come within 250 miles of the New York coastline. The coast of the study area was therefore not depleted of sediment or recovering from a storm event at the time of Sandy (National Hurricane Center, 2012).

Dunes are a major component of a healthy beach. Typically, a coastal profile consists of dune or mainland beach and the foreshore (van de Graaff, 1994). Although dune development depends upon windblown sand collecting in the dune field (Gares, 1987), availability of sand is determined by input of sand to the beach from the ocean which is impacted by offshore bathymetry. A large and continuous foredune is often observed in areas with offshore profiles that are relatively steep, and offshore profiles can alter the dune shape and structure on even a single barrier island (Houser, 2009). It is inarguable that successful and effective coastal zone management practices must consider geomorphological elements of the locations, and it is assumed that areas with wide, vegetated, and tall dunes would be safer during a storm than those without (Pethick & Crooks, 2002).

Dunes are often viewed as an integral element of coastal protection and resiliency (Debaine & Robin, 2012). As such, they are often nourished and built up to protect the communities abutting the dune systems. A continuous line of dunes may prevent surge water from inundating a barrier island, but gaps in the dunes can act as overwash conduits and funnel surge inland (Hamilton et al., 2008; Houser, 2009; Houser, 2013). In many locations in the study area, the dunes have been removed to allow for heavy development, presenting gaps where surge could potentially be funneled inland. These gaps may have catastrophic effects on storm resiliency and protection (Coch, 1994).

Dunes are dynamic features and migrate inland during storm events, they prevent flooding and they also replenish the beaches after they have been eroded. Variations in dune size and shape affect levels of protection afforded to abutting communities (Gares, 1990). However, there are many factors that affect dune responses to storms on barrier islands (Hamilton, et al., 2008). Hurricanes and major storm events damage dunes through erosion and transport of sediment. When these storms are paired with overwash, the damage to the dunes is magnified (Claudino-Sales et al., 2008; Hamilton et al., 2008; ;Bocamazo et al., 2011; Houser, 2013). Nearshore bars replenish sediment on the beach and ultimately the dunes, but storm events erode the sediment off the dunes (Hamilton, et al., 2008).

Storms inflict other major geomorphological effects on vulnerable barrier island coastlines (Dolan et al., 1978; Zhang et al., 2002). Storms often over wash barrier islands; dunes and bathymetry affect locations where over wash and inundation occur (Dolan et al., 1978; Gares, 1990; Coch, 1994; Hamilton et al., 2008; Houser, 2009; Houser, 2013). Massive storms capable of inflicting overwash on a barrier island also result in beach retreat and pronounced erosion. Though more common in tropical hurricane-prone areas of the United States, it is not uncommon for the barrier islands in the Northeast to incur geomorphological changes as a result of storm events. High magnitude hurricanes and nor'easters affect barriers in the Northeastern United States. Each year, from the hurricane season through the winter, major storms affect sandy coastal communities (Dolan et al. 1978). The period shortly after the major storm is one where the beach recovers (Birkemeier, 1979; Zhang et al., 2002; Van Rijn 2009) and over the summer, the beach continues to rebuild. This process of recovery may be complicated when the beaches are developed (Morton et al., 1997).

Storm surge is perhaps the most serious threat to developed coastal communities. Storm surge is the rise of the ocean surface resulting from hurricane winds driving shelf water into shallower areas nearer to the shore, in addition to the surface of the ocean rising due to the pressure in the eye of the hurricane. Essentially, storm surge is a high dome of water on top of which waves develop (Coch, 1994). Often surge hazards are exacerbated by engineering structures (Bernatchez et al., 2011). Certain measures can decrease sensitivity to coastal erosion but increase risk of inundation and flooding by reducing or altering volumes of beach sediment (Bernatchez et al., 2011). Coastal flooding exacerbates beach and dune erosion (Van Rijn, 2009; Bernatchez et al., 2011; Houser, 2013). It has also been found that seawalls can greatly reduce storm surge damage, even if they are old and unkempt (Irish et al., 2013).

How the barrier island responds to major storms is contingent on storm intensity, storm surge, barrier island width, dune morphology, dune vegetation, distance of the dunes from the ocean, the interval between subsequent storm events and overwash morphology, among many other factors (Claudino-Sales et al., 2008). Dunes, dune height, and dune extent play a pivotal role in influencing the barrier island response to storm events (Coch, 1994; Hamilton, et al., 2008). Because nearshore bars provide sediment to dunes and barrier islands, ultimately protecting communities (Hamilton et al., 2008), consideration of geology and offshore bathymetry are very important in generating and considering storm risk models (Lentz & Hapke, 2011; Lentz et al., 2013).

Coastal storms cause erosion through high waves breaking on the beach and dune. The extent to which dunes are eroded by coastal storms depends mainly on their pre-storm height and vegetation characteristics (Coch, 1994). Dunes survive when they are high enough not to be inundated or when they are low and well vegetated. However, frequent hurricanes (or comparable storms) will flood barrier islands and ultimately kill vegetation, which, in turn, leads to increased erosion of the dunes (Coch, 1994).

Storm-inflicted beach and dune erosion has a minimal effect on the overall trend of a barrier island and whether or not it is accreting or eroding sediment. Major events like the notorious Ash Wednesday Storm and storms similar to Sandy have little impact on long term trends (Zhang et al., 2002). Recession or accretion occurs throughout the year in response to various factors (waves, sea level changes, tides) and is often mitigated by humans with nourishment or groins (Dolan et al., 1978). Having occurred in October, Sandy was one of the later storms in the 2012-2013 hurricane season and although the geomorphological effects Sandy wreaked in Northeast were pronounced, it is important to realize that the beaches underwent a period of recovery. Their overall erosion or accretion is more closely related to anthropogenic mitigation efforts, alongshore currents, sea level rise, and overall sediment supply (Zhang et al., 2002).

Much data has been collected on dune and beach long-term erosion rates throughout the region (Nordstrom & McCluskey, 1985; Van Rijn, 2009; Hapke et al., 2013). One study found that Long Island, as a whole, is accreting more sediment than it is eroding (Hapke et al., 2013). However, Hapke et al. (2013) point out that localized disparities due to development and engineering structures invalidate overall accretion. Humans have addressed erosional threats with different methods over time. Initially groins, like those in Long Beach, were the favored means of stabilization. Groins became necessary on Long Island because of its dense development and evidence that the beaches in the East were eroding. Without groins, alongshore current would result in Long Island losing the beaches and barriers on the eastern end of the island while those further west (Long Beach and the Rockaways, for example) would receive the sediment that originated on the eroding eastern beaches. The trapping of sediment all over Long Island with groins and jetties results in the localized disparities that Hapke et al., (2013) discuss.

Increasingly, coastal zone developers and managers are looking to dunes as a preferred means of shoreline stabilization and a way of preventing storm-related retreat (Psuty, 1987). Erosion of the developed barrier island is a function of the balance among the sediment supply, the natural systems, and the anthropogenic modifications. Together the forces result in advance or retreat of the shoreline, but the essential aspect of coastal retreat boils down to an imbalance in sediment supply. Decreased sediment supply results in the shoreline eroding back (Di Stefano et al., 2013).

In addition to extreme sensitivity to storms and upsets in the sediment supply, barrier islands are very susceptible to changes in sea level due to their low elevation (Oost et al., 2012). Because of rising sea level, the shoreline will retreat and sediment will erode; as a result the sediment will be redistributed alongshore (Inman & Dolan, 1989). The rising sea level will also permanently inundate some structures on barrier islands and more frequently inundate structures by storm surge, including structures along the bay (Clayton, 1987).

Many studies have been conducted identifying areas on a barrier island particularly susceptible to storm surge inundation and flooding (Bocamazo, 2011; Houser, 2013; Lentz et al., 2013 ). Models created to identify the areas susceptible to flood and inundation typically consider factors such as island orientation, offshore slope, sediment supply, anthropogenic intervention and hardening structures (Bocamazo et al., 2011; Houser, 2013; Lentz & Hapke, 2011). Surge effects vary between hurricanes depending on meteorological aspects of the storm. Sea surface pressure, distance to center of the storm, and also geomorphological elements of the coastal area including bathymetry, terrain, and the height of the tide at landfall all affect the height of the storm surge (Saffir, 2003). Wind in the front right (in this case the northeast portion of Sandy) is typically much higher than in the left or southwest quadrant of the storm. Long Beach was situated in the northeast quadrant of Sandy and suffered higher wind speeds relative to other locations.

Flooding from the bay is often overlooked as a cause of storm damage. Hurricanes are notorious for tremendous surge, waves, wind, and debris that impact residential structures and less so for the depth of surge from the bay. In some cases, the bay side of a barrier island may have extensive flooding but little structural damage and less structural damage relative to the ocean (U.S. Army Corps of Engineers, 2015). Bay side flooding in barrier systems is a problem that is dealt with perhaps more often than ocean flooding, surge, and waves and will be dealt with more often in years ahead when sea level rises (HR Wallingford, 2015).

Bay-side flooding and surge on barrier islands comes from several different potential sources. Research conducted on a barrier island in New Jersey after Superstorm Sandy concluded the bay flooding came from the increase in barometric pressure related to Sandy's arrival, the inundation of the entire barrier (inundation also occurred in Long Beach, NY), and also new inlet breaches in nearby barrier islands. The direction of the wind in New Jersey also caused a build up of more surge in the southern portion of the bay (The Richard Stockton College of New Jersey, 2014). Weisberg & Zheng (2006) had similar findings to the Richard Stockton College study as they determined that the worst case for storm surge in a bay occurs when the storm makes landfall northward of the mouth of the bay, resulting in strongest winds occuring at the mouth of the bay and subsequently causing a build up of water in the bay. Another study found that surge behavior in Galveston Bay during a hurricane is not dependent on wind speed but rather landfall location and direction of the wind (Sebastian et al., 2014). These studies suggest that surge during Sandy was likely to occur in the bay of Long Beach mainly after the island was inundated and water flowed freely between the ocean and the bay.

## Storms and the Built Environment

The type of damage caused to structures varies by location and storm. Womble et al., (2006) claim that the majority of damage to the human-built environment from hurricanes is a result of wind-induced failures (roof blowing away, debris hitting structures, trees falling), whereas Griffith et al., (2015) found that only minor amounts of damage to the coast of New Jersey after Sandy were caused by wind. Following structural damage from wind, the building is at heightened vulnerability to additional surge, rain, and water damage (Friedland et al., 2007). Wind also poses additional damage from wind-driven surge.

