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Wind, Waves and Surge: An Analysis of the Movement and Post-Storm Recovery of Bushy Point Beach in Groton, CT

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Abstract

Barrier beaches are highly dynamic systems that respond to variations in wave energy, increases in storm surge heights and changes in relative sea level. Bushy Point barrier beach is a barrier spit located in Groton, Connecticut, and is one of the last unconstrained barrier systems in the State of Connecticut. Since 1934, the morphology of the beach has been changing in response to storm events as well as the local rise in sea level. On September 21, 1938, a category three hurricane made landfall in southern New England and devastated many coastal communities, including a summer community on Bushy Point barrier beach. More recently, the storm surge generated by Hurricane Sandy on October 30, 2012 also caused over-wash and significant retreat of the barrier spit. In order to create a history of the beach's movement, multiple elevation transects were performed in 2012, 2013 and 2014, sediment samples were collected and analyzed, and data from multiple previous elevation surveys taken in 2003 after Hurricane Isabel and 2007 after Tropical Storm Noel was mapped. Additionally, five new survey locations were added to the original collection of data, in order to determine profile changes down the length of the barrier. These profile measurements coupled with Geographic Information Systems (GIS) mapping and analysis of historical photographs demonstrate that Bushy Point barrier beach in Groton, Connecticut is moving inland at a rate that directly corresponds with the number of over-wash events associated with storm surge. The system is moving inland at higher rates at different points on the barrier, the highest rates being at the east end near the Bluff. The vulnerability of the east end of the barrier is directly related to the established energy regime of the barrier system, which incorporates fetch, sediment size, and prominent wind directions during major storm events. Sea-level rise due to anthropogenic climate change is causing a significant upward shift in high water levels during storms, and will continue to increase in the vulnerability of these coastal systems to be over-washed and pushed inland.

Key Words: Barriers; storm surge; climate change; sea-level rise; hurricanes; Bluff Point

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1.0 Introduction

Barrier beaches are highly dynamic geologic systems. The movement of these systems is visible on a human time scale as well as a geologic time scale, making them fascinating subjects of study. Barrier systems are found where sediment is abundant, and are especially common along the east coast of the United States from Florida to the southern shore of Long Island for this reason. These systems are highly sensitive to rising sea levels as well as storm events, and respond to changes and adjust to new conditions by shifting inland.

There are three different types of barriers, which include welded barriers, barrier spits and barrier islands. Barrier spits are attached to a headland on one side and end in a point in a bay, or river. Barrier Islands are detached on both sides, whereas welded barriers are anchored by bedrock on both sides of the system. All barrier systems have some type of lagoon or marsh on the inland side, and these lagoons and marshes act as a buffer between the beach and the uplands further inland (Davis and Fitzgerald, 2004).

The south coast of Connecticut is unique in regards to the formation of barriers. Because the area was once glaciated, it lacks the abundant sediment supply that is present to the south of Long Island on the east coast. The Connecticut coast is a rock dominated, relatively low-energy coastline and barrier systems are location specific to where sediment is available. Sediment is locally abundant in the form glacial till and fluvial glacial materials present in the restricted valleys that once were the pathways for glacial melt-water (Lewis and Digiacomo-Cohen, 2000). There is an abundance of research in regards to how barriers develop and respond to physical changes in areas of high energy and abundant sediment supplies, mainly south of Long Island. This thesis will explore a location specific barrier system that is experiencing physical changes through its response to both sea-level rise and storm energy in similar ways to its higher energy counterparts south of Long Island, even though its location is in a sediment restricted, lower energy environment. Barrier movement in southeastern Connecticut is episodic, and rate of barrier retreat inland is directly related to the height of storm surges associated with different storms. Based on a number of factors related to fetch, location along the beach and dune height, certain sections of barrier are more vulnerable to over-wash and barrier rollback than others.

Due to its status as a protected reserve, Bluff Point and Bushy Point barrier beach cannot be developed. This makes Bushy Point barrier beach an interesting site for study, because it is free to migrate in its natural state. Somewhat identical to Bushy Point beach and only a few miles away is Groton Long Point. Due to its status as a housing development providing homes for roughly 5,000 people in the summer months, the barrier has been kept in place with sea walls. Constrained from its natural movement, Groton Long Point features steeper beach profiles than Bushy Point barrier beach with a higher potential for beach erosion (Campbell 2003, Serafin 2007).

