A SPATIAL INVESTIGATION OF NEW YORK CITY'S HISTORICAL SHORELINE

by

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For my parents, Assunta and Giuseppe, who lost everything coming to this country in hopes for a better life. Thank you to my brother Pasquale, for being an unwavering source of comic relief and my boyfriend Anthony for being my biggest supporter.

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List of Abbreviations

DPR	Department of Parks & Recreation
EPR	End Point Rate
GIS	Geographic Information System
HWL	High Water Line
JFK	John F. Kennedy Airport
LRR	Linear Regression Rate
NOAA	National Oceanic and Atmospheric Association
NSM	Net Shoreline Movement
NYC	New York City
NYRCR	NY Rising Community Reconstruction Planning Committee
ODB	Overlapping Double Band
SCE	Shoreline Change Envelope
SLiP-SUM	Shore Line Prediction with Spatial Uncertainty Mapping
WLR	Weighted Linear Regression

Abstract

While the New York City coastline protects its citizens from severe weather, it has been dramatically altered due to human and natural processes over the past century. To analyze these changes over time, two locations that have faced significant coastal erosion over the course of this century were studied: Jamaica Bay and Coney Island/Gravesend Bay of South Brooklyn. This thesis project investigates shoreline changes to these two locations using historical and current maps, to quantify how the shoreline moved from the early 1900s to now. Utilizing storm and shoreline measurement data with geographic information systems (GIS), shoreline changes were measured and compared using reference points. Additionally, records of storm severity in these areas during the same timeframe were analyzed alongside the shoreline movement data. Results from these two sites indicate that accretion has been the prime mode of coastal change throughout this century. These results are contradictory to anecdotal evidence that shorelines have significantly eroded with storm activity. During this 120-year study period, the shorelines have experienced some erosion, but overall, the shorelines have expanded. This study demonstrates, that while erosion has occurred, coastal movement is dynamic and primarily the result of human impact as opposed to natural processes.

Chapter 1 Introduction

Parts of New York City closest to the coast, specifically Coney Island/Gravesend Bay and Jamaica Bay, have undergone a substantial amount of erosion. Shoreline erosion is a natural process that occurs on lakes, streams, rivers, and along the coast. It is the gradual, although sometimes rapid, removal of sediments from the shoreline. The process is caused by several factors including storms, wave action, rain, ice, winds, runoff, and loss of trees and other vegetation. Although erosion is not intrinsically harmful, it can affect natural resources, water quality, ecosystems, and property loss. New York City is an urban area that is surrounded by the Hudson River. The Hudson River leads out into the Atlantic Ocean (NYSDEC – Coastal Management 2020). When Superstorm Sandy struck in 2012, the coastal regions of the city faced severe erosion. However, this is just one event that can attribute to climate change (Climate Signals 2019). As climate scientists predict an increase in storm frequency and strength, the potential to increase coastal erosion exists. By studying how New York City's coastline has changed over the past century, a greater understanding of coastal movement can be garnered. From the results of this project, ways to prevent such damage as well as predictions of shoreline movement can be established.

1.1. Overview of New York City's Coast

Jamaica Bay and Gravesend Bay/Coney Island comprise New York City's coastline which spans a total of 520 miles. New York City is located on the coast of the Northeastern United States at the mouth of the Hudson River in Southeastern New York state. The coastline resides within the New York–New Jersey Harbor Estuary, the center of which is the New York Harbor. New York Harbor contains deep waters and sheltered bays that helped the city grow in significance as a trading city. The city's land has been altered considerably by human intervention, with substantial land reclamation along the waterfronts since Dutch colonial times. This dredging and building up of the bays for the importing and exporting of goods led to much of the natural variations in topography that have been evened out over time, particularly in Manhattan (NYCDCP – Waterfront & Resiliency 2020). According to the New York State Department of Environmental Conservation (NYSDEC – Shoreline Stabilization Techniques 2020), the study site's coastline consists of natural protective features including beaches, dunes and bluffs found within coastal erosion hazard areas. These areas provide protection to the shoreline from erosion by absorbing the wave energy of open water. Dunes and bluffs which are located within the study sites, such as Coney Island Beach, are especially effective against storm-induced high water (NYSDEC – Shoreline Stabilization Techniques 2020).

It was not until October 2012 that the city received an unexpected storm surge in the form of Superstorm Sandy. The storm made evident the need for increased climate resiliency to all New Yorkers (Branco 2016). Superstorm Sandy went through beaches along New York City's river-facing coastline, damaging buildings and homes. Neighborhoods were flooded, significant erosion occurred, and 43 New Yorkers were killed. Such damage revealed a vulnerability within the city, as New York City's officials were not expecting or prepared for such a storm surge. Superstorm Sandy led to thousands of New Yorkers being rendered homeless, including those residing in hospitals located in red zones. With sea levels continuing to rise and more intense storms expected to occur frequently in the future, erosion is inevitable (USEPA 2017).

As the impacts of climate change continue to accelerate over time, as predicted by the United States Environmental Protection Agency, more damage, flooding, and erosion will occur. These impacts are due to the sensitivity of coasts to sea level rise, changes in the frequency and intensity of storms, increases in precipitation, and warmer ocean temperatures. Additionally, the rising atmospheric concentrations of carbon dioxide are causing the oceans to absorb more gas than the oceans are accustomed to. Therefore, the oceans become more acidic. This rising acidity can have negative impacts on coastal and marine ecosystems (USEPA 2017).

The impacts of climate change are likely to worsen problems that coastal areas such as New York City, already face. Confronting existing challenges that affect man-made infrastructure and coastal ecosystems, such as shoreline erosion, coastal flooding, and water pollution, is already a concern in many areas. Addressing the additional stress of climate change may require new approaches to managing land, water, waste, and ecosystems (USEPA 2017). Therefore, it is necessary to understand how the coastline has changed over the past century, to help prevent/plan for future erosional events.

1.2. New York City's Historical Climate

New York City's coastal location allows it to have cooler summers and warmer winters. The city's coastline borders the ocean, as well as rivers, bays, and inlets. The coastline has undergone frequent variance caused by climate and weather. The city has a humid subtropical climate with cold winters and hot, moist summers. In the winter, daytime temperatures generally stay above freezing point, but average lows drop to 27°F (-3°C). Varying amounts of snow and rain are common in winter. Spring in New York is somewhat warm, where the weather heats up to high temperatures of approximately 77°F (25°C) by mid-May. Summers are generally hot and humid, with average highs reaching upwards of 84°F (29°C) (NOAA, 2020). With climate trends continuously changing in an adverse manner, these temperature readings have become less consistent and more unpredictable.

1.3. Evidence of Climate Change & Its Impacts on New York City

There is limited evidence present for climate change's impact on New York City in the earlier half of the century. The evidence that is present focuses on the salt marshes of New York City. According to Hartig et al. (2002), Jamaica Bay, one of this project's study sites has been seeing depletion of the bay's salt marshes since 1924. Possible causes of salt marsh depletion include reduced sediment input, dredging for navigation channels, boat traffic and regional sea level are just some of these possible causes. Historical aerial photographs, such as Figure 1, depict that the salt marshes have diminished by 12% since 1959, including documentation of vegetation loss of approximately 80% (Hartig et al. 2002). The author of this thesis project, the Gravesend Bay/Jamaica Bay project conducted a continuation of Hartig et al.'s project, concluding that the salt marshes of Jamaica Bay have continuously depleted since the previous project was completed in 1998. This is portrayed in Table 1 as significant salt marsh depletion was measured throughout various parts of the bay. Salt marsh depletion represents shoreline erosion in this case, as marsh is the land type for numerous parts of Jamaica Bay. Salt marsh depletion/shoreline erosion is more prevalent on the ocean side of Jamaica Bay's marshes where the measurements were taken from (Table 1).

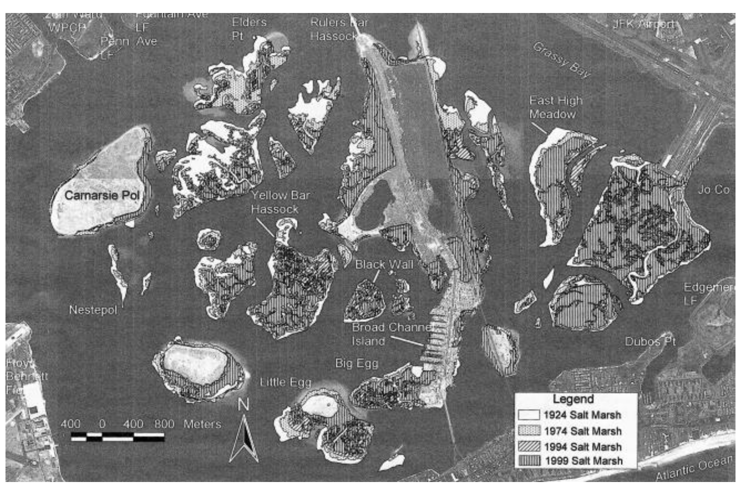


Figure 1. Salt marsh analysis of Jamaica Bay. Source: Hartig et al. 2002

Table 1. Continuation of the salt marsh analysis of Jamaica Bay

Oceanside Area of the Bay	Measurement of Salt Marsh Depletion (Feet)
Floyd Bennett Field	≃223
Plumb Beach	≃250
The Rockaways	≃360

Source: Benincasa 2018

Salt marsh depletion/shoreline erosion stand as just one of the more visible effects of climate change on New York City. The more subtle effects of climate change involve the city's weather and temperature reports. New York City's annual average temperature has risen an average of 2.4°F since 1970, with winter being 4.4°F warmer (NYSDEC – Climate Change 2020). Overall, the city's temperature has been warming at 0.25°F per decade since 1900. Additionally, average annual precipitation has increased across New York State since 1900, with year-to-year variability becoming more apparent. The NYSDEC reports that more precipitation is occurring in the winter, while less precipitation is occurring in the summer. Between 1958 and 2010, the amount of precipitation falling in heavy rain events increased more than 70% across the northeastern United States. In conjunction with heavy rain events, sea levels along New York's coast have already risen more than a foot since 1900, which equates to twice the observed global rate. That rate equates to 0.7 inches per decade over the same period (NYSDEC – Impacts of Climate Change in New York 2020).

According to the New York State Department of Environmental Conservation, spatial modelling shows that New York should anticipate more warming. When compared to the 1971-2000 period, average temperatures will increase up to 3°F warmer by the 2020s, up to 6°F warmer by the 2050s, and up to 10°F warmer by the 2080s. This rise in temperature would also contribute to storm surges and discrepancies in vegetation. Precipitation rates will also gradually escalate up to 8% by the 2020s, nearly 12% by the 2050s, and up to 15% by the 2080s. By the 2050s, sea level is expected to be as much as 30 inches higher in New York's coastal area, as compared with sea level averages for 2000-2004. By 2100, New York's coast could see up to 6 feet of sea-level rise (NYSDEC – Impacts of Climate Change in New York 2020). Figure 2 demonstrates that by the year 2080, all of New York City's coast will be completely flooded. The increase in sea level is problematic for the coast as it allows for an increase in storm surges. The combination of sea level rise and storm surge will lead to significant damage.