Classifying damages to individual structures following a natural hazard is challenging, as going door to door and quantifying damage would be too tedious or cumbersome to produce an entire dataset. As a result, emergency response teams have relied on remote sensing and air photos especially since September 11, 2001 (Womble et al., 2006). Damage assessment is very important for rapidly estimating losses and also applying the findings to response teams and future mitigation efforts (building codes or engineered structures) (Friedland et al., 2007; Womble et al., 2006). It is necessary to be consistent when documenting these structural effects, so abiding by a rubric or criteria like those outlined by the Federal Emergency Management Agency (FEMA) is necessary (Federal Emergency Management Agency Modeling Task Force, 2013). Often satellite imagery is preferred to air photos for classification of structural damage spanning a large area following a disaster (such as a hurricane) because the satellite imagery provides detail to observe conditions of individual structures while capturing a large geographic area (Adams et al., 2004; Womble et al., 2006; Friedland et al., 2007; Womble, et al., 2010). Technology like Visualizing Earthquakes with Satellites (VIEWS) has been used in extreme events (Womble et al., 2006). VIEWS was adapted along with remotely sensed imagery to classify structural damage following Katrina (Womble et al., 2006; Womble et al., 2010). Classification of damages between the minor to moderate levels is often the most difficult to determine based on imagery alone. It was also determined from classification of a debris line that most significantly damaged properties were found seaward of the debris extent, or within the debris line (Friedland et al., 2007).

A 2015 study by Griffith et al. directly examined infrastructure damage along the coast of New Jersey following Sandy using FEMA Modeling Task Force (MOTF) classifications. By exploring properties with major levels of damage or those classified as destroyed directly abutting the beach, specifically, a relationship was found between wide and nourished beaches and level of damage. In locations where beach nourishment had recently taken place, properties were less adversely affected than in locations where nourishment had not taken place (Griffith et al., 2015).

Much research suggests that soft structures are better alleviators of storm-induced damage and offer better protection for people at risk to coastal hazards than hard engineering structures such as groins and seawalls (Claudino-Sales et al., 2008; Hamilton et al., 2008;

Hanley et al., 2013; Houser, 2013; Spalding et al., 2013). Sea walls, groins, and wave breakers may be less effective at mitigating damage than natural coastal ecosystems (Spalding et al., 2013). These hard structures also disrupt alongshore current and inlet migration (Pilkey & Wright, 1988). Coastal habitats, ecosystems, and wetlands also offer protection from storms but Long Island's coastal population lives mainly in areas without coastal habitats. Indeed, over 500,000 of the residents living in coastal regions are at heightened risk of exposure to coastal hazards (Arkema et al., 2013). What Long Beach Island lacks in coastal habitats and dune fields, it makes up for with engineered structures -- groins, jetties, and bulkheads.

Dunes have become a preferred method of alleviating erosion (Psuty, 1987). Humans build artificial dunes on barrier islands for protection purposes and must decide: 1) whether or not to vegetate the dunes, 2) how tall and how wide to build them, and 3) whether or not to add sand fences, among other considerations. There have been numerous studies published on the merits of different dune characteristics in the face of storm events; for example, some argue that woody vegetation is superior to grassy vegetation in securing dunes (Claudino-Sales et al., 2008). In addition to vegetation, fences can also play a role in stabilizing dunes. When securing dune position and building dunes, sand fences are the better method in the short term, whereas vegetation is the better method for long-term stabilization of the dune. Sand fences tend to create dunes with height, and vegetated dunes are of greater width (Gares, 1987).

Hard engineering can damage dunes and coastal ecosystems that offer communities storm protection (Hanley et al., 2013). Dunes being constructed by many communities are unsustainable and constructed out of unnatural material in locations where they are out of equilibrium and will be eroded away quickly. On Fire Island, a semi-developed barrier island thirty miles from Long Beach, only 45% of an artificial, engineered dune was still located within ten feet of its initial position after five years of study (Psuty, 1987). Fortunately the development patterns of Fire Island allowed for the natural migration of this dune, but in Long Beach even the engineered and artificial dunes are fenced into place and unable to migrate as they would in a natural setting. Artificially vegetating dunes causes a loss of sediment transport alongshore and exacerbates erosion in other areas (McLachlan et al., 1994). Issues with artificial dunes tend to result from humans applying knowledge of dune geomorphology, as studied in a natural state, to a developed shoreline with human activity and modifications. Human activity alters the natural state of dunes (Gares, 1987).

Groins alter circulation patterns offshore and can subsequently change offshore bathymetry over time (Nordstrom, 1994). Bathymetry influences circulation, which can influence storm surge and storm damage. Houser (2009) found that offshore bathymetry correlated with damage to a road on the barrier island. Anthropogenic alterations to the coast have the potential to alleviate erosion and achieve their desired effects in the short term, but often long term effects are negative or there are negative side effects to the alterations, like the unintentional alteration of circulation patterns. Pethick and Crooks (2002) argue that anthropogenically-induced changes are perfectly acceptable as long as the impacts from the changes are understood and the temporal nature of infrastructure in the coastal zone is recognized.

Studies of roads and buildings acting in conjunction or on top of geomorphology are not well represented in geomorphological literature (Nordstrom, 1987; Nordstrom, 1994; Jackson & Nordstrom 2011). Roads and parking lots are impermeable surfaces and serve as unobstructed channels for overwash in a storm event. Buildings can alter flow of wind and water and change the direction of sediment accretion. Large buildings can even cause a reversal of regional wind flow and result in onshore transport during offshore winds (Nordstrom, 1994). Variations in height of the foredune can also facilitate overwash and channel the overwash into unstable areas through narrow gaps in the foredune (Houser, 2013).

Houses block the transfer of sediment landward of the dune crest and, when built on top of the dune crest, reduce inland migration, forcing the dunes to increase in height (Nordstrom, 1985). Taller buildings and structures may entirely prevent sand from traveling to the back-dune areas during storms. While such tall buildings may diminish total overwash during a storm, they also channel flow into concentrated gaps between the structures (Leatherman, 1987).

Even every day recreational activities that humans undertake on the beach can affect the natural system. Walking and driving on the beach or the dunes can erode sediment and decrease vegetation (Rickard et al., 1994; Jackson & Nordstrom 2011). Raking of a dune can affect the way the dune builds up over time, and grading the dune can lead to increased degradation by winds (Jackson & Nordstrom 2011). Unconsolidated sand deposits and redistributed storm deposits are unstable and likely to be reworked by winds (Jackson & Nordstrom, 2011). Similarly, removing wrack (litter deposited on the beach by swash) from the beach to facilitate recreation reduces the likelihood for depositional landforms to form in the backshore, and the aeolian transport rates downwind of the wrack are reduced (Jackson & Nordstrom, 2011). Wrack naturally traps sand from blowing off shore and retains more sediment in the backshore during offshore winds; its removal exacerbates erosion (Jackson & Nordstrom, 2011). All sorts of factors act together to adjust the beach face and affect the dynamics of the entire coastal system.

## Hazards and Vulnerability

Hazards are characterized by three main elements: social, economic, and physical (Boruff et al., 2005). There are many elements on a beach that may reduce hazard potential for coastal communities including dunes, hardening structures, coastal ecosystems, and fences, to name a few, and effective coastal zone management needs to consider these elements and how they may influence community damage during a storm event (Pethick & Crooks, 2002; Costanza et al., 2008; Spalding et al., 2013). It is often the areas most densely populated that undergo the greatest levels of geomorphological changes from a storm, which subsequently puts the denser populations at greater risk to coastal hazards (Hapke et al., 2013). Exacerbating this situation is the migration of population worldwide, moving toward the coast (McFadden, 2010). It is a combination of this geophysical risk and socio-economic that vulnerability increases risk factors in coastal communities (Chakraborty et al., 2005; Glavonic, 2008).

Because it is so densely populated, is a wealthy area of the United States, and suffers many storm events every year, Long Island is vulnerable socially, economically, and physically (Boruff et al., 2005). While individual experts may differ in definitions of vulnerability, nearly all would agree it is best understood to involve multiple socio-economic and geophysical components (Chakraborty et al., 2005; McFadden, 2010; McLaughlin & Cooper, 2010; Newton & Weichselgartner, 2013) and is ultimately a function of the efficiency of the government and understanding of the natural environment. "The vulnerability of a coastal community is a function of the state we wish that community to be in, its relations with other communities, the relevant governance arrangements at the coast in question, and linkages or integration with the natural environment of the space it occupies" (McFadden, 2010, p. 217). Vulnerability suggests a community has a “propensity or predisposition to be adversely affected by the impacts of hazards” (Newton & Weichselgartner, 2013, p. 124). Better knowledge of human and beach interaction could enable proactive decision-making and reduce vulnerability (Jackson & Nordstrom, 2011).

Following Superstorm Sandy, publications were released for future planning efforts to make a “Greener, Cleaner Long Island.” These publications were vague in identifying specific preparation efforts to decrease vulnerability to future coastal hazards but had goals of improving resiliency and rebuilding (Long Island Federation of Labor, 2014). Resiliency is a goal many coastal communities hold in high esteem, but it is difficult to attain. At one time, planning and management efforts strived to make communities resistant to threat, but the concept of resiliency is more sustainable. A resilient community adapts to changes without losing function and recovers from events promptly and with only assistance from local and regional resources. Resilient communities use learned experiences to reduce their vulnerability in the future whereas a resistant community employs engineering structures to strengthen defenses (Ewing et al., 2010; McFadden, 2010). The city of Long Beach lost its iconic boardwalk to Sandy and, as a testament to its resistance, has begun rebuilding it in the same spot.

While some advocate retreating from the barrier islands and coastal communities most at risk (Pilkey, 1987), perhaps a more widely accepted ideology is for communities to reduce vulnerability by updating their maps and evacuation plans (Newton & Weichselgartner, 2013). Such evacuation plans could benefit tremendously from more specific and precise identification of areas at greatest risk, and identification of these at-risk areas should consider social factors. The findings of a study conducted after Hurricane Katrina suggested that while affluent suburbs in New Orleans are located in areas of high geophysical risk, though on slightly higher topographic elevation, it was social factors that affected each community's ability to evacuate, resulting in a higher death toll in low-income areas (Glavonic, 2008). Furthermore, following major disasters, unwise planning takes place because residents feel a "right to rebuild," even in an area at risk of another geophysical event (Glavonic, 2008) much like rebuilding the Long Beach boardwalk precisely where it was previously destroyed. Thus, reducing future vulnerability, and also understanding the vulnerability factors of people on Long Beach Island today, requires an in-depth and broad spectrum analysis of geomorphology, planning, and socioeconomic factors.