Over the past century, the morphology of the barrier beach has been changing in response to storm events as well as the local rise in sea level. On September 21, 1938 a category three hurricane made landfall in southern New England and devastated many southern-facing beach dwelling communities. This storm alone caused 488 deaths and nearly 330 million dollars in property damage (American Red Cross, 1938), which translates to $6,325,000,000 in 2014 (NOAA, 2014). It was the greatest damage to property that has ever occurred in a single storm in the United States up until that time (Brooks, 1939), and as of 2015 has still been one of the worst storms to hit the area. According to the American Red Cross 93,122 families suffered property loss of significance, including 6933 summer dwellings on the south coasts of Rhode Island, Southeastern Massachusetts and Connecticut that were destroyed by surge and wind. One of these communities was a long stretch of summer cottages on Bushy Point barrier spit. After the storm washed away the community of summer dwellings, it was decided that the houses should not be rebuilt on the barrier spit or on the nearby rocky headland known as Bluff Point.

Recently, efforts have been made to restore local dune grass species on the relatively barren Bushy Point beach. Numerous tropical systems and large scale extra-tropical systems called nor'easters have affected the study area over the past century and have caused changes in the beach in less drastic, yet similar ways. The purpose of this study is to use Bluff Point barrier spit in Groton, Connecticut as a proxy to study the post-event recovery of barrier beach systems on the coast of Connecticut, a somewhat unique location to support the development of barrier beaches.

Bushy Point beach is important to study because it is one of the last untouched barrier systems in Southern New England. Many of the barrier systems along the south coasts of Rhode Island, Connecticut, and especially south of Long Island have been developed, requiring constant replenishment and mass scale evacuations during storm events. If Bushy Point beach can be used as a template to gain insight to how barrier systems behave naturally in this area, that knowledge can then be used to protect properties and lives on developed barriers with similar energy regimes.

The IPCC (Intergovernmental Panel on Climate Change) estimates that the mean global sea level has risen on average about 1-2 mm per year in the 20^{th} century alone, and will continue to rise due to an increase in average global temperatures since the Industrial Revolution of the late 19^{th} century (Van Alast 2006). Most recent studies indicate that sea-level rise is beginning to accelerate, and may approach rates experienced in the early and mid-Holocene periods (Masselink and S. van Hereten 2014). At the tidal gauge near New London Ledge Light (west-southwest of the study area) the mean sea level has been calculated to have risen 2.25 mm/yr +/- 0.25 mm at a 95% confidence interval between 1938 and 2014 (Connecticut Department of Energy and Environmental Protection 2013). With roughly 55 percent of Americans living within fifty kilometers of the US coast (Davis and Fitzgerald, 2009), this change in sea level is an important factor affecting many homes, businesses and lives that have found their place at the fringes of the continent.

When a barrier is washed over due to a storm surge or high wave action, sand on the beach face is transported to the upper dunes or in some cases, to the backside of the barrier (Serafin, 2009). This creates a system where sand is constantly moving down the length of the beach face due to natural littoral drift, and across the beach face to the dunes and backside during storms and wash over events. Due to the law of conservation of mass, sand cannot disappear as it is eroded from the beach face but is instead transported to different places in the littoral zone both seasonally as well as in response to longer duration changes in natural conditions. This constant movement is also part of the beach's response to a rise in sea level and increases in wave energy associated with the energy of a nearby storm system. Since a rise in sea level will increase the number of overwash events, the beach responds naturally by shifting itself landward through a net movement of sand particles from the beach face to the backside of the beach (Davis and Fitzgerald, 2004). The beach will continue to move inland naturally until it hits rock and ceases movement, or more commonly until it hits a sea wall or shoreline development, and needs to be replenished (Serafin 2009). In Connecticut, this most commonly occurs when a beach exhausts its current sediment supply and develops a source out of the nearby bedrock and overlying till.