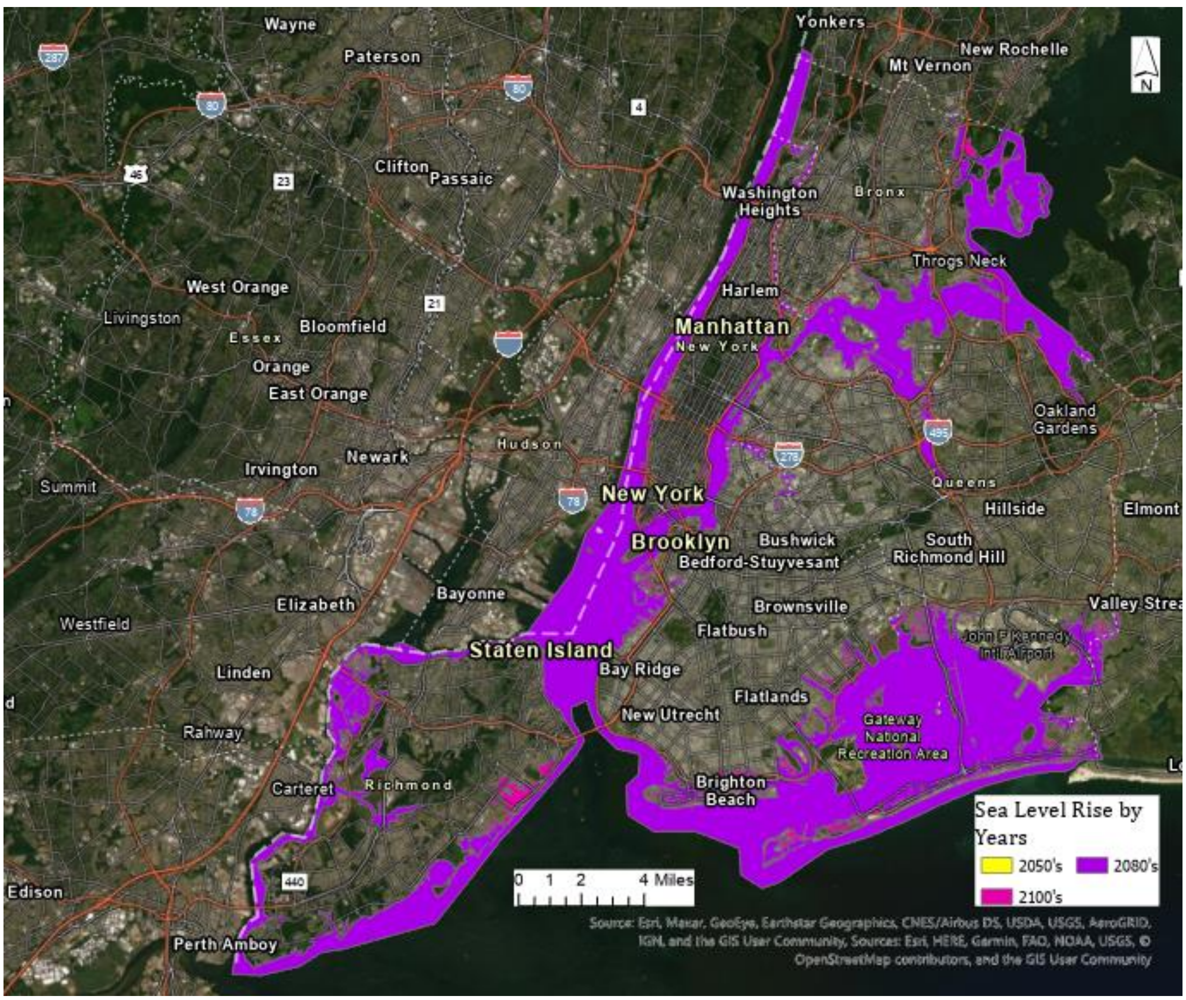


Figure 2. Map depicting New York's projected sea level rise.

1.3.1. Storm Surge Effects on the Coastline

Storm surge is an increase in water levels expedited by the low pressure and wind span of a coastal storm. When the surge encounters a shoreline, it pushes additional water onto that shoreline, often flooding large inland areas. The impacts of Sandy's storm surge were amplified when it encountered water bodies that worked as funnels, such as New York Harbor. It was the combination of waves and their velocity that led to the strength and extent of damage it caused. Storms also produce a broader wave span overall than that of the open ocean (Chen and Curcic 2016).

1.4. Focus Area – Brooklyn, New York

New York Harbor is divided into two parts: The Upper Bay and the Lower Bay. Within the Lower Bay, is the borough of Brooklyn, containing this project's two study sites. Those sites consist of Coney Island/Gravesend Bay and Jamaica Bay (Figure 3).

Figure 3. Overview of Brooklyn, New York.

1.4.1. Jamaica Bay

From the horseshoe crabs that exist within its beaches to the *Spartina Alterniflora* that make up its marshes, Jamaica Bay is a vital ecosystem to the creatures that inhabit this particular estuary, which can be found between Brooklyn and Queens (Rachlin et al. 2016). There has been evidence of salt marsh depletion due to climate change related causes dating back to the 1920s, according to a study conducted by Rachlin et al. Comparing Pre-Sandy and Post-Sandy satellite imagery, marsh loss and decreases in vegetation were observed (Rachlin et al. 2016). Though Jamaica Bay is surrounded by infrastructure, it is protected by the parks department.

1.4.2. Gravesend Bay/Coney Island

Gravesend Bay is an estuary, which is a partially closed body of water in which fresh water meets ocean water. The bay is comprised of a beach, many businesses, an amusement park, and apartment buildings. Gravesend Bay is located at the southernmost tip of Brooklyn. While it may not have the ecological range of Jamaica Bay, it serves as a necessity to the community for recreational purposes. Due to Superstorm Sandy, there was significant coastal erosion and damage to the bay and its surrounding areas. Coney Island is connected to Gravesend Bay. Coney Island has yet to completely recover from Superstorm Sandy. Homes, hospitals, and businesses were flooded and destroyed. Prior to this storm, the most prominent cause of changes within the shoreline emerged from human impact. Dredging of the coast occurred early within the century for trading purposes (Gravesend & Bensonhurst NY Rising Community Reconstruction Planning Committee 2014).

1.5. Storm Effects on New York City

Due to its coastal location, New York City has encountered numerous storms of varying severity. Superstorm Sandy is the only recent hurricane directly impacting New York City.

While it was only categorized as a category 3 storm, its extent of damage was due to storm surge. Superstorm Sandy has proven to be a prominent indicator of climate change. Prior to Superstorm Sandy, there was an uptick in storm occurrence and severity as time progressed. While hurricanes prior to the 1950's were unnamed and poorly recorded for the most part, there was extensive damage noted afterward. For example, Hurricane Able which occurred in 1952 caused about 26.7 million dollars' worth of damage in today's currency. Hurricane Donna in 1960 caused tides that were over 6 feet tall and strong waves which eroded beaches and destroyed nearshore homes. Hurricane Donna killed almost 400 people due to the flash flooding that occurred within its initial state (National Centers for Environmental Information 2020).

As the century went on, more storms materialized towards the tail end of it. In 1985 Hurricane Gloria made landfall in Long Island. The storm caused immense amounts of flooding, which led to mass evacuations. Power lines and trees were knocked down as winds were gusting as fast as 100 miles per hour. Four inches of rain added to the flooding that had already occurred due to a storm surge. There was then a spurt of storms that occurred from 2000-2009.When Hurricane Irene reached New York in its weakened state in 2011, its landfall in Coney Island left 400,000 people without power due to strong winds and flooding. Superstorm Sandy produced the largest surge in New York City by projecting waves upwards of 14.41 feet tall. Homes and businesses were demolished, while tunnels, utility and subway systems were flooded for weeks. Superstorm Sandy caused about 70 billion dollars in damage, a marker of its severity. With a wind speed of 90 miles per hour, it was the combination of a nor'easter during high tide, and the storm initially developing over the Caribbean, that enabled Superstorm Sandy to develop such a surge (Daily News 2015).

1.6. Research Objectives

This project aims to understand to what extent the coastline has eroded or accreted over the past century. New York is home to millions of people with 2.53 million people living in Brooklyn alone. Its coastline, the city's first line of defense against storms and sea level rise, has been left unattended for far too long. To better comprehend whether or not storms have caused changes to the New York City shoreline, shoreline measurements generated within this project will be used in conjunction with storm data. This analysis will be used to identify if there is a correlation as hypothesized. The hypothesis was constructed based on historical geologic processes dictating that storms cause shoreline erosion.

Utilizing both current and historical data to analyze how the shoreline has changed, rate of change for shoreline length will be measured in meters along a transect representing a specific year. The data will be used to determine whether the shoreline transgressed or regressed, expanded or retracted. The measurements will then be overlaid with the storms that have occurred in the area over the past century. In doing so, this will either prove or disprove the hypothesis that the storms that have occurred within New York City this past century, caused shoreline erosion.

To further understand how much shoreline erosion has occurred within the past century, this project will take a chronological approach to analyzing the shorelines of these two sites from 1892-2020. The data will be presented from earliest to most recent, based on what is available. Geospatial technology and historical data will be used to answer the following questions:

- Can nautical T-sheets/historical data be used to map out/analyze the shoreline?
- How has the shoreline of these two study areas changed over time?
- Did the increasing number of storm events cause shoreline erosion or accretion?

By looking at coastal changes that occurred over the past century, we can establish the role of storms in erosion or accretion. The information generated from this project can ultimately help prevent or mitigate the consequences of catastrophic weather events like Superstorm Sandy. The Gravesend Bay/Jamaica Bay project's findings can benefit the entire city of New York and its resilience against climate change and storm events. The Gravesend Bay/Jamaica Bay project can do so by suggesting the need to implement protective measures for the shoreline, as the shoreline serves as the city's defense system.

Chapter 2 Related Work

The related work includes studies and information on coastal variance and means of measuring and analyzing such data. This chapter also discusses using shoreline analysis techniques over various time spans.

2.1. Coastal Erosion

Coastal erosion is a process in which the sediment (sand, silt, clay, etc.) that makes up coasts and shorelines is broken down and transported elsewhere. Whether it occurs on a barrier island impacted by a hurricane, or due to the long-term wearing away of rocky sea cliffs, coastal erosion is the result of a complex interaction of physical processes. Depending on the circumstances, the motions of waves, tides, storm surge, and nearshore currents combine and interact with the coast creating endless possibilities (Figure 4).

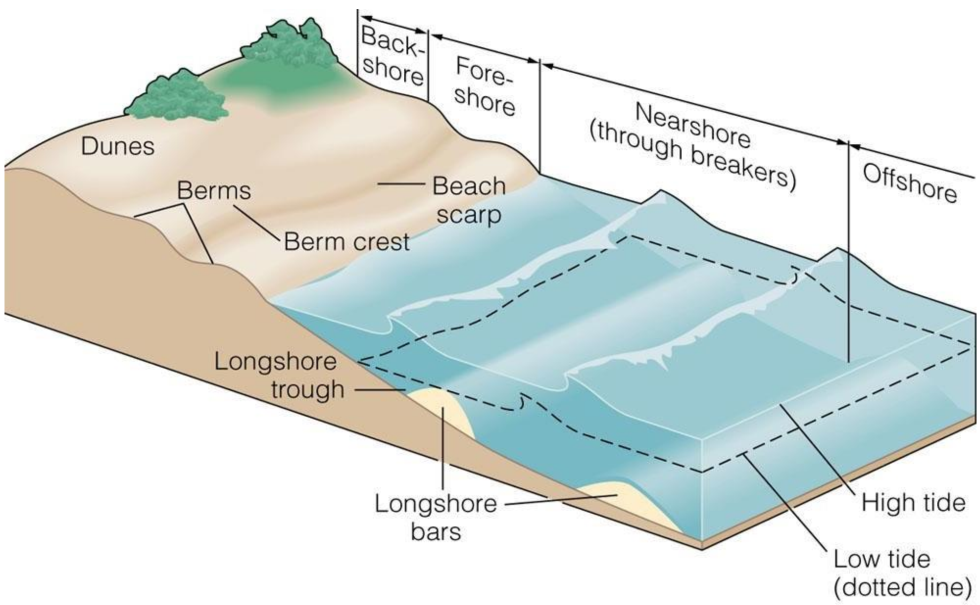


Figure 4. A typical shore profile. Source: Karr et al. 2018

Erosion is the product of several natural processes working in conjunction. As the two work cohesively, waves are the prime erosional factor while wind is secondary. Wind-generated waves are important as energy transfer agents. There is a constant transfer of energy between the waves and wind. As waves obtain their energy from winds and transfer it across the sea, waves deliver that energy to coastal zones where nearshore currents and sand transport patterns can occur. Waves gain strength due to the immense and sudden transfer of more energy when a storm occurs. Three storm factors that drive wave energy are wind speed, the duration of the storm, and the fetch, or area, over which the storm occurs. The duration is important in that the longer the winds have been blowing, the greater the amount of energy that can be transferred to the waves. The fetch/area has a similar effect, as the larger the area, the more energy the waves can gain. This procedure increases when a storm is near or occurring (Komar 2018).

Absalonsen et al. (2011) discussed the characteristics of shoreline erosion based on a study that occurred in Palm Beach County, Florida. The results were divided into three different time periods. The foreshore of this beach faced the most erosion. Cross-shore sediment transport is another beach dynamic process in which seasons and sea level drive how much erosion occurs. Cooler seasons create sand bars as there is less energy and the sediment tends to pile up (Absalonsen and Dean 2011). Absalonsen et al.'s findings benefit the Jamaica Bay/Gravesend Bay project as such findings provide a visual of how coasts can change, the part of the coast that faces the most change, and the array of factors that can be involved.