# Chapter 3: Study Area

There are a number of reasons Long Beach was chosen as the study area for this research. Aside from experiencing tremendous damage as a result of Superstorm Sandy, Long Beach has interesting variations in morphologic characteristics (differing barrier widths, presence of dunes, dunes with paths through them, and areas with no dunes and only boardwalks). In large part because of its proximity to New York City (Figure 3.1), Long Beach is very densely developed. As a result, there are interesting development features to consider that potentially affected storm damage (presence of canals in one region of the beach, inconsistent bulkheads along the bay, groins throughout the area, roads oriented either north-south or east-west, and varying density of structures relative to one another). This chapter discusses Long Beach in depth, including its history, its present state, and its demographics; highlighting the many reasons why it is an ideal study area for this research.

## Geomorphology

Barrier islands are interesting and unique features in geomorphology. While barrier islands have been studied frequently studied, research often considers undeveloped barrier systems instead of the complicated barrier islands with dense development and human alteration of natural features (Nordstrom, 1994). On the East Coast of the United States, barrier islands are features of trailing edge coastlines; they are part of a landmass that moves with the plate away from tectonic regions. The barriers are located near divergent plate boundaries.

**Figure 3.1: Map of the study area**

Trailing edge coastlines have long and gradual slopes toward the continental shelf and wide coastal plains. Coastal barriers are comprised of loose sediment, making them very susceptible to erosion. Bedrock is typically thousands of feet below the surface of the island and does not influence stability of the barrier system (Leatherman, 1987). Sediment sources are mainly detrital from rivers, biogenous remains of marine organisms, and relic sediment from remnant landforms. The sediment on Long Beach Island is relic from the last glaciation and there are no new sources supplying sediment to the region (Inman & Dolan, 1989). Coupled together, the loose sediment with a lack of new sediment supply on any given barrier makes the barrier island more vulnerable to erosion than other coastal systems. Long Beach is just one of many fragile barrier islands on the South Shore of Long Island, NY.

The barrier island on which Long Beach is located is geomorphologically diverse. On the island, there are regions with wide, vegetated dunes but also areas where dunes have been raked into smaller shapes, or where paths cut through the dunes providing beach access for residents of the adjacent neighborhoods. In the city of Long Beach, these same variations exist and there is also a boardwalk approximately two miles long. This boardwalk offers some level of protection to the neighborhoods and buildings behind it and spans that area containing the former hotels and apartment buildings. Prior to storm events and sporadically throughout the year, artificial dunes and sediment fill in the space between the boardwalk and the beach. In addition to varied beach and dune morphology there are changes in the width of the entire barrier (from bay to ocean). In some areas, the island is less than .4 miles wide whereas at its' widest, it is more than double that at .86 miles. The elevation across the entire city of Long Beach is very close to sea level, at the highest point the LiDAR elevation is 11.87 meters but the elevation of the dunes is typically closer to 5 meters (Figure 3.2).

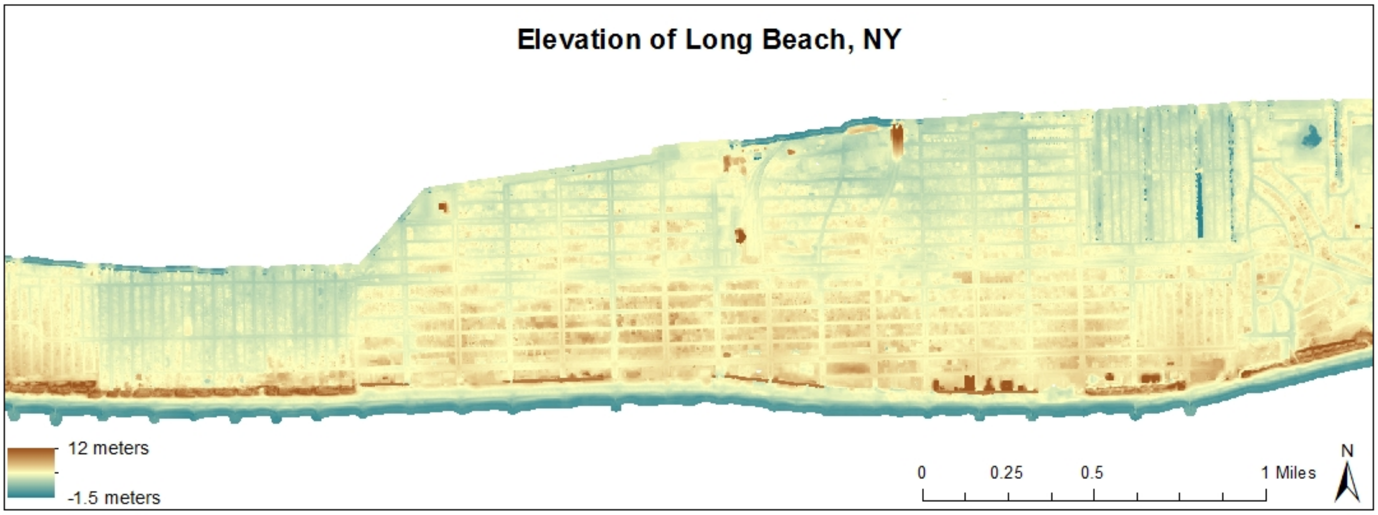

**Figure 3.2: Elevation of Long Beach, NY derived from LiDAR DEM. Elevation along the bay is much lower than along the beach as is typical with most barrier islands.**

Long Beach is the major city on a barrier island which consists of four different communities including (from west to east) Atlantic Beach, Long Beach, Lido Beach, and Point Lookout. Alongshore drift moves sediment from east to west so nourishment efforts that have taken place in Lido Beach and Point Lookout are relevant to the condition of Long Beach.

## Neighborhood Characteristics

Long Beach is densely developed and variations in the orientation of neighborhoods and housing density are pronounced (Figure 3.3). In some areas of the city, roads are tightly packed and oriented North-South, aligning perpendicular to the barrier island, whereas others are less dense and align East-West, aligning to the orientation of the beach. There is also a section of Long Beach where roads are irregular and align in neither direction. In the northeast portion of Long Beach, four canals facilitate boat access to the bay (Figure 3.4). These canals are immensely attractive to boaters looking for access to the ocean from their property. Nearly every house has a dock and a boat in the canal. This area is also identified as a region highly susceptible to flooding due in part to its low elevation but exacerbated by the presence of these canals (Tanski, 2007). Ultimately the canals provide a recreational outlet for a small number of properties situated on them but cause grievance and headache to a much larger area as they frequently exacerbate bay-side flood events.

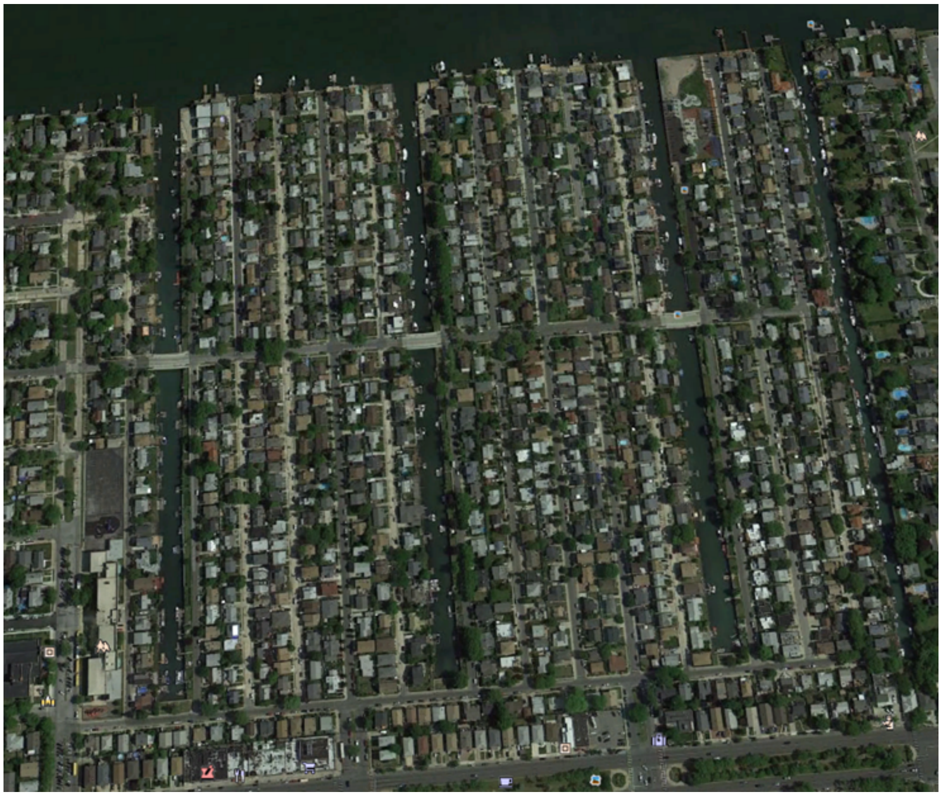

**Figure 3.3. Air photo of canals**

**Figure 3.4. Photograh of a canal at ground level**

## History

Long Beach, NY is a city on a barrier island off the south shore of Nassau County, NY. It is approximately 20 miles east of Manhattan and connected to the city via the Long Island Railroad which first serviced Long Beach in the 1880s. Long Beach, like the other barrier islands on the western end of Long Island, is populated year round with residents and businesses. The bay is known as “Reynolds Channel,” and on the south side of Long Beach is the Atlantic Ocean.

Long Beach is one of the oldest and most established communities on Long Island. It was founded in 1880 and was historically a vacation area for wealthy New Yorkers (City of Long Beach, 2015). This resulted in many high rise hotel buildings being built along the ocean side of the city (City of Long Beach, 2015). Long Beach peaked as a tourist destination in the early 1900’s. A senator named William H. Reynolds, for whom the bay “Reynolds Channel” is named, took over Long Beach and planning efforts in 1907. Reynolds had already developed multiple neighborhoods in Brooklyn and was well known throughout the region. Reynolds hoped that Long Beach could become an improved version of Coney Island and ultimately the “Riviera of the East” (City of Long Beach, 2015). He dredged the bay and used the sediment to fill in wetlands and inlets on Long Beach. He then used elephants to aid him in building the iconic boardwalk in 1907 along with more hotels. Reynolds imposed strict aesthetic regulations for all future development of Long Beach and the wealthy flooded the area (City of Long Beach, 2015). Senator Reynolds also has notoriety as a corrupt figure in the history of the city, with numerous indictments for dishonest real estate dealings and misusing official city funds, and was even accused of pocketing the money from parking meters (Jackson, 2013).

At the onset of the great depression Long Beach fell into a period where crime and corruption was rampant (largely due to prohibition,) and the wealthy began to leave (Jackson, 2013). After the period of corruption and crime, the hotels were no longer kept and the buildings were then used throughout the 1970s as welfare housing and temporary housing for the elderly. Today these massive buildings are apartments but are also the most under-used space in the city. An amusement park was built on Long Beach in the 1960s, but it became a haven for drug trafficking and was torn down in the late 1970s (Jackson, 2013). Ever since the most recent periods of corruption and drug trafficking, Long Beach has been in a state of improvement and urban renewal. New condominiums and houses are replacing older buildings, and people continue to be attracted to the community for its accessibility to the ocean and the beach (City of Long Beach, 2015).