Bushy Point beach was chosen for study because of its undeveloped nature, being able to fully respond morphologically like barrier spit should in its natural state. By performing multiple elevation transects, taking sediment samples, and mapping data from multiple previous elevation surveys taken in 2003 after Hurricane Isabel and 2007 after tropical storm Noel, a 10-20 year history of the beach's movement in response to major storm events during that period can be effectively pieced together. Five new survey locations were added to the original collection of data, in order to determine the movement and development of the system as a whole. These new measurements, coupled with GIS mapping of historical data demonstrate that the rate of inland movement of the system changes throughout the length of the barrier. Bushy Point barrier spit in Groton, Connecticut is moving inland at a rate that directly corresponds with the number of over- wash events, and that the system itself is moving inland at higher rates at different points on the barrier. Locations along the barrier that are closer to Bluff Point to the east are more vulnerable to overwash, therefore are moving inland at a faster rate than other locations further away from the Bluff. The vulnerability of certain areas of the barrier is directly related to the established energy regime of the barrier system, which incorporates fetch, sediment size, and prominent wind directions during major storm events. The data collected at this site for this study will be used to demonstrate how the beach responds to storm-surge, that this response is event-driven, and that the certain sections of the barrier are more vulnerable to overwash than others.

2.0 Background

Coastal dynamics, especially those along a rock dominated coast that is relatively sediment starved, can be an extremely difficult topic of study. Many interrelated forces are involved in the formation of shorelines, with each location requiring a slightly different formula to connect these complex energies. Factors such as tectonic setting, prominent wind and wave directions as well as their magnitudes, and sediment type are just a few of the elements used in describing a coastal setting and why it responds the way it does. Understanding these factors as well as those that directly affect Connecticut's beaches is the key to drawing conclusions about these particular systems, specifically Bushy Point beach.

2.1 Geologic History of Connecticut and Long Island Sound

The geologic history of southeastern Connecticut can be grouped into a series of compression and tension events due to the formation and separation of continents, followed by glacial advance and retreat (Ritter, 2002). The bedrock foundation of the landscape was built from west to east over the course of four tectonic collisions (Lewis, 2014). When the continents were coming together, an island arc system called Avalonia accreted to the side of the North American Continent, being separated by the North American Continent by Iapetos Ocean Terrane (Ritter 2002). Avalonian Terrane now makes up southeastern Connecticut, Rhode Island and parts of the coast of Massachusetts. Every time there was a collision of continents, rock was heated and metamorphosed. Metamorphic rock can be found in much of Southeastern Connecticut and parts of Rhode Island, providing evidence of the superheating of rock during multiple historic collisions of continents.

The Mesozoic era (roughly 250-67 million years ago) is characterized in Connecticut bedrock through extensional faults that were formed as the continental crust stretched and led to the eventual formation of the Atlantic Ocean (Lewis, 2014). Many of these faults along with the main rift system can still be found today in the state of Connecticut. Today, the rift system is known as the Connecticut River Valley, or the Central Valley/Pomperaug Basin (Lewis, pers. Communication 4/2014). Rifting systems bring with them trace amounts of volcanism, evidence of which can still be found in the river valley within the patterns of rock. Faulting is found throughout the state, the majority of which is going in the same direction, providing further evidence of the split (Stone, et.al, 1988). Accretion from west to east is responsible for both the north/south grain of bedrock in the state of Connecticut and its coastline. These ridges are still visible in the north-south bedrock promontories that make up much of the coast (Lewis, pers. communication 2/2014). These ridges of resistant rock form many of the hills in the state, whereas the valleys would have been the more easily weathered rock or fault and fracture zones. These valleys now form the north-south drainage pathways.

2.2 Barrier Systems

Barrier systems account for roughly 15 percent of the world's coastlines (Ritter, 2002). The coastline of the United State alone is comprised of 3,100 km of barrier systems, topping India at 680 km, the North Sea and Europe at 560 km and Eastern Siberia at 300 km of barrier coasts (Davis and Fitzgerald, 2009). Barriers are found along coastlines where sediment is in high abundance. They occur along passive tectonic margins where wave energy favors sediment accretion. Barrier systems also occur where sediment is locally abundant, the Connecticut coast being an example of one of these places. Sediment sources for barrier spits vary with geologic setting. Sources include materials eroded from nearby headlands, glacial till, and biogenic material. In the case of Bushy Point beach, the primary sediment source is material left behind by glacial meltwater flows which formed a delta into Glacial Lake Connecticut.