Sea level is a driving force in the process of coastal erosion. For over three million years, water has been frozen within large continental glaciers and then released, producing alternating sea-level lowering and rising. The freezing, unfreezing and refreezing of glaciers has made it, so sea level has changed by more than 100 m exerting a considerable influence on our coasts. This particularly concerns this past century's shorelines as it has consistently continued rising (Komar 2018). Considering a particular study area, Komar concluded that sea level rise was the culprit for about 20% of Florida's west coast erosion. Long-term tidal gauge recordings support a present-day rise in sea level averaging 2-3 mm per year (Figure 5). Figure 5's depiction of tidal height readings cover several areas across the United States. One area in particular is the location of the Jamaica Bay/Gravesend Bay project, New York City. The line graph below depicts that New York City's tidal gauge readings which represent its sea level height, have continuously increased throughout this century. This consistent rise in sea level may lead to significant and steady erosion (Komar 2018). Burningham & French (2013) confirmed this through their analysis of climate's effects on the geomorphology of coastlines. The study was conducted using coastal signatures dating back to the Holocene Epoch. Burningham & French verified that with the variance in climate there was a rise in sea level. The scientists' findings will benefit the discussion of the Jamaica Bay/Gravesend Bay project's findings.

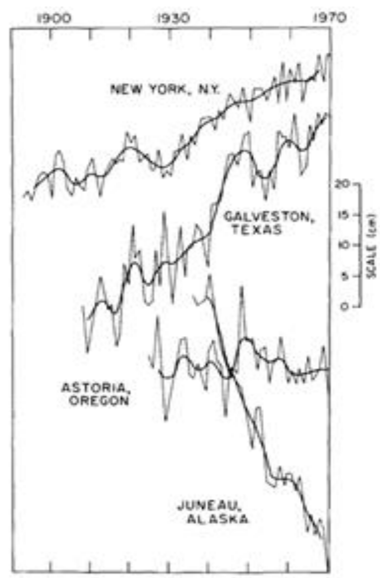


Figure 5. Long term tidal gauge readings. Source: Komar 2018

2.2. Shoreline Analysis

By assessing how others have conducted shoreline analyses, a methodology for the Gravesend Bay/Jamaica Bay project was constructed. For example, a study that examined the evolution of the shoreline of Sardinia, Italy utilized a wide range of datasets spanning 1955-2010 (Virdis et al. 2012). The datasets consisted of aerial photographs, satellite imagery, light detection and ranging data, a terrestrial laser scanner, and both recent and historical topographic maps. Field work was conducted to retrieve recent shoreline data readings. These results were evaluated by time interval and change rate (Virdis et al. 2012). The Sardinia study's use of a plethora of datasets more than likely contributed to its success.

According to Virdis et al. (2012), the more time transpired, the greater the rate of erosion was recorded. Virdis et al. concluded that shoreline erosional trends generally moved from east to west over the years, especially from 1970-2000. There was also a noted decrease in sediment volume for a 300-meter-wide stretch of the coast. It was observed through the Sardinia study that a combination of varying amounts of wind, waves and currents contributed to such shoreline erosion. The Sardinia project depicts what the Gravesend Bay/Jamaica Bay project aims to emulate, shoreline erosion witnessed throughout the course of many years. While Sardinia is not as large or urban as New York City, it somewhat resembles it geographically as a coastal region. Spatial measurements were taken from field data as well as current and historical maps. This methodology provides a guide for the Gravesend Bay/Jamaica Bay project, as to what to look for and include when working with historical data.

Similarly, a study conducted in Central Vietnam, monitored the shoreline dynamics of the Cua Dai estuary from 1964-2014, paying specific attention to timeframes in which the most coastal change occurred (Tuan et al. 2017). The shoreline analysis utilized field survey data, GIS techniques, multi-temporal satellite images and remotely sensed images such as Landsat and ALOS-AVNIR2. Similar to Virdis et al.'s study, Tuan et al. applied many types of data and datasets. Tuan et al. divided this shoreline analysis into three-time frames: 1964-1980, 1981-

2000, and 2001-2014. By separating shoreline analysis into designated time frames, the results of this study revealed that the greatest amount of shoreline erosion occurred within the 1964-1980 timeframe (Tuan et al. 2017).

The analysis techniques described in both Tuan et al. and Virdis et al.'s studies are replicated in the Gravesend Bay/Jamaica Bay project, specifically utilizing a wide array of datasets and dividing resulting data into various time frames. These techniques are replicated due to both studies yielding the ideal result of shoreline erosion. The resulting measurements were taken by dividing parts of the shoreline down into several different transects, which is a technique that the Gravesend Bay/Jamaica Bay project also implements. Since the maps used in this project are being taken from different sources: remote sensing and satellite images, algorithms are used to georeference the maps when necessary. In the Gravesend Bay/Jamaica Bay project, satellite images are occasionally referred to or used when retrieving data from historic maps as they need to be georeferenced.

Wernette et al. (2017) constructed a study similarly demonstrated how to handle georeferencing these historic maps, as they may be problematic to decipher. This was done through a method of accounting for positional uncertainty. The uncertainty-aware and zero ground referenced process, which is specifically designed for shoreline analysis, takes a buffer centric approach since most historical shoreline analysis projects contain primitive data. Wernette et al. utilized this technique via historical aerial imagery of the state of Michigan's shoreline, spanning 1938-2010. The key factor throughout this process was an epsilon band. This band was created and placed around each shoreline with a radius equal to the combined source and interpretation error for each image. The bands were then merged and intersected to test whether the observed change is factual or not (Wernette et al. 2017). Therefore, the method of handling uncertainty if it were to occur within this project is to simply use the buffer tool.

By creating a buffer around known lines, calculations can be made to clarify any misconceptions. An overlapping double buffer (ODB) is used to account for the effects of source and interpretation errors on shoreline position. This tool assesses the degree of overlap. The ODB improves upon standard shoreline analytical techniques, which utilize normally spaced shoreline transects to measure the direction and magnitude of change without error (Wernette et al. 2017).

Results indicate that Wernette et al.'s project was a success. The ODB tool worked for analyzing changes in linear features when a more accurate source is unavailable. Wernette et al.'s methodology provided a valuable solution to the issue of data lacking ground reference, a problem that is extremely common when attempting to complete a shoreline analysis, especially when utilizing historical data. The ODB method works to handle uncertainty, and since the Gravesend Bay/Jamaica Bay project uses similar data, it exercises the ODB method as well (Wernette et al. 2017).

2.2.1. Measurement Techniques

Due to the involvement of calculations in the Gravesend Bay/Jamaica Bay project, it is essential to evaluate the role of calculations in measuring shoreline movement to develop an ideal methodology. Kankara et al. (2014) developed a study, focused on the Chennai coast that describes the role of three methods of calculation: End Point Rate, Linear Regression Rate, and Weighted Linear Regression (WLR). This methodology was responsible for calculating shoreline change rate from 1990-2013. Comparable to previously mentioned studies, timeframes and study areas were divided into segments. Four zones were divided into 412 transects, each spaced 50 m with a length of 200 m. By dividing the data into such a manner, Kankara et al. concluded that the northern part of the coast faced the most erosion, with a rate of 5 m per year.

Kankara et al. (2014) focused on the role that error plays in shoreline analysis. The WLR calculations, errors, and uncertainties associated with each shoreline measurement need to be included in the analysis process. Also, the division of data was the measurement of short term vs. long term, an approach the Gravesend Bay/Jamaica Bay project incorporates. For short term analysis, smaller areas were taken into account (4 distinct zones), while long-term shoreline analysis was just a reflection of the entire area. The Gravesend Bay/Jamaica Bay project also divided shoreline data by time frame.

Spatial uncertainty is a recurring challenge when combining current data with historical data. San et al. (2018) combated this recurring predicament with the use of a spatial uncertainty algorithm called the SLiP-SUM (Shore Line Prediction with Spatial Uncertainty Mapping). The proposed approach was tested on the coast of Kumluca, a dynamic coastal area in Turkey. Future shoreline predictions were made for 2020, 2025, 2030 and 2035 based on remotely sensed data. San et al.'s method consists of five major steps in the following order: preprocessing of data sets (i.e. aerial photos and/or satellite images), extraction or delineation of the existing shorelines with a snake algorithm, prediction of the upcoming/future shorelines using linear regression, preparation of spatial uncertainty mapping using kriging, and producing possible shorelines with spatial uncertainty. The SLiP-SUM algorithm takes pixel sizes and estimation errors into consideration as well. The process has greatly diminished the amount of spatial uncertainty that the project's dataset initially contained, reporting transgressive shorelines via both maps and transects (San and Ulusar 2018). While the Gravesend Bay/Jamaica Bay project does not necessitate the use of such an algorithm, it is beneficial to understanding the overall process of analyzing shoreline data.

The Gravesend Bay/Jamaica Bay project involves two very different types of data sets: historic (Raster) vs. current (Vector). Pollard et al. (2018) created a reference dataset for North Norfolk in England. The reference dataset demonstrated how beneficial it is to combine two sets of data into one dataset at a local, smaller scale. The datasets that were combined in this study were remotely sensed imagery and coastal field based topographical images. A validation of the field data was conducted through LiDAR imaging, and the grand reference dataset was configured to depict data in the same spatial resolution. Even though the Gravesend Bay/Jamaica Bay project will refer to such means when measuring shoreline, as it uses a similar form of data visualization.

In “Shoreline Mapping Techniques”, a geomorphologist named Laura J. Moore, describes a similar project that relied on cartographic advances such as aerial photography and high-resolution imagery to conduct measurements of the shoreline (Moore 2000). She discusses the potential errors associated with the use of historical maps or National Ocean Service Topographic sheets, or T-sheets. To combat these errors, she suggests the use of these T-sheets in conjunction with aerial photography and georeferencing. The Gravesend Bay/Jamaica Bay project emanates these means of error prevention. Moore also stated that aerial photography is the most used data source in shoreline mapping (Moore 2000). When mapping, the wet/dry line or the High Water Line (HWL) is considered the point/line of measurement. Metric mapping is conducted via a grid which requires reference points (Moore 2000). The Gravesend Bay/Jamaica Bay project uses aerial photography as a source of data for the most recent shorelines and conducts measurements via reference points. A similar study by Hil (2019) takes a simple approach to measuring shorelines. Each shoreline/transect is divided by year and measured from the HWL. The value attained from such a measurement is referred to as Net Shoreline Movement (NSM). The NSM serves to project just how much the shoreline has moved when compared to its baseline or reference point (Hil 2019).

2.3. Storm Damage

Shoreline measurements are key to assessing storm damage. The impact of storms on shorelines was demonstrated by Sue Brooks and Thomas Spencer (2017) who conducted their study in North Norfolk, the same area as Pollard et al.'s (2018) project. Storm impact was analyzed using aerial photography, bi-annual cross-shore profiles, detailed alongshore ground surveys, and offshore/inshore wave buoy and regional tide gauge datasets. Through the use of these tools, Brooks and Spencer observed that the barrier dune crest has been progressively eroding since 2006 due to three storm events. The shoreline eroded at a rate of 5-8 m during each storm event. However, a fourth storm produced no significant shoreline change. This lack of significant shoreline change demonstrated that the threshold for morphological change is a function of the combined effects of still water level and wave height at the shore. Time and severity also play a role, as the magnitude and duration of these components, the timing of their interaction and the periods of time between storm events, influence damage. Also, tidal gauge readings of North Norfolk indicate sea levels increasing in height (Brooks & Spencer 2017). The evidence of storm impact on shoreline erosion and explanation of it, benefits the discussion of the outcome of the Gravesend Bay/Jamaica Bay project.

Storms generally have a greater impact on low-lying areas such as Gravesend Bay/ Jamaica Bay and Western Alaska. Storm impact was observed in Western Alaska through time-lapse photography as it has become susceptible to storm surge impacts due to current warming trends leading to accelerated rates of erosion and further inland extent of marine inundation. The destruction of important infrastructure and cultural resource was also factored into the data for evaluation purposes (Overbeck et al. 2017). Unfortunately, time-lapse photography is not available for the Gravesend Bay/Jamaica Bay project to utilize. However, as exercised by Overbeck et al., the Gravesend Bay/Jamaica Bay Project will utilize storm damage data.