## Beach Nourishment and Protection

Between 1930 and 1961, the seaside communities on the barrier island along with the State of New York built a total of fifty rubblemound and timber groins to stabilize the eroding shoreline and promote accretion. They also constructed two jetties at either end of the barrier island to stabilize the adjacent inlets between Jones Beach to the east and the Rockaways to the west. The groins in the City of Long Beach were constructed in the 1930's at the onset of the stabilization project. Groins are uniformly spaced throughout the barrier island at between 180 and 220 meters apart. Recently, the US Army Corps of Engineers cited the groins at the opposite ends of the island, nearest the inlets, as being in moderate to significant need of repair (U.S. Army Corps of Engineers, 1998).  Many of the dunes in Long Beach are artificially created and maintained, undergoing raking of debris and maintenance of pathways connecting the dunes to the roads (Coastal Planning & Engineering, Inc., 2009). It was evident in the Coastal Planning & Engineering (2009) Oceanside report that the boardwalk and many buildings in the east and west edges of the city are situated exactly where the natural dune system would occur. The city has maintained artificial dunes by bulldozing sediment into place and fencing it in and occasionally by planting grass. After Sandy, the city recognized the need to reinforce its dunes and has built dune walkovers at a heightened elevation to help alleviate some of the direct contact people have with the dunes as they approach the beach (The City of Long Beach, 2014a), they have hosted grass planting events to revitalize the dunes (The City of Long Beach, 2014b), and have restored the dunes using old christmas trees (The City of Long Beach, 2013).

Nourishment projects have never taken place in the Long Beach city limits. However, Lido Beach (the community immediately east of Long Beach) underwent 200,000 cubic yards of beach fill in 1962 and Point Lookout (immediately east of Lido Beach, the eastern tip of Long Beach Island) experienced a beach fill in 1995 of 459,000 cubic yards of sediment (Western Carolina University, 2015).

It is well known the city has a problem with flooding from the bay-side of the barrier island after major storm events, from rainfall, surge, and tides alike. The 2009 Coastal Planning and Engineering “Bayside Flood Protection Plan,” submitted to the Long Beach government, notes that ongoing studies by the US Army Corps of Engineers had not considered bayside flooding as an issue in Long Beach. The 2009 plan recognizes issues with bulkheads being semi-continuous along the bay and being of insufficient heights to block out storm surge. Some areas are without bulkheads entirely whereas others are lined with bulkheads even up and down the canals. The bulkheads vary in elevation (Figure 3.5) others are inferior and are riddled with holes (Figure 3.6). It was determined that, for the system to be effective at all, all bulkheads should be elevated to 9 feet, continuous over the entire bay-side of the barrier island (Coastal Planning & Engineering, Inc., 2009). Some homeowners adjusted their own bulkheads accordingly, whereas others were maintained by the city. As of 2009, the city of Long Beach was focusing on elevating bulkheads along the canals and at street ends.

**Figure 3.5: Bulkheads in the study area of differing elevations. Courtesy of Coastal Planning & Engineering: Bayside Flood Protection Plan 2009**

**Figure 3.6: Bulkheads of inferior quality. Courtesy of Coastal Planning & Engineering: Bayside Flood Protection Plan 2009**

In February 2014, about 16 months following Sandy, Senator Charles Schumer announced a federally-funded project ($180 million) for a dune and groin protection system in Long Beach. This project entails construction of a beach berm and dune and groin system to reduce potential storm damage along the shoreline. It specifically called for rehabilitation of sixteen groins and creation of three additional groins as well as an additional 4 million cubic yards of sand (Pharumph, 2014).

## Demographics

The population of Long Beach was estimated at 33,552 in 2013. The median per capita income in Long Beach is $42,505 with median home values around $467,961 (in 2012). Demographically, the city is 75.5% white, but somewhat segregated in terms of where the white population lives (Figure 3.7). Of the four towns on Long Beach Barrier Island, Long Beach has the greatest population and population density (Long Beach has 15,023 people per square mile versus an average of 411 people per square mile throughout the rest of New York State). (United States Census Bureau, 2015).

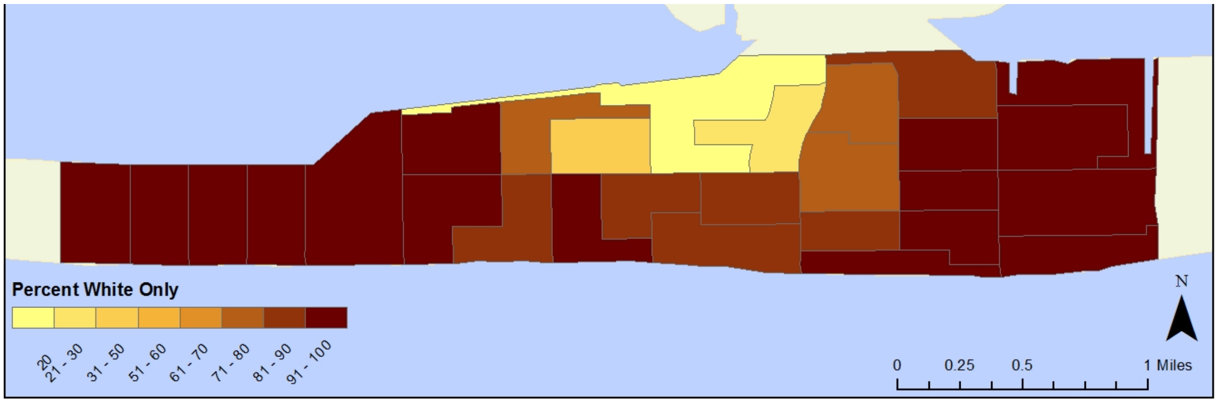

**Figure 3.7: White population by block group, 2010.**

## Superstorm Sandy’s Effects on Long Beach

Superstorm Sandy cost millions of dollars to the city of Long Beach alone; the city was awarded $25 million to rebuild (NY Rising Communities, 2014). Long Beach was under a mandatory evacuation during Sandy but many residents remained behind to weather the storm, some explaining their choice to remain at home because Irene had come through the previous year and not caused nearly as much damage as was predicted. However, Sandy caused much devastation on the Island, and Long Beach was without power or running water for at least two weeks following the storm. The iconic boardwalk was completely destroyed. It was one of the City’s first acts of business with the FEMA relief fund to rebuild this boardwalk.

Long Beach is an interesting location with a rich history and much community pride. The dense level of development adds incentive and value to this type of a study but there are also many variations in Long Beach that make it ideal for a study of small-scale infrastructural damage disparities. There are huge variations in geomorphology, the width of the island, and the state of the dunes and beach in addition to varying levels of housing density, the presence of canals, and orientation of roads. The effect that inferior bulkheads may have inflicted on some area of the bay is also of great interest. There are a number of elements that, when compounded, are unique to Long Beach and make it an ideal study area.

# Chapter 4: Data and Analysis

In order to evaluate patterns of infrastructure damage as related to both geomorphological and anthropogenic factors, a number of steps were taken to complete this research. Each is described in the following section. Figure 4.1 provides an overview of this process which began with a general observation of the study area and overview of the damage patterns seen, progressed to an assessment of some of the pre-storm geomorphology and the changes to the geomorphology after Sandy, then a random sample of properties was collected to further classify some variables at each location and run a statistical analysis and ultimately the observations were made and research questions answered. For an overview of all the variables assessed see Table 4.1.

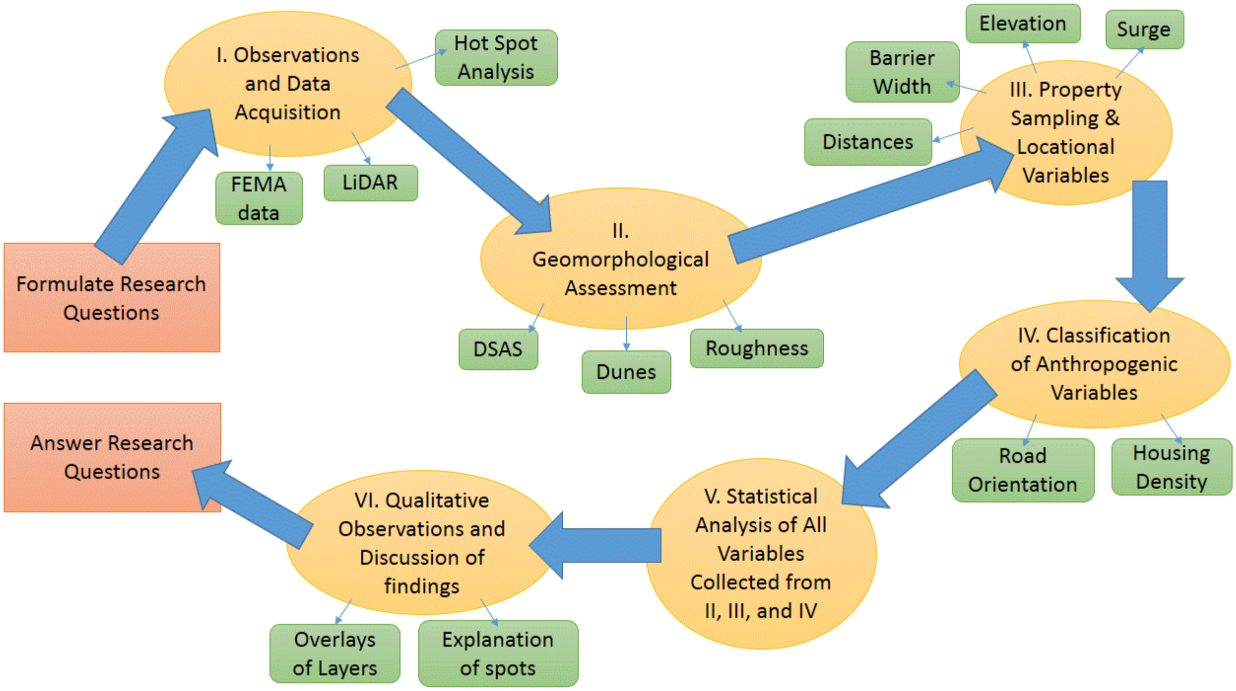

**Figure 4.1: A flowchart of the process taken to complete this research.**

| Variable | Source |
|---|---|
| Damage Level (dependent) | FEMA MOTF |
| Surge Depth | FEMA MOTF |
| Net Shoreline Movement | User generated with DSAS |
| Beach Condition (dune or boardwalk) | User classified with orthophotography |
| Road Orientation | User classified with orthophotography |
| Housing Density | User classified with orthophotography |
| Barrier island width | User classified with orthophotography |
| Elevation | User generated from LiDAR |
| Topographic Roughness | User generated from LiDAR in Excel |
| Distance to Ocean | User classified with orthophotography |
| Distance to Bay | User classified with orthophotography |