Barrier spits respond readily to increases in wave energy associated with storms (Komar, 1998). Barrier beaches are important to coastlines because they act as a natural breakwater to protect vulnerable coastal areas from coastal flooding. Because of their high importance, the migration and changes in the morphology of barrier beaches causes a significant threat to low lying and fragile salt marshes on the coastal plain as well as vulnerable infrastructure. Delicate systems such as salt marshes and lagoons depend on the natural breakwater for protection, and are highly affected by the migration of barrier systems. Although much has been discovered about the morphology of beaches and their natural responses to changes in energy and sea level, an exact formula for barrier system aggradation, retreat and erosion is still not fully understood by coastal geologists (Williams et al., 2011).

Welded barriers feature a rocky headland on both ends of the barrier beach with a saltwater or brackish water lagoon on the landward side of the beach whereas barrier spits are bound on one side by a headland or bedrock promontory and on the other side by a bay or river mouth. Welded barriers and barrier spits are sensitive to sea-level rise (Davis and Fitzgerald, 2009), and are common on glaciated coasts where sediment supply is localized, such as the coastlines of Connecticut to northern New England, southeastern Canada and Nova Scotia (Masselink and Hughes, 2003). Because of the lack of available sediment in Long Island sound, the coast of Connecticut differs from its counterparts south of Long Island. Due to glaciation, the coast is relatively sediment stripped and primarily rock dominated. Where there is enough sediment to support barrier development, it is usually in the form of barrier spits that are growing and developing primarily from east to west (Lewis, personal communication 3/2014).

Barrier beaches on the coast of Connecticut are a unique class of systems. They work on a limited sediment budget, and their sediment supply is often cut off by the presence of bedrock headlands. The development of a sediment budget can often provide an explanation of what is causing erosion of a system (Komar, 1998). The law of conservation of mass states that mass cannot be created or destroyed. Sediment moves laterally down the length of a barrier in a process called longshore drift (Figure 2.2), and can be transported across a barrier system in events where the beach is overwashed by a storm surge. The main sediment source for Connecticut's barrier systems is glacial in origin, coming directly from meltwater deposits during glacial retreat. Sediment was transported through natural north-south depressions in the Connecticut landscape formed by plate tectonics and was deposited into Glacial Lake Connecticut as a glacial delta (Lewis and DiGiacomo-Cohen 2000). For this reason, barrier systems along the coast of Connecticut are most commonly found in isolated pockets rather than in widespread areas of shoreline, making them a rare find and unique to their tectonic setting.

2.3 Waves

Waves are one of the major factors in changing the morphology of a beach system. There are three classifications of waves that strike beaches. The first, spilling breakers tend to occur on beaches with low slopes with steeper waves. These are considered depositional because they tend to create a net movement of sediment from the breaker zone to the beach face. The second type of wave is the plunging wave, which is more common on steeper beach profiles and beaches of intermediate steepness. These waves dissipate their energy in a more concentrated area, and plunge downward abruptly, causing this type of wave to be the most erosive. The third type of wave is the surging wave, which peaks just before reaching the beach face, but instead surges up the beach face in a way that the crest quickly dissipates. Surging breakers tend to occur on beaches of high steepness with low energy waves (Komar 1998). Patterns of surf and wave energies are dependent on the shape of the beach profile, and can then cause changes in the beach profile. Beaches that have gently sloping profiles will create an environment for a uniform distribution of energy along the surf zone. If the profile is uneven and jagged, the waves will break over the shallow area of the surf zone and will build up over the deeper areas of the surf zone profile, creating a more complex energy distribution (Komar 1998).

When waves approach the coast, their shape and mechanics are influenced by subtleties in both the near-coast continental shelf and the shoreline. Wave geometry is a function of water depth (Komar 1998). Because changes in depth can be related to irregularities in the local shoreline, waves have the ability to slow down and bend in order to orient themselves to the shape of the irregular shoreline. This process is known as wave refraction (Ritter 2002). Wave refraction can cause different amounts of energy to focus on different parts of the shoreline, creating an energy imbalance along the length of the beach. Due to the fact that coastline irregularities depend on both tectonic and geographic setting, the energy dispersion will vary from place to place (Komar, 1998).