While Superstorm Sandy of 2012 is the most recent storm to affect Gravesend Bay/Jamaica Bay, in 2017 the Atlantic had a hurricane season that consisted of 33 storms. Hurricanes Harvey, Irma, and Maria amounted to over $200 billion dollars in damage alone. These storm events suggest that the frequency of these high intensity Category 4 and 5 hurricanes is increasing. This trend emphasizes the need for effective damage mitigation techniques that improve the robustness and resiliency of coastal communities. Therefore, cost-effective solutions such as structures, are necessary to mitigate waves and storm surge before they reach developed coastal areas (Tomiczek et al. 2018). Even though Tomiczek et al.'s study did not focus on shoreline erosion, it did discuss damage assessment and the need to mitigate storm impact. The Gravesend Bay/Jamaica Bay project includes damage assessment in the form of storm severity and damage costs. The goal of the Gravesend Bay/Jamaica Bay project is to be used to implement a plan to mitigate storms that are foreseen in New York City's future to prevent significant damage from occurring again.

Phillips et al. (2017) published a study that benefits the analysis of the Gravesend Bay/Jamaica Bay project, as it not only discussed shoreline erosion but shoreline accretion. The Australia based project quantifies the variability of shoreline recovery on a high-energy sandy coastline using a 10-year dataset of daily shoreline and sandbar positions from a Coastal Imaging station at Narrabeen-Collaroy Beach, Australia. Involving a total of 82 individual storm events, rates of the cross-shore return of the shoreline to its pre-storm position were analyzed. There was shoreline erosion, but rates of shoreline recovery measured out to ~ 0.2 m/day. These results revealed that rapid rates of shoreline recovery occur when sandbars are closer and attached to the shoreline (Phillips et al. 2017). Phillips et al.'s study is important to the Gravesend Bay/Jamaica Bay project, in that it depicts accretion after storm events. Phillips et al.'s findings clarify some of the Gravesend Bay/Jamaica Bay project's results. Each related work mentioned in this chapter contains a similar methodology or ideology which the Gravesend Bay/Jamaica Bay project duplicates.

Chapter 3 Methods

This chapter describes the process of acquiring spatial data, digitizing, measuring shorelines, and recording storm data. The goal of the analysis is to examine storms' erosional processes and if shoreline expansion or retraction is a product of those storms. Using historical shoreline surveys, current shoreline surveys, and local storm information, shoreline measurements are analyzed to see whether there is a correlation between storms and shoreline erosion.

3.1. Overview of Methodology

By using several intertwining processes, shorelines are measured and organized along storm severity data to prove or disprove a correlation between the two factors. Historic shoreline surveys are converted from raster to shapefile to compare with current shoreline surveys through digitization. The historic shoreline surveys/T-sheets are originally downloaded in the form of either a JPEG or TIFF file. The shoreline survey data is then uploaded into ArcCatalog for organizational matters and then into ArcGIS Pro for digitization. Once in ArcGIS Pro, the historic shoreline surveys are georeferenced and converted into shapefiles. Shorelines are then traced as polylines from these files for clarity purposes. Shoreline lengths are then calculated using the measure tool as measurements from these polylines and recorded in an Excel spreadsheet. The Excel spreadsheet works as a tool to organize the shoreline measurements and the storm data that is utilized for this project, which is comprised of storm damage in dollar amounts, severity, and year of occurrence. By analyzing these datasets in conjunction with one another, one can determine whether a correlation is present (Figure 6). Figure 6 which is depicted below, provides an overview of this thesis project's workflow. The workflow is divided into three phases: digitization, data processing and data organization. Figure 6 describes each phase's components in chronological order.

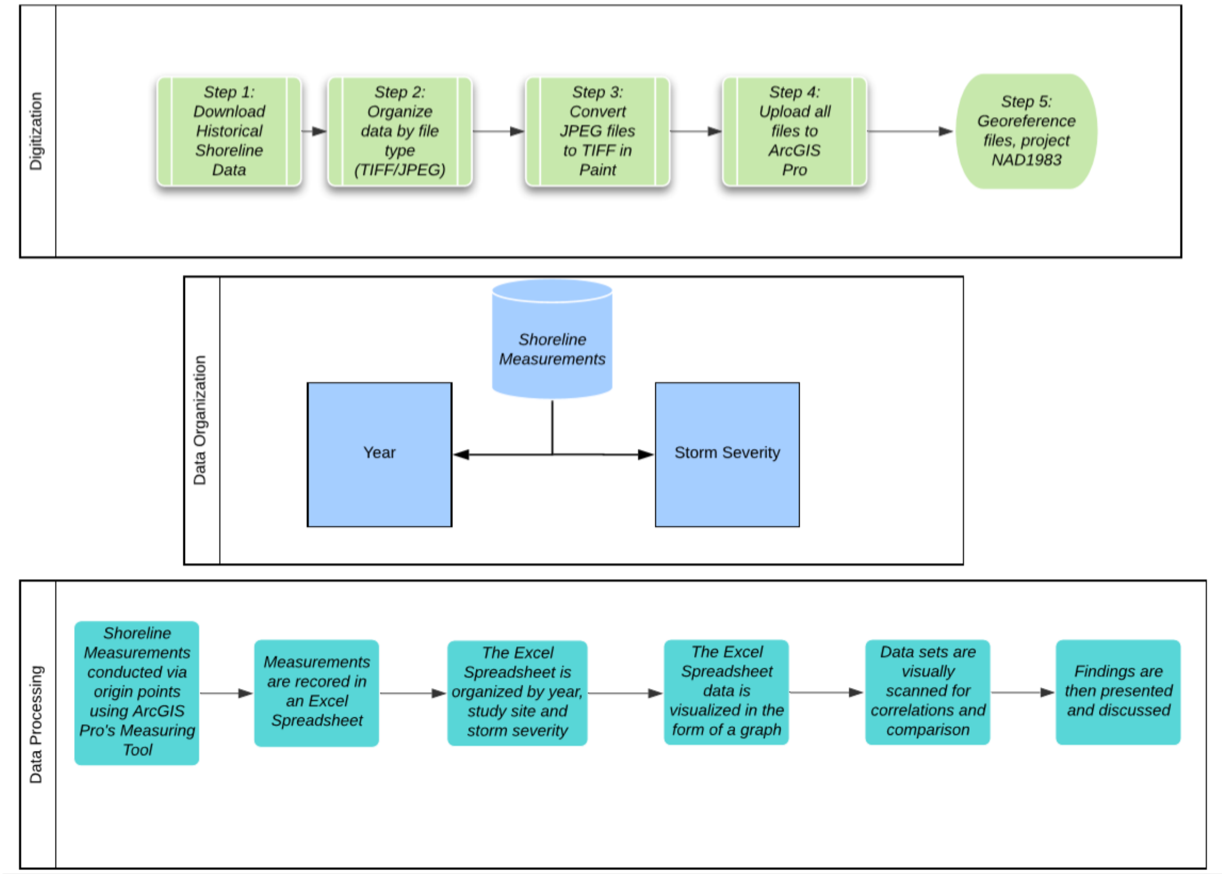


Figure 6. Overview of thesis project workflow.

3.2. Data Description

The datasets for this project are meant to depict and measure historical and current shoreline data, storm severity and damage. As seen above in Figure 6, the digitization stage is extensive. The data is organized as it applies to the shoreline measurements. As the data is recorded and processed, it is analyzed for correlations between storm data and shoreline data. Spatial datasets for this project are available from NOAA (National Geodetic Survey 2020). The primary dataset for this project is the shoreline data, which is downloaded in the form of a raster type of file (TIFF or JPEG), and then converted into vectors via Esri ArcGIS software (Esri 2016). These files are nautical charts in the form of hand drawn maps and T-sheets representing

New York City's shore from 1934 (Figure 7). The scale of these T-sheets varies from 1:10,000 to 1: 60,000. Shoreline data from as far back as 1999 is available in vector form.

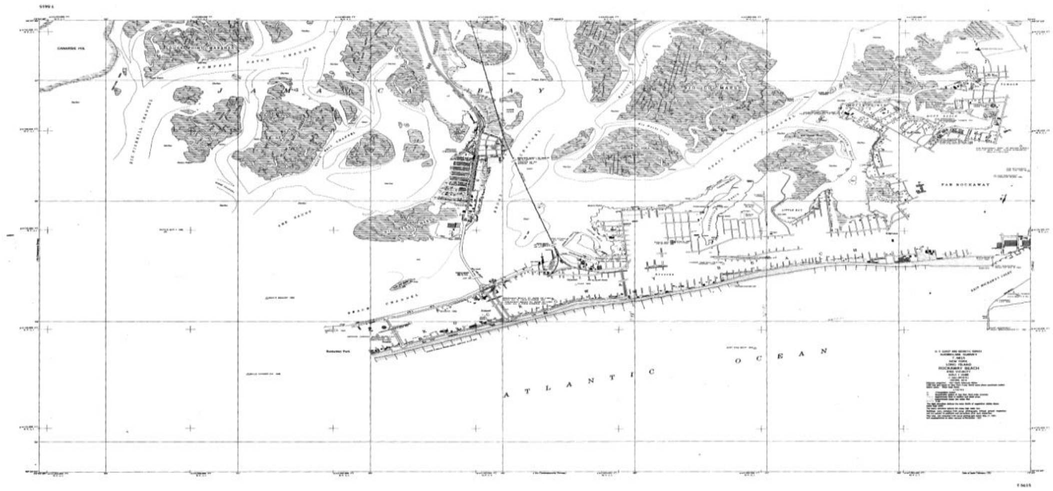


Figure 7. A historical shoreline survey/T-sheet in JPEG form of Jamaica Bay.
Source: NOAA

The secondary set of data is storm severity, which includes when the storms occurred and the extent of their damage, in both their year of occurrence and current monetary value (NOAA 2020). This data is then converted using an inflation calculator (US Inflation Calculator 2020). These two datasets are both from NOAA, therefore they have been reviewed for accuracy. NOAA is the nation's trusted authority when it comes to climate and weather. Its National Center for Environmental Information, a division that develops national and global datasets, has been around for over 60 years and is continuously updated to provide an accurate map (National Centers for Environmental Information 2020). Once the historical shoreline surveys are digitized using the two registration/reference points on the basemap, measurements are then taken from these two points to measure how the shoreline has changed over the past century. The two points are measured a total of three times each and then averaged. Each measurement is based off a 180° line for each point. The details of the shoreline surveys and storm datasets are available in Table 2, as it explains what each dataset consists of.

Table 2. Description of source data.

Location	Data	Time Frame/Years	Quality
• Jamaica Bay	• NOAA Historical Shoreline Survey Sheets • Raster • Scale Range: 5,000-10,000	• 1892 • 1933 • 1934 • 1974 • 1999 • 2015 • 2020	Verified by NOAA, accurate.
• Gravesend Bay/Coney Island	• NOAA Historical Shoreline Survey Sheets • Raster • Scale Range: 5,000-10,000	• 1892 • 1934 • 1974 • 1999 • 2013 • 2015 • 2020	Verified by NOAA, accurate.
• New York City	• Hurricane Damage in $, severity	• 1892 – 2020	Collected from NOAA and then calculated/converted manually into today's dollars.

3.3. Data Processing

3.3.1. Shoreline Delineation

Historic and current shoreline surveys provide the maps that shorelines are measured from. Shoreline surveys are downloaded from NOAA. All files have a datum of NAD 1983 and are framed in a geographic coordinate system (decimal degrees). The older surveys (1892, 1933, and 1934) are JPEG files and are converted into TIFFs with Microsoft Paint. All shoreline files are then loaded into ArcGIS Pro and georeferenced to reflect NAD 1983 and the geographic coordinate system, there is no change prior to measurement. The shorelines are then manually digitized in ArcGIS Pro and added to an ArcGIS Pro project of either Gravesend Bay or Jamaica Bay and measured. Each shoreline year is digitized as an individual polyline for analysis and visualization.

3.3.2. Shoreline Measurements

Shorelines are measured from two designated reference points on opposing sides of a site each year, to calculate how much the shoreline has changed. Reference points for study site #1 Gravesend Bay/Coney Island (Figure 8) and study site #2 Jamaica Bay (Figure 9) are chosen at the location of a historical street intersection with the measurement bearing directly north and south (site 1) or east and west (site 2). This technique is used to measure how the shoreline moved from year to year. The “Measure Distance” tool was used to complete this task. Once the tool was opened a “Geodesic” option is automatically selected. A unit of measurement is manually selected, in this case it is “Meters”.

Each shoreline transect is measured three times from the point of reference on both axes, resulting in six readings for each study site for each year across a 180° directional line. For example, when measuring the year 2000, starting from the reference point/marker as highlighted and shown in Figure 8, a line of measurement is created from the reference point and ended at the year in question. This is done on each side, for reference points A and B. Each measurement exercise is conducted three times for each side. Each number/measurement is then averaged for a total, representing a true measurement/shoreline distance for the specified year. For each shoreline that is measured, several totals are produced. The total that represents the recorded measurement of the shoreline for the thesis analysis is referred to as the “Path Net Distance”. The “Path Net Distance” is the measurement that represents the distance between the reference point and where each year’s respective shoreline land. Measurements are then recorded in an Excel spreadsheet, combined, and compared alongside storms that have occurred throughout the past century, noting their damage and severity.