**Table 4.1: Overview of the variables collected and where they were collected**

## I: Observations and Data Acquisition

Data were acquired from a number of sources and many different datasets were experimented with before the following were selected for analyses of variables and observations. The information in Table 4.2 shows the datasets and their sources. Data had to be manipulated for use in GIS. Specifically, LiDAR and raster datasets were projected to UTM Zone 18N, vertical units of meters with vertical datum NAVD88. FEMA data from Sandy was in vector format only needing projection to UTM 18N. All measurements were made in meters.

| **GIS Data and Sources** | | |
|---|---|---|
| **Dataset** | **Created By** | **Obtained From** |
| Sandy FEMA Data | Post-Sandy FEMA collected information | http://content.femadata.com/MOTF/Hurricane_Sandy/determination_points_11_04_2013_1900PST.zip |
| Pre-Sandy LiDAR | 2011-2012 NYSDEC Coastal LiDAR | NOAA Digital Coast Data Access Viewer |
| Post-Sandy LiDAR | 2012 USACE Post-Sandy LiDAR: NJ and NY | NOAA Digital Coast Data Access Viewer |
| Sandy Surge DEM | Post-Sandy FEMA created | http://www.arcgis.com/home/item.html?id=307dd522499d4a44a33d7296a5da5ea0 |
| Post-Sandy Imagery | From 11/1/12, flown by USACE | http://storms.ngs.noaa.gov/storms/sandy/ |

**Table 4.2: The datasets and sources used for this research.**

FEMA data on property damage were used in the analysis (Table 4.3). These data were used in two ways, first to develop a hotspot analysis showing spatial trends in damage and second, to determine the properties selected for detailed analysis.

| **FEMA Property Damage Classification Information** | | | | | | |
|---|---|---|---|---|---|---|
| FEMA Damage Classification | | Visible Imagery Based Classification | | | | Inundation Assessment |
| Level | Observable Damage | Roof Covering | Roof Diaphragm | Collapsed Walls | Other | |
| Affected (0) | Superficial damage to the structure (loss of tiles on the roof) | Up to 20% affected | None | None | Gutters or awning; loss of vinyl or metal siding | Verified flood or surge depth >0 to 2 feet relative to ground surface. |
| Minor (1) | Solid structures sustain exterior damage (missing roof segments) some mobile homes or light structures may be destroyed or displaced | Greater than 20% | Up to 20% | None | Collapse of chimney, garage doors collapse inward, failure of porch or carport. Mobile homes off foundation | Verified flood or surge depth 2 to 5 feet |
| Major (1) | Wind: Some solid structures are destroyed, most sustain exterior and interior damage.<br>Surge: Extensive structural damage or partial collapse to surge | Greater than 20% | Greater than 20% | Some exterior walls collapsed | Mobile home could be completely off foundation, may or may not be repairable | Surge depth greater than 5 feet. Substantial damage (greater than 50% of the building value) defined by the National Flood Insurance Program may occur |

**Table 4.3: Damage classifications from FEMA.**

## II: Geomorphological Assessment

From the LiDAR data, geomorphological analysis of the beach prior to and post-Sandy was conducted. Net shoreline movement, either accreting or retreating, was initially hypothesized to relate to levels of damage sustained by individual properties. The USGS publically available tool, DSAS, the Digital Shoreline Analysis System, was used to compare pre-storm conditions to post-storm changes in specific locations on the beach. Using DSAS, transects were chosen to relate properties on each transect with morphology of the beach while also representing a wider section of the barrier. Transects were placed 150 meters apart.

Typically the use of DSAS is reserved for analysis of long-term erosional or accretional trends in shorelines, analyzing data from many different years or seasons. The use of DSAS for a post-storm analysis is somewhat atypical. When DSAS is used for long-term trends in shoreline changes, the user must rely on orthophotography to digitize a high-water line because LiDAR digital elevation models are not available. LiDAR data is widely available before and after Sandy.

After Sandy, the beach was inundated and the high-water line visible in the orthophotos was very inconsistent. Because of this inconsistency in the high-water line, it was decided that using a specific elevation from LiDAR would provide a better and more consistent measurement of shoreline change. So shorelines were generated by creating a contour at 1 meter elevation in the LiDAR flown before and after Sandy. This method was also used in the 2007 USGS report.

Some methods use a technique that buffered the lower shoreline to create a “baseline” that parallels the natural shoreline from which the DSAS transects would be generated (U.S. Geological Survey, 2009). Per this method, however, it was found that the transects crisscrossed throughout the study area so manually drawing a baseline oriented east-west south of the barrier island so the transects would not overlap was undertaken to allow properties to be sampled and spaced uniformly apart.

Finally the DSAS tool was run on the two 1-meter shorelines with a baseline parallel to the beach, distanced about 100 meters offshore in the Atlantic Ocean. Although DSAS provides the user with many variables including shoreline change envelope, end point rate, and linear regression, only net shoreline movement was considered for this analysis. These results were recorded in an Excel document for later reference. Transects were cast 150 meters apart, generating a total of 36 transects in the study area.

At the site of each transect, topographic roughness prior to Sandy was extracted from LiDAR data. Topographic roughness is a variable that describes the land and how much elevation changes or deviates within a specific location (Grohmann et al., 2011). This was done using the interpolate line tool on the beach at each transect and exporting the points to Excel, mimicking the method found superior by Grohmann et al., (2011) the standard deviation of these elevation values was calculated and recorded in a separate excel document. Data was then plotted in order from west to east before and after the storm. For statistical analysis of the roughness data, the pre-storm values were used.

Initially at each transect, the dune was classified based on its width (as observed with pre-Sandy imagery,) and also whether or not there was a path cutting through the dune within 15 meters of the transect. In locations where a dune was not present, this was indicated as were locations where there was boardwalk instead of dunes. Ultimately for the analysis of these variables, this information was simplified to a categorical “0” for boardwalk or “1” for a dune or beach without a boardwalk.

Island width was obtained for each transect, and the value for the entire transect was assigned to each property abutting the transect. Width was measured from the pre-Sandy shoreline to the location of the bay on the North side of the island along each transect. The distance from each of the sampled properties to the bay and also to the ocean was measured and recorded.

Surge was collected from the surge DEM by using the identifier tool at each property location. The surge DEM used was generated by the FEMA MOTF and was field-verified by FEMA for accuracy. It utilized storm surge sensor data from the USGS and High Water Markers to interpolate a water surface elevation, which was then subtracted from the best available bare earth DEM to generate a depth grid of the Superstorm Sandy storm surge. This is the same method that FEMA used following Hurricane Katrina in 2005 (Melton et al., 2010)

Elevation data was obtained from the best available LiDAR using the identifier tool at each sampled property.

## III: Property Sampling and Consideration of Locational Variables

The properties to be used in the analysis were randomly selected using a set of 200 out of the 7580 (2.6%) properties. These properties had to be within 15 meters of a DSAS transect so that their characteristics could be related to the morphology of the beach at the base of the transect. To determine the sample, all properties within 15 meters of a transect were extracted from the FEMA dataset, then the random sample was collected with the Create Random Points tool in ArcGIS. The characteristics of the sample were reflective of the trends seen in the entire population (Table 4.4). The individual levels of damage were also heaviest along the bay in the sample properties (Figure 4.2).

| Damage Level | Percent of total (7580) | Sample (200) |
|---|---|---|
| **Affected** | 31.7% | 39.5% |
| **Minor** | 67% | 59.5% |
| **Major** | 1.3% | 1% |
| **Destroyed** | 0.1% | 0% |

**Table 4.4: Percentages of damage levels in study area.**

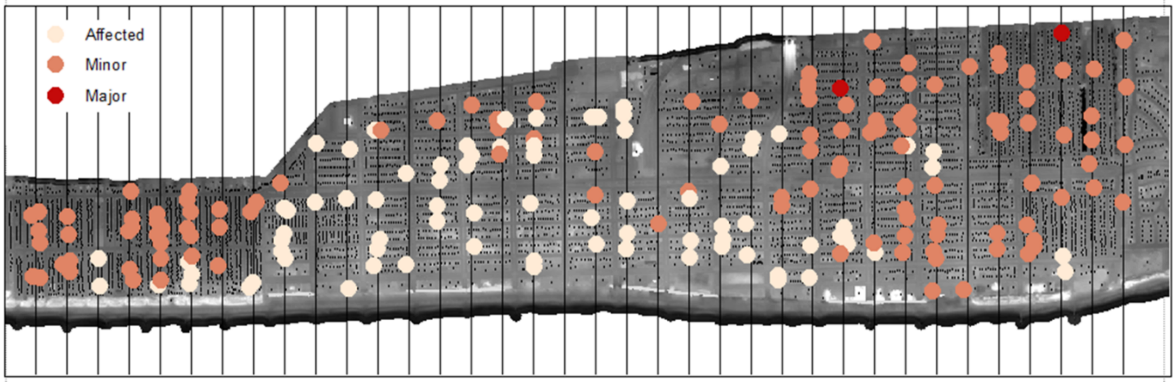

**Figure 4.2: Location of sampled properties with their corresponding levels of damage.**

## IV. Classification of Anthropogenic Variables

Creating a buffer of 15 meters from each sampled property, the number of properties contained within the buffer were summed and used as a housing density value. Orientation of the roads at each property was determined and categorized on a basis of north-south, east-west or other. Nearly all roads in Long Beach are oriented along a grid-like pattern. In locations where the block of houses was wider (east-west) than it was long (north-south,) there are portions of the area where the roads are aligned in a semi-circle.

## V. Statistical Analysis of All Variables

To conduct an analysis of the quantitative variables recorded in Excel, many variables had to be reclassified into categorical variables. First, the dependent variable of damage had to be altered. Although the sample was relatively representative of damage levels compared to the overall population of Long Beach, the data had to be reclassified into two categories – Affected versus Minor Damage or greater, because not enough properties fell into the major damage category for there to be any statistical significance in inclusion of the higher levels of damage. Therefore, within the Excel dataset and ultimately in the SPSS statistical analysis, all properties affected were given a value of "0" and all properties with minor or major damage received a "1."

The road orientation was initially recorded as "north south," "east west," or "other." Because only one property actually fell in a location where the road was oriented "Other," the property was classified as "East West" because this more closely reflected its directionality and enabled use of a categorical variable (Figure 4.3 A & B).