2.4 Tides

In Long Island Sound, water is constantly in motion due to daily sea-level fluctuations that are area specific and known as tides (O'Donnell, 2014). Tides exist because of an imbalance between gravitational and centrifugal forces on the earth's surface and earth's interactions with gravitational fields of the sun and moon. The distance between the moon and earth is less than the distance than the center of masses, which creates an imbalance of forces. If these distances were the same, the gravitational pull the moon has on the earth and the earth on the moon would be the same. However, because of this imbalance, the moon has a gravitational pull on the earth's oceans as the earth rotates (Davis and Fitzgerald, 2009). This creates a bulge or wave of water on either side of the planet that moves over the planet as it rotates. If the crest of this wave is over a certain area, it would be high tide, whereas if the trough was over this same area, it would be low tide at that location.

The sun also has an effect on daily tides. Much like how the moon has a gravitational pull on the earth's water due to its close proximity to the earth, the sun has a gravitational effect on the earth's tides due to its high mass. Both relationships can be determined from Newton's equation of universal gravitation (EQ 2.1):

$$F = G\frac{m_1 m_2}{r^2},\ G = 6.67 \times 10^{-11} \qquad \text{[EQ 2.1]}$$

This formula indicates that an increased mass will have a significant effect on gravitation if placed at the same distance as an object with smaller mass. For this reason, the sun can still have an effect on the earth's tides because it has a high mass.

Tides occur in cycles and can be diurnal, where high tide and low tide occur once a day, semi-diurnal, two cycles a day, or mixed, where both occur. Tides will not occur exactly every twelve or six hours of each other. Since the moon has a period of 27.3 days, and the earth has a period of 24 hours, there is a discrepancy between the lunar cycle and earth's rotation cycle. For the earth to compensate for this difference, it must rotate for an additional 50 minutes. Therefore, high and low tides in diurnal settings will occur every 12 hours and 25 minutes, whereas tides semi diurnal settings will occur every 6 hours and 13 minutes (Davis and Fitzgerald, 2009).

Solar and lunar interactions with tide at the same time create two events called spring and neap tides (Masselink and Hughes, 2003). A spring tide occurs when the moon is positioned between the sun and the earth, creating a dual gravitational pull from both the sun and the moon. Spring tides are considered local extremes of tides, creating extreme high tides as well as extreme low tides. A neap tide, on the other hand is when the earth is at a 90 degree angle to the sun and moon, and will experience tides at very low extremes, because the sun and moon's gravitational pull is not in sync (Davis and Fitzgerald 2009).

Tides will produce variations in the width of the surf zone, the area of impact of waves on the beach face, and the extent of beach that is considered surf zone (Campbell, 2004). This will impact the amount of erosion and water-driven sediment movement that occurs on sandy beaches such as Bushy Point beach. The daily tidal range influences the natural area of impact of waves on the beach and is site specific.

2.5 Storm Surge

Storm surges are driven by a combination of two forces involved in storm activity: decreased barometric pressures and wind. Lower pressures over a large area of water will cause a buildup of water that will move with the storm as it moves. The second and most important factor that causes storm surge is wind. Strong winds that travel over a large area of water have the ability to cause a buildup of water that is directly caused by the storm (Masselink and S. Van Heteren, 2014). This is the reason that storm surges are more severe in the eastern quadrants of cyclonic systems that strike New England, because the forward velocity of the storm is added to the wind velocity of the cyclone creating a potential for greater wind-driven effects. Local geometry in coastal features and continental shelves can cause and amplification of storm surges. For example, the gentle slope of the shallow continental shelf south of Long Island causes an increase in the storm surge severity as water is pushed upward and built up on the shelf (Coch, 1992). The shape of Long Island also makes it vulnerable to increased effects of storm surges.

2.6 Tropical Systems

Tropical systems, known as tropical storms and hurricanes, are low-pressure systems that spin counterclockwise and form just north of the equator in the tropical waters off the coast of Africa, the Carribbean, and the Gulf of Mexico. Hurricane season starts in June and ends in late November. However the strongest storms are normally seen through the months of July, August and September. In New England, tropical systems are most commonly experienced in late August and September. Along with the warm tropical waters, hurricanes need vertical instability in the atmosphere in order to develop and grow into a large-scale low-pressure system. Most of the storms start as low-pressure waves coming off the coast of Africa, or start as thunderstorm convection in the tropics. From there they intensify based on whether or not atmospheric conditions are favorable. Favorable atmospheric conditions feature low wind shear, high humidity and high vertical instability (Williams and Sheets, 2002). These storms last on average nine days, peaking in August when storms can last up to twelve days. The storms will last as long as they are over warm water and in a humid environment that acts as an energy source. Hurricanes will lose energy if they come into contact with colder water, or make landfall. The friction of land slows the storm down and makes it unable to intensify any further by cutting off the storm's energy supply (Lemons, 1957). Storms of similar characteristics that are found in the Pacific basin are known as typhoons.