Figure 8. Reference Point for Site #1, line dictates direction of measurement.

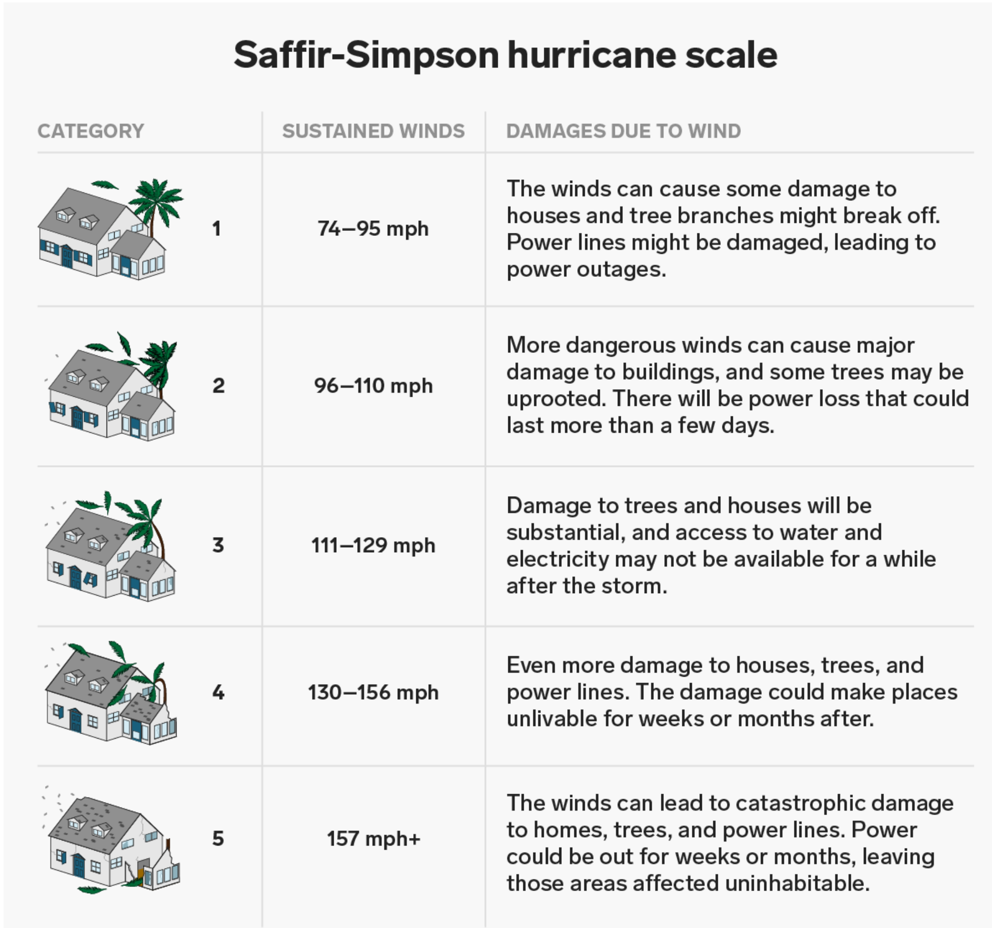
Figure 9. Reference Point for Site #2, line dictates direction of measurement.

3.3.3. Storm Data

Storms and storm surges are hypothesized to be the driving force behind coastal change. The severity of the storms for this study period are quantified through an estimation of their damage amount and converted from the year of the storm to 2020-dollar amounts (US Inflation Calculator 2020). Each storm's damage amount in 2020 dollars, year of occurrence, name and category is recorded (Table 3). Storm category is derived from the Saffir-Simpson Hurricane Scale (Figure 10).

Table 3. Table depicting recorded and calculated storm data.

Year	Name	Estimated Damage (millions - 2020 dollars)	Estimated Damage in Year of Occurrence (Millions)	Category
1952	Able	26.7	2.75	2
1955	Diane	8,008	814	2
1960	Donna	8,540	980	4
1972	Agnes	12,960	2,100	1
1976	Belle	453.3	100	3
1985	Gloria	2,157	900	4
1991	Bob	2,841	1,500	3
1999	Floyd	18	5	4
2000	Gordon	20.8	11	1
2003	Isabel	639.2	450	5
2008	Hanna	191.7	160	1
2009	Bill	55.5	46.2	4
2011	Irene	12	10	3
2012	Sandy	77	69	3



Saffir-Simpson hurricane scale

CATEGORY	SUSTAINED WINDS	DAMAGES DUE TO WIND
1	74–95 mph	The winds can cause some damage to houses and tree branches might break off. Power lines might be damaged, leading to power outages.
2	96–110 mph	More dangerous winds can cause major damage to buildings, and some trees may be uprooted. There will be power loss that could last more than a few days.
3	111–129 mph	Damage to trees and houses will be substantial, and access to water and electricity may not be available for a while after the storm.
4	130–156 mph	Even more damage to houses, trees, and power lines. The damage could make places unlivable for weeks or months after.
5	157 mph+	The winds can lead to catastrophic damage to homes, trees, and power lines. Power could be out for weeks or months, leaving those areas affected uninhabitable.

Figure 10. Saffir-Simpson storm category scale. Source: Mosher & Lee 2018

Strength of winds dictates what category each storm falls into (Figure 10). Storms that are considered the most devastating are categories 3 and above, with 5 being the most devastating. At the very start of the century, there were no viable records of storms until 1952. It is highly unlikely that no storms transpired until the year 1952. Instead, it is probable that there is no record of storms occurring due to the lack or limit of technology available within that time frame.

The analysis portion of the Gravesend Bay/Jamaica Bay project focuses on two factors to measure storm severity: category and damage costs. The storm data is attributed to the assessment of shoreline movement in verifying a correlation between storms and accretion or erosion. New York City has dealt with a significant amount of storm damage over the past century, or more specifically the latter half of the century due to Superstorm Sandy. The earlier half of the century's account of storms is limited. This lack of data leads to a gap in analysis when assessing the shorelines that are present prior to 1952. However, from 1952-2020, there are 14 recorded storms affecting New York City. Table 3 depicts that even storms that are low on the Saffir-Simpson scale still cause a significant amount of damage. For example, Hurricane Diane, which occurred in 1955, was a category 2 that caused over $814 million dollars in damage; this translates to over $8 billion in today's dollars.

Chapter 4 Results

This chapter details the results of the methodology documented in Chapter 3 to digitize and analyze the shoreline of New York City. The research questions which were outlined earlier and are answered in this chapter, include: (1) Can nautical T-sheets/historical data be used to map out/analyze the shoreline? (2) How has the shoreline of these two study areas changed over time? (3) Did the increasing number of storm events cause shoreline erosion or accretion?

4.1. Digitization

The products of the digitization process depict shorelines recorded throughout the century as seen in Figures 11a-c and 12a-c below for each study site. After the historical shoreline surveys are digitized, the shorelines are traced as polylines. The chromatic color scheme (yellow to red) demarcates the change in shoreline over the years. Figures 11a and 12a provide an overview of each study site and their respective shorelines. By observing all of the shorelines through Figures 11a and 12a, it becomes apparent that accretion was the dominant form of coastal change. Figure 11b displays the strong variance between shorelines in Gravesend Bay as 2020's shoreline depicts how far the shoreline has accreted. Figure 11c depicts a significant increase in accretion from 2013 to 2020.

While accretion is consistent throughout this entire project, there are observed instances of erosion. Figure 12b focuses on Rockaway Beach which shows mostly erosion occurring as the 1934 shoreline is further from the reference point than the 2020 shoreline. Figure 12c depicts what is left of the salt marshes of Jamaica Bay, as some that were present in the 1930s have completely disappeared. The representation of the shorelines diminishing throughout the years in Figure 12, signify that not only are the salt marshes of Jamaica Bay depleting, but that these salt marshes have been depleting for many years.

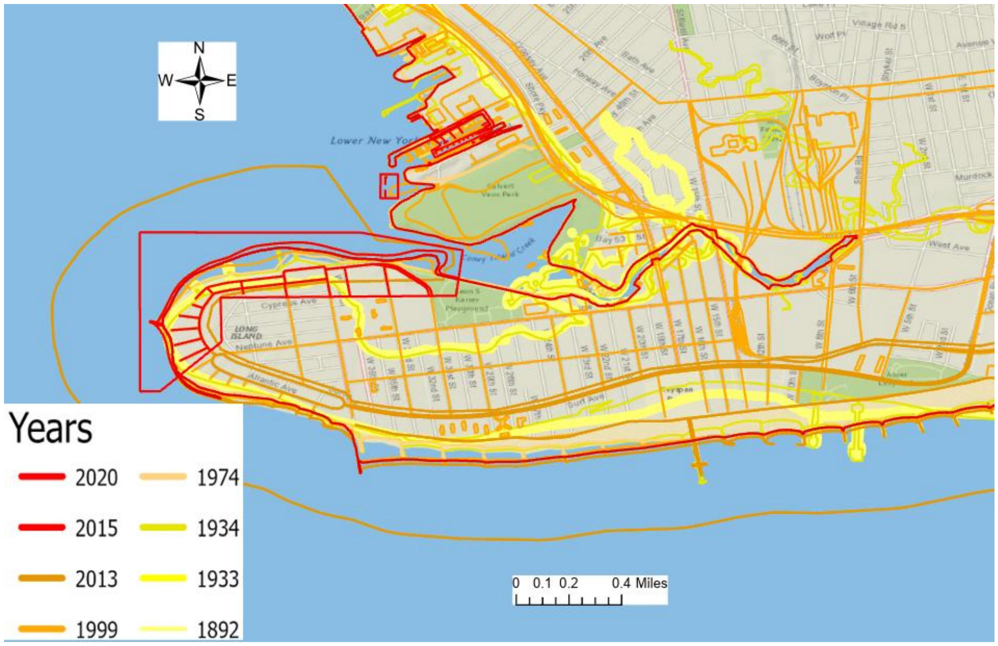


Figure 11a. Digitized Shoreline for Site #1.

Figure 11b. Part of Site #1 shoreline with substantial change.

Figure 11c. Detailed view of coastal change for Site #1.

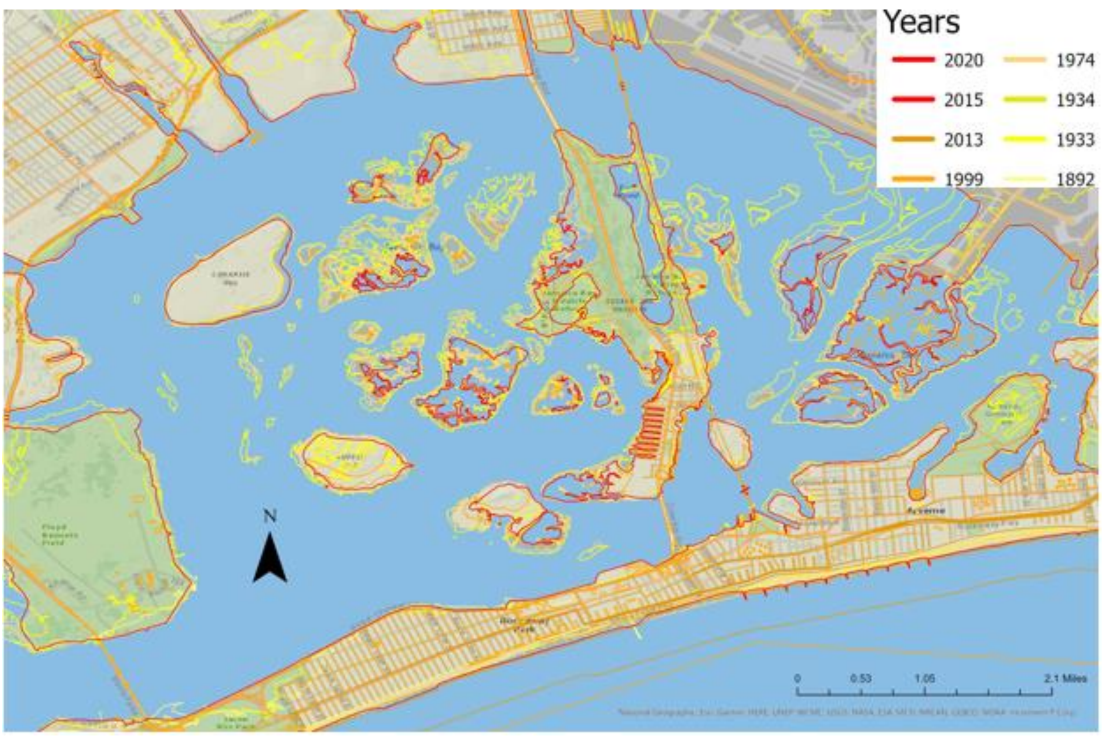


Figure 12a. Digitized Shoreline for Site #1.