**Figure 4.3 A: Example of "North South" (left) and "East West" (right) road orientation**

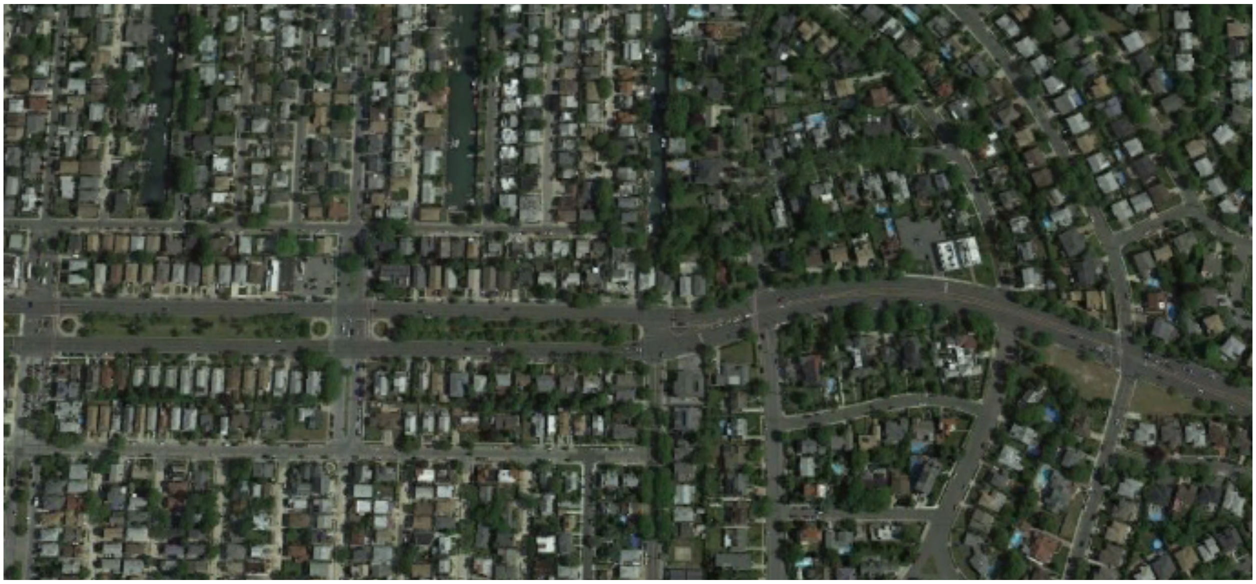

Figure 4. 3B: Example of “Other” orientation of the roads

The type of damage sustained by each property was obtained from FEMA (Table 4.1). Within the sample properties 4 were classified as “Damaged from Inundation and Wind or Debris,” 192 were classified as “Damaged from Inundation,” and 4 as “Neither or other.” There is not enough variation within this variable for it to be included in any type of analysis and it was therefore omitted from the statistical portion of this research.

Classification of the dunes was the most subjective portion of the analysis. Data had been collected about whether the dune had a path cutting through it, the width of the dune, and the apparent vegetation of the dune. Unfortunately, the boardwalk of Long Beach occupies over half of the transects in the study area so this variable was condensed to either “Dune” (receiving a value of 0), or “Boardwalk” (receiving a value of 1). The continuous variables that needed no alteration included depth of surge, elevation, distance to the ocean, distance to the bay, housing density, barrier width, net shoreline movement, and pre-storm beach roughness.

The dependent variable is damage level. A simple Pearson correlation was run on all of the variables against the dependent variable. Those with a Pearson outcome greater than .4

were examined more closely. For the continuous variables, a T-Test was run on each versus the dependent variable and for the categorical variables with suitable Pearson results, a Chi-square test was run. The T-Test was selected to determine whether the means of each of the variables are statistically significant from one another. The Chi-Square test was used to analyze the associations between the two categorical variables.

These results are examined and discussed in the next chapter as they relate to the dependent variable. Ror more detail about how these variables were correlated with one another see the Appendix.

## VI. Qualitative Observations

Although some of the results are statistical in nature, this thesis has a number of variables that are difficult to quantify. For example, using a categorical classification of dune versus boardwalk produced a statistical outcome, but this does not fully describe the damage patterns. As a result, a discussion of these variations is helpful when considering why some of the properties may have been damaged. The discussion portion of this thesis explores the omitted variables (dune characteristics, damage type, etc.) and also explores the properties that suffered “major” damage and discusses why these may have been more damaged than their neighbors. This portion utilizes GIS overlay analysis.

The directionality of the wind during Sandy in the study area was northwest at a maximum of 70 mph. Although wind damages are often severe in hurricane and tropical storm events, in Long Beach the bulk of the damage was not caused by wind. The FEMA dataset used to quantify individual damage levels for this research offered an explanation for each property as to how the damage level was determined.

The FEMA MOTF explained for each property if the level of damage was based on visible imagery alone, the presence of absence of indunation alone, or both the presence of iunundation and analysis of imagery. In Long Beach, all but seven of the sampeld properties were classified as “affected” or “damaged” by inundation alone. The other seven were classified as some degree of damage having been incurred by wind. However, every single property in the study area was inundated by surge. Because it was clear from the MOTF data that over 96% of the sampled properties were affected or damaged by inundation alone and every single property in the study area was inundated, wind speed was disregarded from further analysis as a factor that caused damage. Albeit, for seven properties the wind may have exacerbated damages.

# Chapter 5: Results

This research sought to address questions about how physical land characteristics (the dune, shoreline movement, roughness, barrier width, and elevation), coastal structures (the boardwalk), and anthropogenic characteristics of the island (road orientation, housing density, and canal presence) affected damage patterns during Superstorm Sandy. The results section of this thesis is organized to answer each of the originally posed research questions. Some observations of the region and damage patterns are further discussed in the next chapter of this thesis.

## RQ1: What trends can be seen in patterns of infrastructure damage on Long Beach?

The hot spot analysis conducted on damage levels provided surprising results. Immediately it became clear that the initial expectation that damage patterns would be densest along the beach due to changes in geomorphology of the dunes or beach width – or protection offered to properties from the boardwalk,-- was unfounded. Instead, the area along the bay, which presumably experienced less wave action and water turbulence during the event, was significantly higher in levels of damage (Figures 5.1 and 5.2).

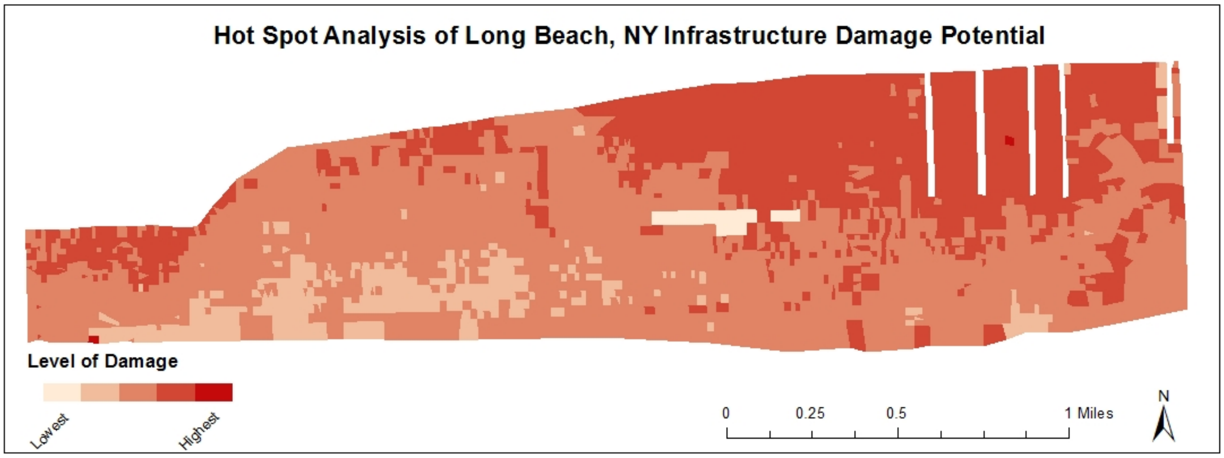

Figure 5.1: Hot spot analysis of damaged regions

The hot spot analysis revealed pockets of infrastructure deemed most likely to be damaged (as determined by a sampling of the surrounding properties and their levels.) Figure 5.2 depicts the individual properties on Long Beach shaded to their level of damage. The patterns between the hot spot analysis and actual levels of damage are very similar. The southeast corner of the study area is somewhat different between the hot spot analysis and actual damage levels. Nonetheless, both analyses provide the same general picture of infrastructure damage: more severe damage occurred along the bay than along the beach.

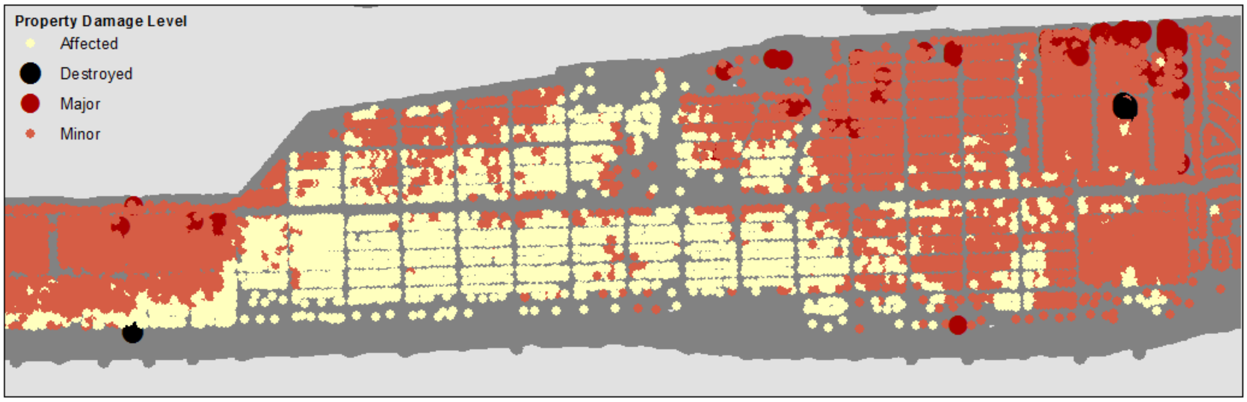

Figure 5.2: Actual levels of damage to structures

Significance tests and Pearson correlations were obtained for each of the independent variables (Table 5.1) Based on the Pearson correlation, variables with values less than |.4| were omitted from further statistical analysis. A |.4| was selected as the threshold for omission of variables because |.36| was the average correlation between all variables and the dependent variable, therefore only those with correlations above average were considered in the analysis. Significant continuous variables were subjected to a T-Test and categorical variables to a Chi-Square analysis. Values omitted included road orientation, topographic roughness, barrier width, distance to ocean and distance to bay and housing density.

## RQ2: What physical characteristics of the barrier island are related to infrastructure damage?

A major component of this research was to evaluate how the geomorphology of the barrier island related to infrastructure damage. Several elements were initially identified for analysis including the width and vegetation of the dune, height of the dune, whether the dunes had a path, the roughness of the dunes and beach retreat, island width and distance of properties to the ocean and the bay.

### RQ2, A: How did the geomorphology of the beach change and by what measure? Is there a spatial relationship between changes and patterns of property damage?

The DSAS-generated variable, Net Shoreline Movement, was utilized for statistical analysis and the location of the DSAS-generated transects were used to determine several other variables including which properties were sampled. The results of DSAS indicate that the shoreline retreated an average of -23 meters throughout the study area and it had not accreted sediment after the storm. Shoreline movement was sporadic throughout the study area. No one section produced a more defined trend than another. Figure 5.3 depicts shoreline movement from west to east after Sandy.

| | | Damage level |
|---|---|---|
| Dune or boardwalk | Pearson Correlation | -0.422 |
| | Significance | 0.000 |
| Road Orientation | Pearson Correlation | 0.252 |
| | Significance | 0.000 |
| Topographic Roughness (Pre Sandy) | Pearson Correlation | 0.145 |
| | Significance | 0.040 |
| Net Shoreline Movement | Pearson Correlation | 0.518 |
| | Significance | 0.000 |
| Barrier Width | Pearson Correlation | 0.071 |
| | Significance | 0.315 |
| Surge | Pearson Correlation | 0.802 |
| | Significance | 0.000 |
| Elevation | Pearson Correlation | -0.606 |
| | Significance | 0.000 |
| Distance to the ocean | Pearson Correlation | 0.322 |
| | Significance | 0.000 |
| Distance to the bay | Pearson Correlation | -0.255 |
| | Significance | 0.000 |
| Housing Density | Pearson Correlation | 0.230 |
| | Significance | 0.001 |

**Table 5.1: Pearson results and significance of each independent variable and damage level**

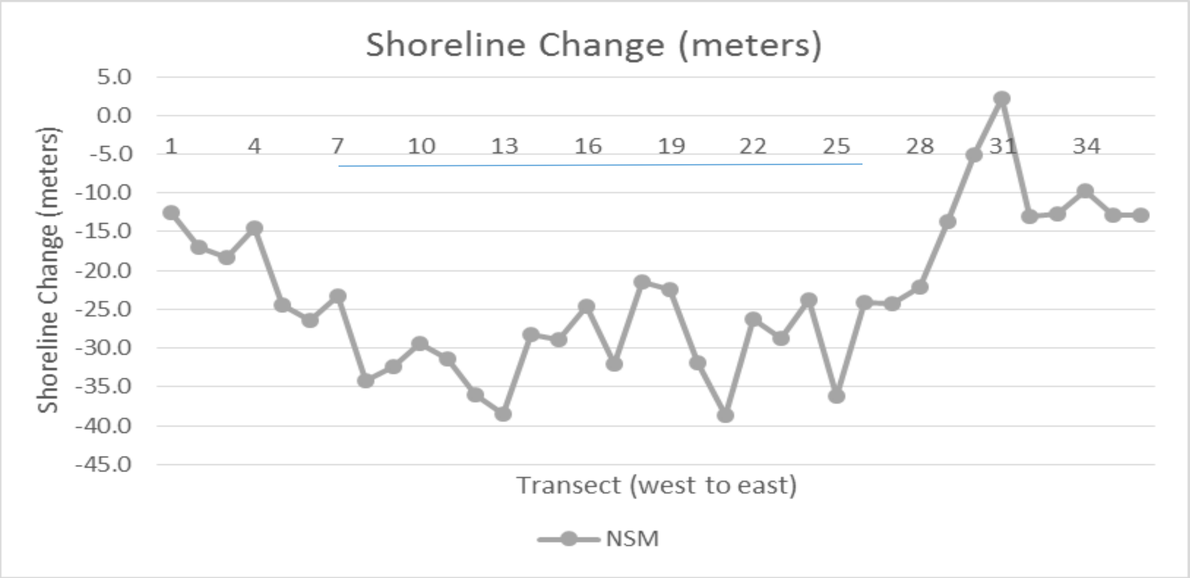

**Figure 5.3: Net shoreline movement from West to East, with the boardwalk**

Net Shoreline Movement, the variable collected by the DSAS tool, produced a significant and strong Pearson Correlation of .518. Because it was a continuous variable and also proved significant in the initial test, a T-Test was conducted against Net Shoreline Movement. The T-Test was selected because it explores whether the difference between the two variables was likely to have occurred by chance or randomly. A strong T-Test has a large sample size with minimal variation within each of the two. This was the case with Net Shoreline Movement. The T-Test produced a value of 8.8 (Table 5.2). This result suggests that net shoreline movement affected levels of infrastructure damage.

| | Surge | Elevation | Net Shoreline Movement |
|---|---|---|---|
| Pearson Correlation | 0.8 | 0.6 | 0.5 |
| T-Test | 19.9 | 11.1 | 8.8 |
| P Value | .000 | .000 | .000 |

**Table 5.2: T-Test results for the continuous independent variables**

## RQ2, B: To what extent is elevation or depth of surge related to severity of infrastructure damage?

Surge produced the strongest relationship to infrastructure damage with a Pearson Correlation of .802. Like Net Shoreline Movement, surge was also a continuous variable and was subjected to a T-Test where it produced a 19.9 value (Table 5.2) Generally the higher the T-Test result, the stronger the relationship between the two values and 19.9 is significant. This result proves that, not surprisingly, surge depth affected levels of infrastructure damage. Because elevation produced similar results with an initial Pearson Correlation of -.606 and a T-Test value of 11.1, it too impacted infrastructure damage. Though surge and elevation are related to each other (surge versus elevation produced a Pearson Correlation of .7,) each variable was considered individually.

## RQ2, C: Is there a relationship between infrastructure damage and physical location on the island?

The width of the barrier island was the weakest indicator of infrastructure damage, producing a Pearson correlation of 0.071. Similarly, the distance of the property to the bay or the ocean also produced insignificant Pearson values of -0.25 and 0.32 respectively. With these results, the expectation that physical location had no influence of infrastructural damage was validated.

## RQ3: How do damage patterns differ between areas where properties are abutting dunes as compared to areas where dunes are absent?

Although a strong Pearson correlation typically has a value greater than .5, the properties abutting the dune versus those abutting the boardwalk produced interesting results. The Pearson value was 0.422. Given that both the dependent variable and the dune or boardwalk variables were categorical, these results were then analyzed with a Chi-Square test (Table 5.3).

The Chi-Square produced a significant result. In cases where the dune was present, of the properties behind the dune, 86.8% were damaged versus only 13.2% affected. In cases where the boardwalk was present, 44.4% of the properties were damaged and 55.6% were affected. Results suggest that more properties in locations with dunes were damaged than those behind the boardwalk; perhaps properties were safer behind the boardwalk.

| | Affected Properties | Damaged Properties |
|---|---|---|
| Dune present | 13.2% | 86.8% |
| Boardwalk present | 55.6% | 44.4% |
| $X^2 = 35.6$, $P= 0.00$ | | |

**Table 5.3: Chi-Square results for the categorical variable boardwalk/dune**

## RQ4: To what extent did characteristics of the built environment influence damage patterns?

Because Long Beach is densely developed, it was presumed that the built environment could have exacerbated or alleviated damages in a variety of ways. The presence of groins is one of the most obvious anthropogenic alterations of the study area when looking at orthophotography. The groins were ultimately not included in the analysis because they are spaced at precisely the same distance apart consistently through the entire study area and each groin extends the exact same distance from the beach and were all built at the same time. Other characteristics presumed to have impacted the area were the canals, the orientation of the roads, and the density of development.

## RQ4, A & B: What is the relationship between density of development, road orientation, and the severity of damage?

The Pearson correlation for these variables were both very low, suggesting that neither is related to damage severity.

## RQ5: For individual properties, what were the compounding factors that put them most at risk for higher levels of damage?

So far this chapter has explored what happened overall to affect Long Beach and the patterns and levels of damages. To consider the individual properties and the factors that put them most at risk, this section extrapolates the properties initially grouped into the “Minor +” category of damages for statistical analysis, the two “Major” damaged properties (Figure 5.4).

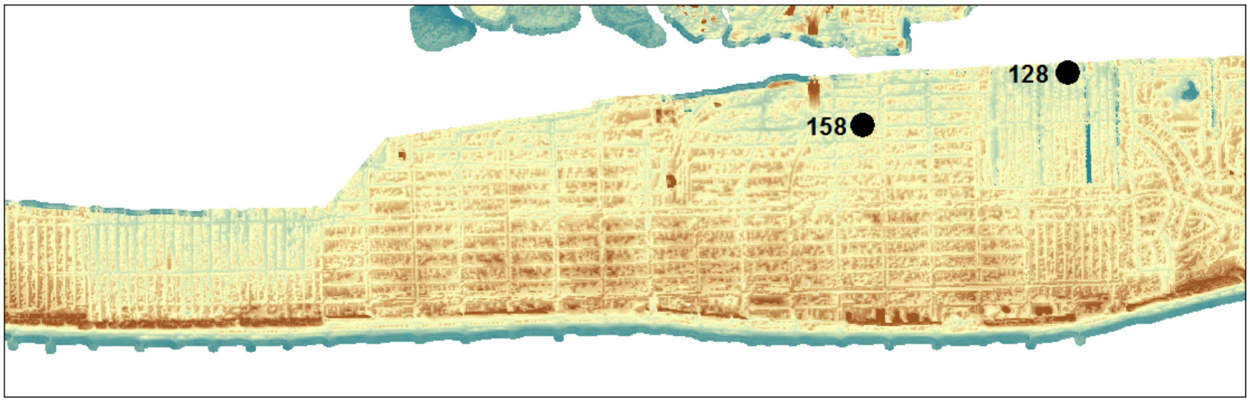

**Figure 5.4: Location of the two most damaged properties in the sample**

It might be assumed that these properties having suffered the most damage out of the entire sample would have very similar values for all of the significant independent variables (Net

Shoreline Movement, Boardwalk or Dune, Elevation and Surge). The individual values for each property are shown in Table 5.4

| Property Number | NSM | Boardwalk/Dune | Elevation | Surge |
|---|---|---|---|---|
| **158** | -24.2 | Boardwalk | 1.81 | 5.1 |
| **128** | -9.8 | Dune | 1.5 | 5.6 |

**Table 5.4: The two major damaged properties with a comparison of the significant indicators of damage**

While the primary drivers of damage, surge and elevation, are similar between the two properties, they have very different ocean-front characteristics. One was behind the boardwalk and the other behind the dune, and one suffered a much greater than average amount of shoreline movement while the other suffered a significantly lower than average amount. These properties also had different road orientations but the same housing density (of 5). They were each on a part of the barrier island that was about the same width (ocean-to-bay) and situated close to the bay. The experiences of these two properties suggest that shoreline movement and the presence or absence of the boardwalk may not be the strongest predictors or indicators of storm damage, despite having a relationship with damages overall.