Figure 12b. Coastal changes of Rockaway Beach in Site #2.

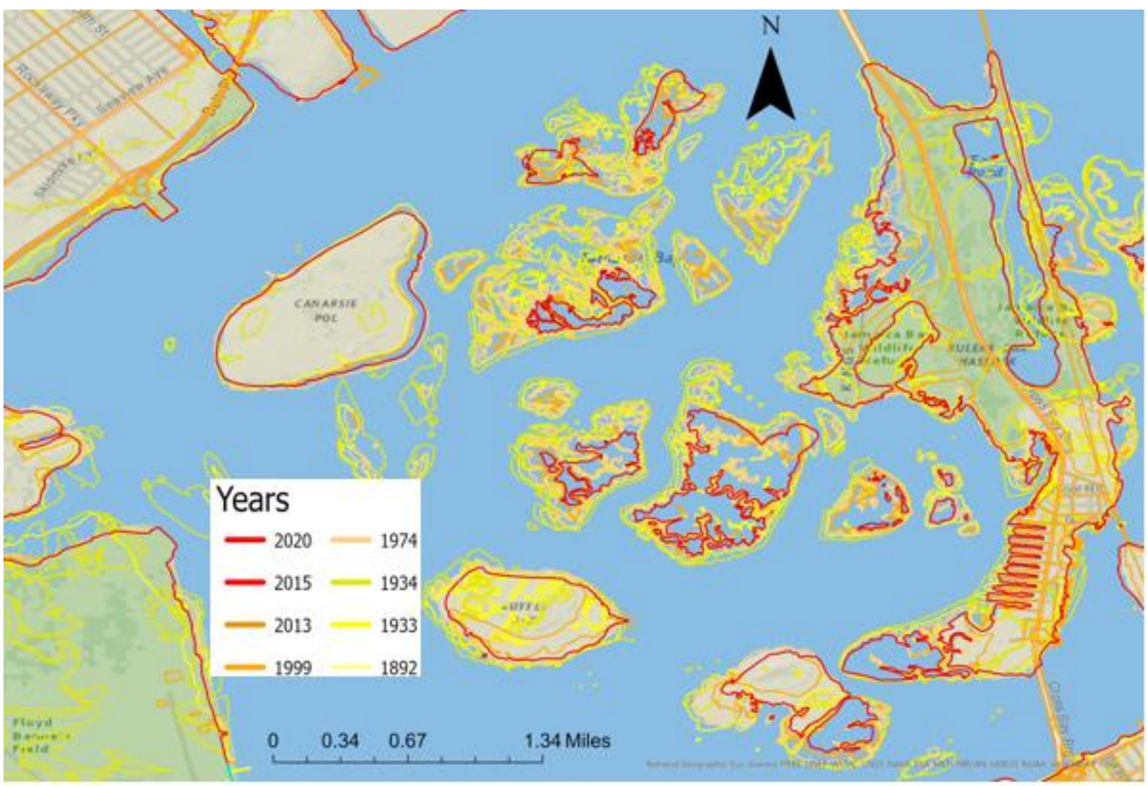


Figure 12c. Depletion of the salt marshes of Site #2.

4.2. Shoreline movement over time

Analysis of shoreline movement over time reveals that there is both evidence of shoreline regression and accretion. Additionally, this study reveals a large difference between the Gravesend Bay/Coney Island measurements and the Jamaica Bay measurements (Table 4). Nevertheless, both study sites' shoreline movements each stabilized after 2013. Over the study period, there is an average increase in shoreline of 439.75 m. The average increase is calculated by subtracting the current shoreline distance for each study site's point A and B side (2020) from its initial distance (1892) and dividing by 4 (each side per site). The average increase can be further divided into an average yearly increase in shoreline of 3.66 m. The average yearly increase was calculated by dividing 439.75 into 120 (The total number of years involved in this study).

Accretion totals for each of the four measurement totals ranges from 321 m to 672.5 m. Gravesend Bay/Coney Island's Point A's accretion totals 321 m in comparison to Point B's total accretion of 446 m. Therefore, Gravesend Bay/Coney Island's Point B side experienced more accretion than Point A over the study period. Study Site #1's total amount of accretion is similar to the findings of Study Site #2's accretion rates. Study site #2/Jamaica Bay's Point A has a total accretion of 672.5 m: slightly higher than its Point B total accretion of 571 m. This is the opposite of Study Site #1. Overall, Jamaica Bay sustained more accretion than Gravesend Bay/Coney Island as is reflected in all four measurements. Table 4 also reveals that there is one year per site where measurements are missing. Those missing years are 1933 for Gravesend Bay/Coney Island and 2013 for Jamaica Bay. This lack of measurements is due to those years' T-sheets not covering both study sites. The T-sheets that were used for this project, due to their being historical imagery, fit together as a puzzle when uploaded into ArcGIS Pro.

Table 4. Measurements of shoreline distance/expansion from reference points.

	Study Site 1- Gravesend Bay/Coney Island		Study Site 2- Jamaica Bay	
	Distance from Reference Points (Meters)		Distance from Reference Points (Meters)	
Year	Point A	Point B	Point A	Point B
1892	1156	1997	127	326
1933			391	238
1934	1072	1931	494	308
1974	1477	2050	932	755
1999	1530	2398	1174	823
2013	1605	2441		
2015	1616	2442	780	912
2020	1477	2443	810	635

4.2.1. Gravesend

Figure 13 depicts how Gravesend's measurement data varies greatly between the study points. In the earlier half of the century, Gravesend's Point A measurements show erosion with a slight difference between distance to the reference point from 1892 to 1934. Following 1945, a steady increase in shoreline growth or expansion existed until 2015. Both Point A and Point B's measurements progress throughout the years. A consistent increase in shoreline mass/distance from Point B is evident, which contributes to consistent expansion with some slight variance. For example, the side/point B measurements of Jamaica Bay decreased from 1,997 m in 1892 to 1,931 m in 1934 and increased to 2,050 m in 1974. Gravesend Bay's Point B had the greatest accretion in recent years. From 1999-2020, it increased from 2,398 m to 2,443 m. Though it may be a minimal change over a 21-year span, it is an extent that no other part of the bay experienced.

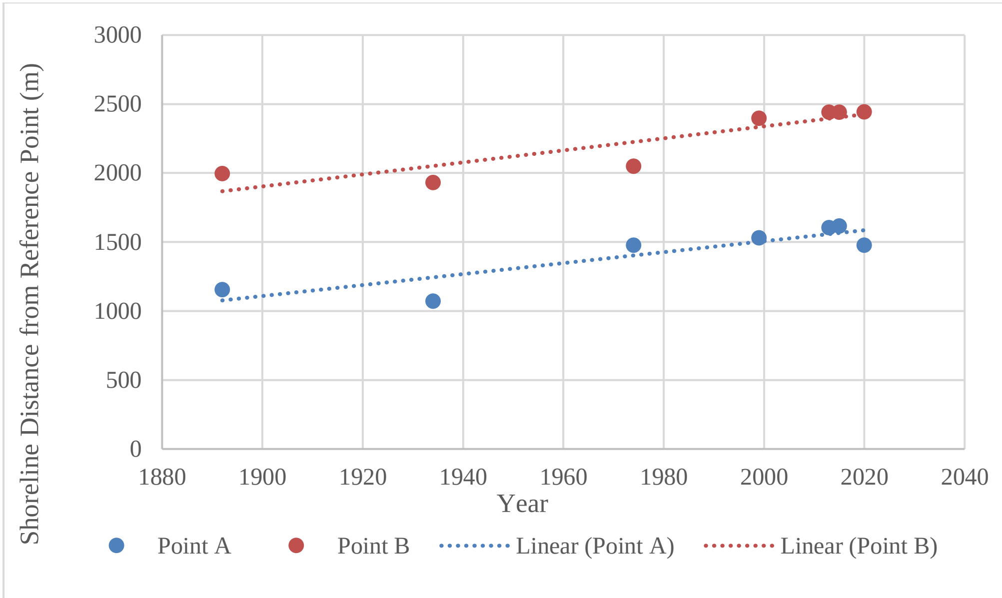


Figure 13. Gravesend Bay/Coney Island (Site #1) shoreline measurements for Point A and Point B from reference point depicting a linear trend.

Both points in Gravesend Bay depict a general increase in shoreline distance signifying expansion. There is a subtle difference/increase in the shoreline for Point B located far from the reference point. Point A's accretion average is just as consistent, as observed in Figure 13, starting at 1,156 m and gradually expanding to 1,616 m. In measuring where the shorelines are in 2020, there is approximately a 500 m difference between the two sides/points of the same site. Additionally, and consistent with study site #2, more data is available later in the century because more shoreline delineations occurred from the 1970's and onward (Figures 13 and 14).

4.2.2. Jamaica Bay

Figure 14 depicts a general increase in distance from the reference points outward to the shore for both Point A and Point B. This is slightly higher for Point A, but both still depict consistent accretion from the years 1892 -1999. The rate of this constant accretion is 9.7 m per year over the course of 107 years. Both the highest and lowest measurements of accretion for this study site are present in Point A. After 1999, Jamaica Bay sees significant and continuous erosion until 2020. This is seen in both Point A and Point B. Point A's shoreline measurements decrease from 1,174 m in 1999 to 780 m in 2015, displaying a 394-meter difference. Point B's shoreline measurement for 1999 was 823 m. The shoreline then expanded out to 912 m before eroding down to 635 m in 2020, equating to 277 m less than it was 5 years prior. While the decrease in shoreline is larger for Point A than Point B between 1999 and 2015, there is an overall increase over the study period as indicated by linear regression lines of shoreline distance from origin (Figure 14). However, all the shoreline measurements are consistent. Figure 14's linear regression line shows accretion is occurring most of the time with very few erosional events. The erosional events did not impact the regression line significantly because of the small amount of erosion.

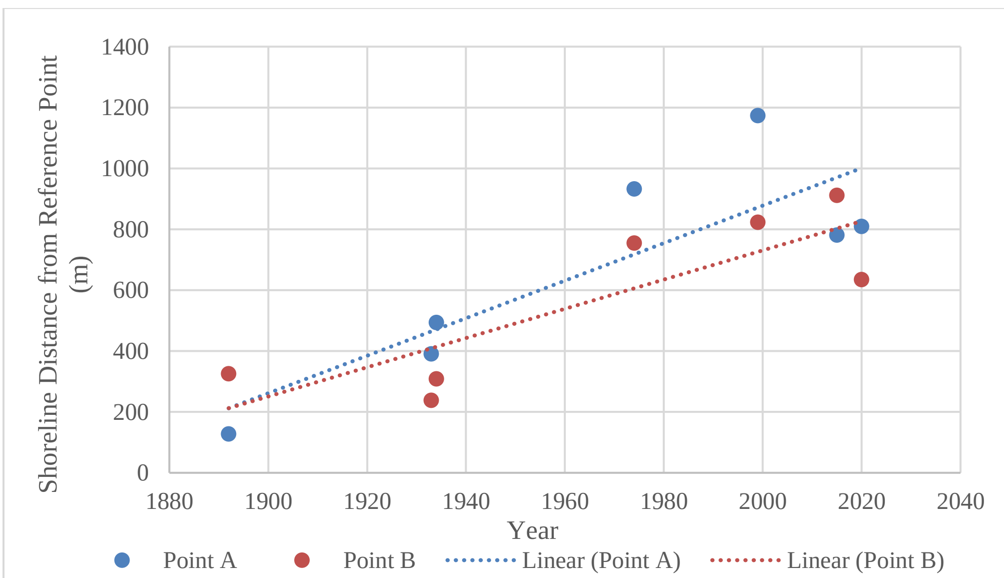


Figure 14. Jamaica Bay (Site #2) shoreline measurements for Point A and Point B from reference point depicting a linear trend.

Demonstrated in Figure 14, Point A and B in study site #2 contains little to no variation. Both lines start at similar points and end at similar points, representing the cohesiveness of this study site. There are no outliers with a consistent slope of accretion. For example, 1934's measurement for Point A was 494 m, while Point B was 308 m, which is not a significant contrast. Figure 14 depicts the cohesion and consistency of accretion; any instances of erosion are left undetected.

4.3. Storm Data Analysis

Numerous storms have impacted New York City over the course of the past century (Table 5). Ironically, the first recorded storm of the century caused the least amount of damage. Hurricane Able which occurred in 1952, was a category 2 that caused $2.75 million dollars in damage during that year. As time progressed, storms of varying severity began to occur. The city did not encounter a devastating storm until 1960, with the arrival of Hurricane Donna. Hurricane Donna is the city's first recorded category 4 storm. However, as Table 5 depicts, a shoreline survey was not conducted for New York City until 1974, fourteen years later. Both storm and shoreline data are a rarity in the earlier portion of the century.

The lack of storm data rendered this period of the analysis incomplete as no other storms were recorded until 12 years later. The next recorded storm was Hurricane Agnes, a category 1 storm, which occurred in 1972. In 1972's dollar amount, Hurricane Agnes caused 2.1 billion dollars worth of damage. Hurricane Agnes caused the most damage out of all the storms that have occurred within this past century. It is contradictory of the category under which it falls. From 1976-1999, the city encounters only category 3 and 4 storms. Four storm events occur within this timeframe which equate to 1 storm every 5.75 years. A year later, Hurricane Gordon became the first of many storms to occur frequently within a twelve-year time period. From 2000-2012, a storm occurred at a rate of every 2 years, 6 in total. These storms were both more frequent and occurred in proximity of each other, which could be indicative of climate change. Even though this is a notable trend, the analysis is based on recorded storm data and it is unclear how consistently storms were recorded prior to 1952.

4.4. Combination of Storm & Shoreline Datasets

Following the descriptive analysis of how Jamaica Bay and Gravesend Bay's shorelines have moved from their reference points over time (section 4.2), this section looks for how the presence of storms are correlated with these identified shoreline changes. The section addresses possible causes to the shoreline changes, specifically looking at the presence of storm surges and sea level. Analysis however concludes that there is not a correlation between the shoreline erosion and storm presence/severity, contradictory to the project's hypothesis.

Table 5 depicts shoreline expansion in both sites consistently from 1892 to 1974, with several severe storms occurring within that time frame. From 1974-2020, both sites largely stabilize their shoreline movement maintaining their distance from the origin points. Therefore, although it is a rare occurrence, erosion did occur in Jamaica Bay following 1974. It also occurred in the narrow window from 1892 to 1934 at Gravesend. Prior to 1974, four storms occurred from 1952-1972. Two of these storms were Category 2 (Hurricanes Able and Donna), the other two were Category 1 (Agnes) and Category 4 (Donna). The shoreline measurements, taken after these storms occurred, were next in 1974. The 1974 measurements depict a substantial increase in shoreline expansion throughout the entire study. For Gravesend Bay, its Point A measurement greatly increases in distance, from 1,072 m in 1934 to 1,477 m in 1974. Point B's measurements also increase though not as significantly, from 1,931 m to 2050. Jamaica Bay also sees increasingly distant measurements as its Point A measurements expands from 494 m to 932 m and its Point B measurements expand from 308 m to 755 m.

Table 5 depicts that the shoreline measurements vary significantly; both between the points within a study site and between the study sites. Gravesend Bay/Coney Island's measurements are in the thousands for most of the century. This contrasts with Jamaica Bay's measurements which are mostly in the hundreds. There was a broad range of shoreline measurement/distance with Gravesend Bay's Point B shoreline accreting as far as 2,442 m away and Jamaica Bay accreting out 1,174 m. Despite there being a large difference between the two sites' farthest points of accretion, continuity was present in both Jamaica Bay and Gravesend Bay overall. The continuity is apparent when observing the range of the shoreline measurements within each respective site.

The input of the storm severity data portrays how the measurements may or may not be the result of storm surges, or generally how storm events impact shoreline movement over time. From 1952-1974, storms were being recorded, but the lack of shoreline surveys prevent additional analysis. Regardless, within that duration there is only one devastating storm in 1960, Hurricane Donna (category 4). Neighboring this timeframe, there was a level 2 that occurred in 1952 (Hurricane Able) and another level 2 that occurred 1955 (Hurricane Diane). Then, a level 1 that occurred in 1972, Hurricane Agnes.

From 1976-2012, the city of New York was impacted by 10 storms, mostly by category 3 or higher, which have caused severe devastation to the city. It is within this time frame that the most storms were recorded. The most powerful storm was Hurricane Isabel, a category 5 that occurred in 2003. Coincidentally, it was followed up by one of the weakest storms recorded. That storm was a category 1, Hurricane Hanna which occurred in 2008. It was followed by several strong storms afterward. The shoreline measurements taken during this period, as compared to the most recent ones before 1974, do not however depict significant shoreline movement. Afterwards in 2013, very slight accretion was recorded. Regardless, the shoreline surveys do not line up with the storm records. No shoreline survey was conducted right after a storm was reported. Generally, however, both sites displayed accretion during this period as they do overall throughout the study.

Table 5. The combination of storm and shoreline data.

Storms			Study Site 1-Gravesend Bay/Coney Island		Study Site 2-Jamaica Bay	
			Distance from Reference Points (Meters)		Distance from Reference Points (Meters)	
Year	Storm Name	Storm Severity	Point A	Point B	Point A	Point B
1892			1156	1997	127	326
1933					291	238
1934			1072	1931	494	308
1952	Able	2				
1955	Diane	2				
1960	Donna	4				
1972	Agnes	1				
1974			1477	2050	932	755
1976	Belle	3				
1985	Gloria	4				
1991	Bob	3				
1999	Floyd	4	1530	2398	1174	823
2000	Gordon	1				
2003	Isabel	5				
2008	Hanna	1				
2009	Bill	4				
2011	Irene	3				
2012	Sandy	3				
2013			1605	2441		
2015			1616	2442	780	912
2020			1477	2443	810	635

4.4.1. Instances of Erosion

Erosion is rarely seen throughout this entire project. For Gravesend Bay/Coney Island, it was observed largely at the start of the century. The first year in which a shoreline survey was conducted and available for this project, measured out to 1,156 m. The shoreline eroded slightly then in 1934 to 1,072 m. Similarly, Gravesend Bay/Coney Island's Point B saw erosion during that time frame as well. The 1892 measurement for Point B was 1,997 m and then slight erosion occurred, causing the next measurement that was taken for the year 1934 to be 1,931 m. Gravesend Bay underwent erosion once more in recent history, which resulted in Gravesend Bay's Point A shoreline measurement dropping down from 1,616 m in 2015 to 1,477 m by 2020.

Jamaica Bay went through the same form of coastal change to a lesser degree for its Point B measurements. Jamaica Bay specifically experienced this in the years 2020 and 1933. For Jamaica Bay's Point B measurements, the shoreline recedes from 326 m in 1892 to 238 m in 1933. Over the course of 41 years, only 88 m of shoreline have been eroded or 2.1 m of shoreline erosion per year within that time frame. Jamaica Bay's Point B measurements incur shoreline erosion again in the year 2020. However, the decrease in shoreline for this timeframe was more significant. When the shoreline was recorded in 2015, Jamaica Bay's Point B measurements depicted a continually expanding shoreline of 912 m. The next time the shoreline was recorded, for the year 2020, the shoreline eroded severely, decreasing 277 m to 635 m. This sudden decrease in shoreline measurements equates to the shoreline eroding at a rate of 55.4 m per year over the 5-year time span. For Jamaica Bay's Point A side, erosion occurs in 2015 and 1974.

4.4.2. Gravesend Bay & Storm Data Analysis

Gravesend Bay experienced significant change in the past 40 years. From 1934 to 1974 there is consistent accretion, especially on the Point A side. This accretion is correlated with an increase in documented storms, though these results contradict the hypothesis that severe storms caused erosion (Figure 15). The limited number of storms recorded from 1892 to 1934, prevent the attributing of erosion in Point A to severe storms. Figure 15 also depicts the increase in documented severe storms following 1999. This however overlaps a period of shoreline stabilization beginning in 1974. While there remains moderate shoreline movement following 1999, it is inconclusive if this is related to severe storms.

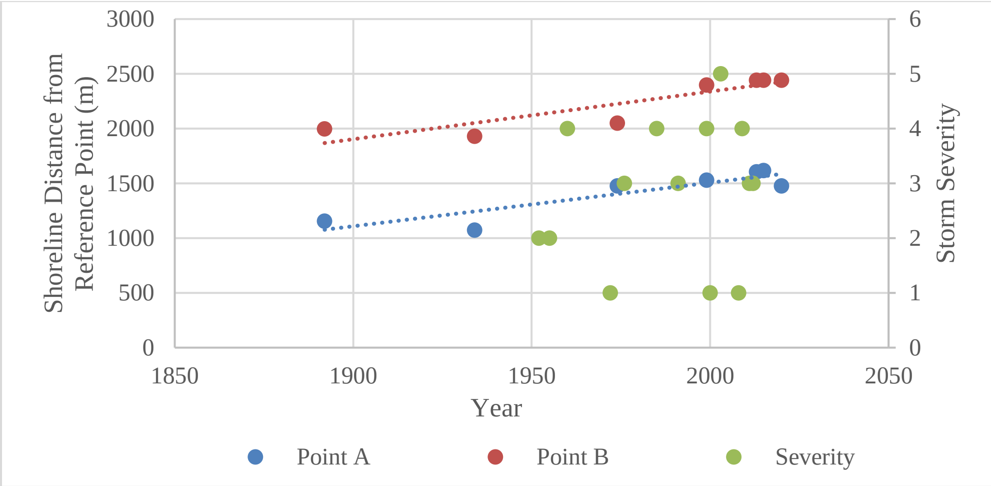


Figure 15. Gravesend shoreline measurements with storm occurrences and their severity between 1890 and 2020.

4.4.3. Jamaica Bay & Storm Data Analysis

As opposed to the Study Site #1, both the two measurement points in Jamaica Bay recorded consistent results, with only slight differences over the years. Figure 16 depicts that both points are consistently accreting over time which correlates with an increase in both storms and storm severity. As with study site #1, this contradicts the study's hypothesis that extreme weather contributes to erosion. It is possible that some of these severe storms may have brought a surge which resulted in accretion, but it is more likely that these changes are due to city efforts to extend the shoreline.

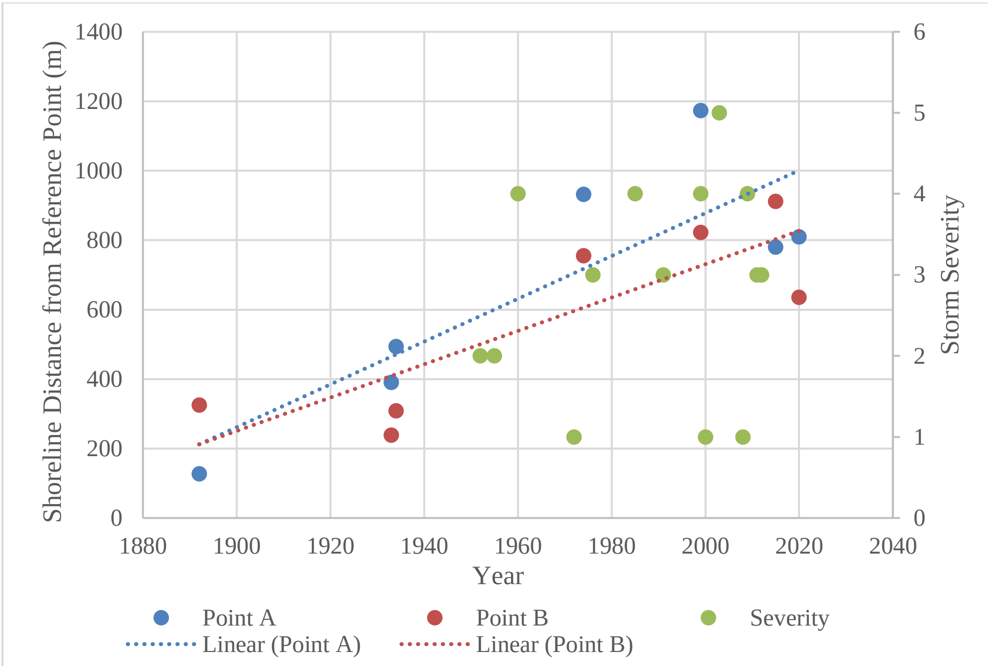


Figure 16. Jamaica Bay shoreline measurements with storm occurrences and their severity between 1890 and 2020.