# Chapter 6: Conclusions

The statistical results produced some interesting findings. It was expected that depth of inundation would affect damage levels. The results from the statistical analysis of surge and elevation reinforced and supported this. Surge is the primary driver of damage in Long Beach. There are a number of reasons why surge may have been amplified in certain locations or affected houses along the bay differently. Perhaps the distance between the bay sides of Long Beach to mainland Long Island was influential. The bay differs in width throughout the study area between 553 meters to as little as 129 meters. The differences in bay widths may have acted in a way that funneled more water into narrower sections than wider ones or trapped water in the narrower section while the rest of the water was able to retreat. Further, perhaps distance to the bay could have been measured as distance to the base of canals as the canals may have acted in a way that brought the bay further inland on the barrier island.

It is more likely that variations in the condition of bulkheads contributed to the damage discrepancies along the bay. In some places, bulkheads are missing or are entirely different heights than in neighboring sections of Long Beach (Coastal Planning & Engineering 2009). The bay communities most at risk for bulkhead-related inundation are the ones with canals servicing their properties. This location in the Northeast section of Long Beach coincidently has some of the highest levels of damage out of the entire study area, verifying the theory that bulkheads of varying heights, material, and quality amplified damage from surge along the bay.

Given that most of the higher levels of damages occurred along the bay, many of the geomorphological characteristics studied may not be significant, such as the classification of properties as abutting either the dune or the boardwalk and shoreline retreat. Somehow the dune versus boardwalk produced interesting results in terms of property damage but perhaps more surprisingly, the shoreline movement produced significant results with a correlation of

0.518 to the damage levels. Why shoreline movement was related to damage remains to be determined. It could be that in the locations where damage was most prevalent, the beach was at a higher elevation to begin with so even after Sandy came through, the movement at the locations with higher pre-storm elevations was smaller than those with lower beach elevations. However, the regions with the smaller amounts of shoreline movement are often in locations where there are dunes and there were higher levels of infrastructure damage. If shoreline movement was minimized by the presence of dunes, this result reiterates the Chi-square test that found, with respect to damage, a stronger association between properties abutting dunes than those abutting the boardwalk. So if shoreline movement was minimized by dunes (whose presence related to high levels of infrastructure damage) it makes sense that smaller shoreline movement would be an indicator of increased damage because greater movement occurred in front of the boardwalk. More research in different locations would be needed to confirm this.

Long Beach has not undergone any beach nourishment in recent years. The last beach fill project was completed in 1962. Although beach nourishment is claimed to have spared many New Jersey communities from tremendous damage (Griffith et al., 2015), it had no effect on Long Beach because the area had gone unnourished for so long. Perhaps because of the lack of beach nourishment and the unnatural state of the dunes – where all of the dunes in this study area are cleanly raked into place with paths cutting through them – the dunes offered little protection from storm damage to properties abutting them.

A major caveat to this research that should be made clear to any potential coastal planner is that this is a case study. From the results of the Chi-Square test, which suggest that dunes offered little protection to properties behind them when compared to the boardwalk, one may argue that the answer to protecting our coasts and infrastructure is to “armor up” and build giant seawalls and bulkheads everywhere. Dunes are very valuable to a sustainable coastal community. If dunes were replaced everywhere with bulkheads and hard structures, beaches would erode faster as they would no longer be able to migrate landward as they do in a natural setting. Furthermore, the dunes of Long Beach are not “healthy” or “natural” dunes. They are intermittent, frequently interrupted, artificially vegetated, raked and fenced into place. At the time of Sandy, people walked right over them on their way to the beach and this foot traffic exacerbated the erosion of the dunes and affected their vegetation. If the results of this study were to have any meaning or negate the value of dunes in any way, then healthy and natural dunes should be analyzed as compared to bulkheads and seawalls over the course of many storms in a long time frame because even though the structures may have protected the first few rows of houses, they do not protect and in fact destroy beaches.

Some of the anthropogenic elements of this barrier island can also be considered in relation to the damage patterns exhibited. Although housing density and road orientation were insignificant in relation to damage levels, the size of some of the old hotel buildings along the boardwalk may have alleviated damage alone or in conjunction with the boardwalk on the beach.

## Limitations and Suggestions for Further Research

This research is a case study. Generalizing the findings and applying them to any barrier island anywhere in the United States should be undertaken with great caution. Griffith et al., (2015) conducted similar research along the ocean with the same dataset but found different results. They determined that in New Jersey damage discrepancies for lower levels of damages (unaffected, affected, and moderate) were mostly due to wind and not to inundation from surge. Storms affect different islands in different locations very differently. Applying this study to a developed barrier island in Florida would be dangerous because storms are stronger in Florida, so assuming that flooding from the bay would be the major cause of damage is irresponsible.

More research like this should be done in other locations so those on individual barrier islands can identify their risk for future storm threats and identify ways to become more resilient to a repeated disaster. Sandy certainly reiterated the 2009 study of bulkheads in Long Beach and the importance of bringing them to a uniform code.

There are a number of elements this research could further analyze. If it were to be repeated, future research should incorporate several other factors into its assessment of infrastructural damages. Obtaining information regarding the age of structures would be beneficial, especially in other locations. In Long Beach, age was not incorporated into the analysis because many of the structures appear to be in the same condition and are of the same size and were built around the same time when Long Beach experienced its peak development. However, in other locations, age is most definitely a factor that would need to be considered.

Future research may do well to consider an entire barrier island and not just a section of one. Perhaps the transect method should be abandoned in the future and a random sample taken of all the properties on a barrier island and a hot spot analysis could be utilized to determine what specific areas would be assessed at a more in-depth level. It would have been helpful to conduct a ground assessment of the bay-side bulkheads before undertaking this research project as well. If future researchers choose to address bay-side flooding and its potential effect on infrastructural damage, a ground assessment of the bay would be beneficial.

Lastly, with this research in particular it seems the duration of time each property sat in storm surge may have played a role in determining the amount of damage sustained by the property. If one considers the small pocket of damage in the southeast portion of the study area that is situated closer to the ocean and not behind the boardwalk, this location could have been more adversely affected because its low elevation made it so that it took longer for storm surge to drain out after Sandy subsided. Modeling how the surge retreats after any major event would perhaps show some relationship to the damage patterns exhibited

## Contributions

Considering the history of Long Beach, there are numerous valuable community assets that need to be preserved. Maintaining the traditions of Long Beach and upholding the many once-notable hotels and the iconic boardwalk are becoming more difficult as storms grow more severe and inflict greater amounts of damage. Becoming resilient to storm threats and recovering quickly is more of a challenge to Long Beach as it faces the impending storms and sea level rise in the upcoming century. Long Beach needs to recognize what puts their built environment most at risk to storm threats and this study aims to assist them in doing just that.

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# Appendix

| | | Surge Depth | Elevation | Distance to Ocean | Distance to Bay | Housing Density | Island Width | Shoreline Movement | Roughness | Damage Level | Road Orientation | Dune or Boardwalk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Surge Depth | R | 1 | -7.67 | 0.446 | -0.428 | 0.306 | 0.016 | 0.493 | 0.199 | 0.802 | 0.359 | -0.471 |
| | P | | 0 | 0 | 0 | 0 | 0.819 | 0 | 0.005 | 0 | 0 | 0 |
| Elevation | R | -0.767 | 1 | -0.52 | 0.711 | -0.376 | 0.215 | -0.22 | -0.19 | -0.606 | -0.352 | 0.354 |
| | P | 0 | | 0 | 0 | 0 | 0.002 | 0.002 | 0.007 | 0 | 0 | 0 |
| Distance to Ocean | R | 0.446 | -0.52 | 1 | -0.585 | -0.246 | 0.449 | 0.178 | -0.053 | 0.322 | -0.151 | 0.113 |
| | P | 0 | 0 | | 0 | 0 | 0 | 0.012 | 0.458 | 0 | 0.033 | 0.111 |
| Distance to Bay | R | -0.428 | 0.711 | -0.585 | 1 | -0.379 | 0.462 | 0.114 | -0.097 | -0.255 | -0.346 | 0.24 |
| | P | 0 | 0 | 0 | | 0 | 0 | 0.109 | 0.174 | 0 | 0 | 0.001 |
| Housing Density | R | 0.306 | -0.376 | -0.246 | -0.379 | 1 | -0.686 | 0.055 | 0.25 | 0.23 | 0.629 | -0.56 |
| | P | 0 | 0 | 0 | 0 | | 0 | 0.44 | 0 | 0.001 | 0 | 0 |
| Island Width | R | 0.016 | 0.215 | 0.449 | 0.462 | -0.686 | 1 | 0.32 | -0.164 | 0.071 | -0.547 | 0.388 |
| | P | 0.819 | 0.002 | 0 | 0 | 0 | | 0 | 0.02 | 0.315 | 0 | 0 |
| Shoreline Movement | R | 0.493 | -0.22 | 0.178 | 0.114 | 0.055 | 0.32 | 1 | 0.03 | 0.518 | 0.203 | -0.443 |
| | P | 0 | 0.002 | 0.012 | 0.109 | 0.44 | 0 | | 0.678 | 0 | 0.001 | 0 |
| Roughness | R | 0.199 | -0.19 | -0.053 | -0.097 | 0.25 | -0.164 | 0.03 | 1 | 0.145 | 0.201 | -0.384 |
| | P | 0.005 | 0.007 | 0.458 | 0.174 | 0 | 0.02 | 0.678 | | 0.04 | 0.004 | 0 |
| Damage Level | R | 0.802 | -0.606 | 0.322 | -0.255 | 0.23 | 0.071 | 0.518 | 0.145 | 1 | 0.252 | -0.422 |
| | P | 0 | 0 | 0 | 0 | 0.001 | 0.315 | 0 | 0.04 | | 0 | 0 |
| Road Orientation | R | 0.359 | -0.352 | -0.151 | -0.346 | 0.629 | -0.547 | 0.203 | 0.201 | 0.252 | 1 | -0.837 |
| | P | 0 | 0 | 0.033 | 0 | 0 | 0 | 0.001 | 0.004 | 0 | | 0 |
| Dune or Boardwalk | R | -0.471 | 0.354 | 0.113 | 0.24 | -0.56 | 0.388 | -0.443 | -0.384 | -0.422 | -0.837 | 1 |
| | P | 0 | 0 | 0.111 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | |

**The correlations between each of the variables used and one another**