Chapter 5 Discussion and Conclusion

This chapter discusses the questions this research was designed to answer:

1. Can nautical T-sheets/historical data be used to map out/analyze the shoreline? Yes, T-sheets can be used to quantify shoreline change over time.

2. How has the shoreline of these two study areas changed over time? In all cases, shorelines have expanded gradually with limited periods and locations of erosion.

3. Did the increasing number of storm events cause shoreline erosion or accretion? While increasing severe weather has impacted the shoreline from storm surges and sea level rise, human efforts at shoreline expansion have played a more significantly role.

5.1. Using T-sheets for Shoreline Analysis

Nautical T-sheets/Historical Shoreline Surveys are the primary source of data for this research. The transformation/digitization of these T-sheets consumed the initial phase of this project, converting the T-sheets from JPEG and TIFF files into shapefiles. These T-sheets enabled measurements of the city's historic shorelines. Unfortunately, only seven time periods were available. It is unclear if these records exist, but are not present in the NOAA archive, or if there were no shoreline surveys conducted outside of these years. This is a finding and disappointment in this study as these records offer more than just shoreline surveys, but also a great deal of history. From the research and discovery phase of this thesis, these historical shoreline surveys were foundation for which this project was built upon.

5.2. Measuring Shoreline Changes

To manually delineate the shorelines, the measure tool of ArcGIS Pro became an integral part of this thesis. This tool enabled the accurate and consistent measurement from one reference point to a shoreline without limitation. Upon completion of the data gathering, it was apparent that all study sites and points were accreting. Expansion of the shoreline was occurring throughout the century, and not erosion as initially hypothesized. There were instances of shoreline erosion, however it was not a frequent occurrence. Many studies described in Chapter 2, such as Hartig et al. (2002) supported this project's initial hypothesis. Hartig et al. described shoreline erosion in New York as prevalent, specifically in Jamaica Bay. Shoreline erosion/salt marsh depletion has been reportedly occurring in Jamaica Bay since the early 1900's. Gravesend Bay/Study Site #1's measurements showed a consistent general trend, as did Jamaica Bay/Study Site #2. Even though these two study sites are in close proximity, the two bays lead into differing bodies of water. Gravesend Bay is part of New York's Lower Bay which leads into the Hudson River. Jamaica Bay leads out into the Atlantic Ocean. It is unclear as to whether or not the study sites' localities played a role in their results.

5.3. Causes of Coastal Change

The Gravesend Bay/Jamaica Bay project documented consistent accretion over time. To understand why accretion, as well as small amounts of erosion happened, shoreline measurements were compiled along with storm severity. This was organized in section 2.1 describing factors in coastal geomorphology. Most of these factors are related to climate and weather, such as wind and seasons. Storms are forceful and a driving impact in coastal movement, they were hypothesized to be a primary factor in coastal change. This hypothesis was supported by anecdotal evidence due to Superstorm Sandy's persisting impact on New York City.

As Chapter 2 describes, shorelines can either expand or recede with their movement being dictated by beach dynamics. It was hypothesized that storm events would cause coastal erosion. However, Chapter 2 also discussed that while coastal erosion can be caused by storms, storms can also cause the opposite shoreline movement, called accretion through overwash. During a storm, strong winds are produced, and waves pick up more sediment than usual. If a storm surge is present, it then can carry a large gathering of sediment inland, into the dunes or seaward towards the waves. The sediment of the shore is then eventually washed up on land, in which it then reshapes the beach. This is especially true when there is a significant amount of time between storm events as the beach or shore has time to recover. The instances of erosion that were recorded, involved the sediment being taken away from its source and distributed elsewhere.

While storms and shorelines naturally interact in a dynamic way, other factors intervene. One factor often overlooked is time. A shortcoming of this project was the inability to immediately record or retrieve a record of a shoreline immediately following a storm. The closest sets of data retrieved through this project were the shoreline survey/T-sheet for the year 1974, two years after Hurricane Agnes, and the shoreline survey that was conducted in 2013 following one year after Superstorm Sandy. This complicated the understanding of the impact storms of this past century had on the shoreline. Other factors likely intervened between the storms and subsequent measurements.

Another contributing factor is human impact. As mentioned in Chapter 1, New York City's bays were used for trading since colonial times. The dredging of shores for transporting and exporting goods in New York City, was a frequent occurrence until the mid-1900's. Historical use of the city's coast for trading coincides with the earliest shoreline measurements, the erosion recorded in Gravesend Bay between the years 1892 and 1934. It is possible that human impact could have been cause for those instances of erosion. However, as mentioned in Chapter 2, human impact can also cause accretion.

During the earlier part of the century, bays were built-up, extended outward for ease of trading. It is very possible that human impact was responsible for both the accretion and erosion of Gravesend Bay. This theory is also consistent with Jamaica Bay. Its earliest shoreline measurements, representing the years 1892, 1933, and 1934 respectively, are the lowest measurements for the study area. The site then shows continuous and gradual accretion. Therefore, humans may have caused accretion by building up the bay over time for the importing and exporting of goods. Humans may have also caused accretion by conducting beach nourishment, as a restoration effort post-storm, or if the coast was lacking sediment in general. The construction of structures, such as jetties and beach groins which are present along parts of Jamaica Bay and Gravesend Bay, may have caused either form of coastal change.

In Chapter 2, the New York State Department of Environmental Conservation was cited for the organization's explanation of climate change and its impacts on New York City. Among those changes listed were sea level rise and increased precipitation rates. These changes are due to human activity causing the planet to become warmer. The planet becomes warmer than usual through the emission of carbon into the atmosphere which depletes the ozone layer, raising temperatures and therefore sea levels. Rising sea levels lead to shoreline erosion. Climate change is also linked to more frequent and severe weather events, which may explain the increase in storms used in this thesis' analysis. Specifically, within the past twenty years, more storms occurred than the rest of the study period, 8 to be exact. Only 2 of those 8 storms were weaker than a category 3. The pattern of stronger and more frequent storms is reflective of climate trends changing for the worse.

5.4. Future Improvements

There were several areas for future improvement. Because of the limited number of historic shoreline surveys/nautical T-sheets, there were gaps in data analysis. If more frequent coastline surveys were available, more compelling results may have been yielded. Additionally, more detailed historic maps could help clarify whether human impact or natural causes were responsible for observed accretion or erosion. Studies mentioned in Chapter 2, such as Virdis et al. (2012) and Tuan et al. (2017) had such high success rates due to the utilization of numerous, detailed shoreline surveys.

Accessible storm data was also an issue, there was only sufficient data available for storms that occurred after the 1950s. This led to an inability to analyze the role of storms in coastal changes in more cases, as the storm data never coincided with the year of a shoreline survey. An example of such is Hurricane Donna, which struck New York City in 1960. A shoreline survey was not available until almost 14 years later. If shoreline surveys were conducted immediately after a storm had occurred, different results could have been yielded and a correlation would be identified.

The other major limitation that delayed the completion of this project was the Digital Shoreline Analysis System (The DSAS Tool). The DSAS tool was expected to complete measurements of shorelines. However, repeated issues with the shoreline measurements prevented its use. It was later discovered that the tool would only work with an older version of ArcMap. Previous studies such as Kankara et al. (2014) utilized this tool as discussed in Chapter 2. Also, the shoreline analysis process would have benefited from data that contained more details such as: shore height, structures present, and sediment volume. Details such as this would improve and strengthen projects such as this one. It would have also benefitted from the inclusion of climate change data and its effects. For example, sea level and temperature readings would be beneficial for future studies.

Finally, future related projects could be strengthened through the use of more advanced geostatistical approaches such as the SLiP-SUM algorithm, which was proposed by San and Ulusar (2018). The algorithm is used for spatial uncertainty and predictive measures. Satellite imagery could also benefit future studies, being used to verify detected shorelines.

5.4.1. Sources of Error

There are several sources of error in this project. The most significant error was mistakes were made in the manual measurement of shoreline change across all time periods. In the initial phase of conducting shoreline measurements, Gravesend Bay's 1892 and 1934 measurements for Point A were recorded as negative numbers. Later these inconsistent measurements were remeasured and the author realized that the 1892 and 1934 shoreline measurements that were first measured were not taken from the reference point but a similar looking benchmark that was meters away. This is one example of how manual measurements can produce incorrect data. Anomalous calculations and measurements should be revisited to make sure there is no human-based error.

A second source of error was using the measure tool in ArcGIS Pro on T-sheets that were in a geographic coordinate system. By using the measure tool on imagery displayed in a geographic coordinate system, the curvature of the Earth is not considered. Future work should convert all imagery involved into a projected coordinate system and measure within that system. By following this step, more precise results can be achieved.

5.5. Value of Research & Future Work

New York City's sea level is expected to rise significantly over the next century. This thesis was created to explore the effects of climate change on New York City's shoreline as it serves as a guard to the people it surrounds. The study was also designed to analyze how climate change could impact the shoreline with concerns that unless climate trends change for the better, coastal changes are just one of the many types of negative environmental impacts to occur.

As evident throughout this entire project, the shorelines of the two sites have had significant changes over the past century and there may be more in the future if sea levels continue to rise. Sea level rising could lead to significant flooding. This thesis worked to better understand the shoreline, with the hope that the city could provide better protection to prevent environmental damage that has occurred in the past. The project is meant to serve as an educational tool making the city of New York and its citizens aware of the effects of severe weather events.

Climate change may lead to stronger storms occurring more frequently. Within the past twenty years New York has seen more frequent, stronger storms. The most recent being Superstorm Sandy, which debilitated both study areas and required years of rebuilding. It brought destruction to homes and the environment as massive amounts of overwash and salt marsh depletion were observed. Superstorm Sandy indicated that better protection for the city is required. For example, after Superstorm Sandy, National Grid, Brooklyn's provider of gas and other utilities reconstructed gas mains by making them all plastic and placing them further away from the shore.

As a learning tool, this project would benefit New York State's Department of Environmental Conservation and the New York City Department of City Planning as it outlines changes the shoreline has experienced throughout this past century. Future works could build upon this research to predict what the city's shoreline will look like in the future. Future work, with additional data sources, could lead to the creation of a spatial model that would predict what Gravesend Bay and Jamaica Bay will look like in the future.

Future works building off this project would contain remotely sensed, timed satellite imagery to verify shorelines of the past. It would include more details about the shoreline such as sediment content and output, height, etc. Points or images of jetties, beach groins and other man-made structures would also add more detail. The inclusion of more detail would help enable more advanced measurements, producing a more complex and accurate map and analysis. Finally, a future work could focus on the salt marshes of Jamaica Bay, observing and discussing their depletion over the course of time. This future work would need more historical data and it would ideally include more climate and weather-based factors.

5.6. Conclusions

Due to the duration of the digitization phase, a hindrance occurred in this project's research progress. However, after the shoreline surveys were uploaded to ArcGIS Pro and the shorelines were measured from their respective origin points, it became apparent that the coast was moving. The shoreline was moving in primarily one direction – outward. It was expanding except for a few occasions in which the shoreline regressed. This was contradictory of what was initially hypothesized to be the main movement of the shoreline. Once the shoreline measurement data was arranged next to the storm data, it was observed that storms could have furthered the shoreline accretion. However, the shoreline data and the storm data did not occur within similar time frames for most of the project and it was difficult to decipher if there was truly a correlation between storms and shoreline movement.

Though the Gravesend Bay/Jamaica Bay project faced setbacks and limitations, it was able to achieve its intended goals. The intended goals were: 1) digitizing historic shorelines, 2) using those historic shorelines to map out how the shoreline has changed over the past century and 3) utilizing storm data to explore if their occurrence is related to shoreline movement.

While there was a lack of a direct correlation between the shoreline data and the storm data, the two datasets did bring forth other observations. These include that most storms, at least those that were recorded, occurred during the latter half of the century. A significant amount of them were a category 3 on the Saffir-Simpson Scale or higher. The data tables and graphs show that storms may have increased the accretion process. The data also depicted that the category of a storm does not necessarily correlate with how much damage is recorded. The inflation calculations that were conducted for the storm data revealed some storms that were of the highest category, did less damage than those that were considered a category 1.

This study's recorded shoreline changes and the growing occurrence and strength of storms point to the dynamism of New York's coastline. Future work could include additional details which could lead to the creation of a detailed spatial model depicting shoreline movement and sea level rise. This spatial data and model would help make New Yorkers aware of how dynamic their shoreline is and how their actions impact the shoreline, whether directly, or through contribution to climate change.

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