The formation of hurricanes due to vertical instability in the atmosphere in the tropics can be different depending on which month you look at (Williams and Sheets, 2002). In September, the air lifted into the upper levels of the atmosphere is warmer than the surrounding air, leading to a high level of instability in those upper layers of the atmosphere. Taking the month of

February as a comparison, this level of instability is lower, because the temperature of the rising air approaches the temperature of the sinking air (Palmen, 1941).

Hurricane strength is explained through a ranking system called the Saffir-Simpson Hurricane Strength scale (Table 2.1). According to the Saffir-Simpson scale, an organized low-pressure system reaches tropical depression status when its sustained winds reach 25 miles per hour. It reaches tropical storm status at 39 miles per hour, and officially becomes a category one hurricane when its sustained winds top at 74 miles per hour. A major hurricane is a classification for a storm of category three status or higher. These massive storms occur two to three times per hurricane season on average (Williams and Sheets, 2002), and have proven themselves to be highly destructive forces of nature.

Table 2.1: The Saffir-Simpson Hurricane Strength scale is defined in the following table. Categories of storms are based on wind speed and surge height. Major hurricane status is given to storms reaching category 3 or higher.

Saffir-Simpson Scale

Status	**Wind Velocity (mph)**	**Surge Height**	**Destruction**
Tropical Depression	25-39	----	Minimal
Tropical Storm	39-74	1-2 feet	Minimal
Category 1	74-95	4-5 feet	Minimal
Category 2	96-110	6-8 feet	Moderate
Category 3	111-130	9-12 feet	Excessive
Category 4	131-155	13-18 feet	Extreme
Category 5	155+	19+	Catastrophic

The formation of tropical storms and tropical depressions is highly driven by sea-surface temperature. Years where there are higher sea-surface temperatures, especially in the middle to northern latitudes, there will be a greater chance that hurricanes will reach major hurricane status further north of the equator. Increased temperatures in the middle and upper latitudes will also increase the chance that a major hurricane will come up the coast without losing its energy over cooler waters, which is what usually happens as storms make the turn north. Nevertheless, the direct relationship between increased sea-surface temperatures associated with global climate change and frequency and intensity of hurricanes is uncertain (Masselink and S. van Heteren, 2014), however it is known that in 2005 the sea-surface temperatures were at record highs. The 2005 hurricane season was also one of the most intense on record, featuring seven major land-falling hurricanes (Masselink and S. van Heteren, 2014).

The early to middle part of the 20th century was a period of time where hurricanes formed frequently, many of them striking or nearly missing New England. In the 40 year period from 1916 to 1955, 142 tropical storms and hurricanes that formed in the tropics of the Atlantic made landfall in the United States, causing over $3 billion in damages (Lemons, 1957). In the period from 1925 to 1955, inland flooding was ranked as the number one most costly and deadly disaster in the United States, with hurricanes ranking at a close second. This was mainly due to the Great New England Hurricane of 1938, which caused many deaths and extensive property damage (Lemons, 1957). Since then however, tropical storm activity in the Northeast has been relatively calm, other than a few smaller storms such as Hurricane Bob (1991), which took an easterly curving track into the North Atlantic, Hurricane Gloria (1985) whose impact was dampened by its arrival at low tide (Coch 1994), Hurricane Isabel (2003) and finally Tropical Storm Noel (2007) whose storm surges and waves did not reach heights of expected values (Campbell, 2004; Serafin, 2009). These storms were significant enough to cause wind damage to homes and inland flooding, however they were not as catastrophic or as memorable as the New England Hurricane of 1938 or the Atlantic Hurricane of 1944 (Brooks and Chapman, 1945). Coch (1994) claims that this sense of complacency driven by this hurricane “dry spell” in the

Northeast has led to unprecedented population increases on the coasts of New England, putting more and more people in the path of future potentially destructive systems.

The level of intensity of a storm that makes landfall in a specific area is highly dependent on storm size, overall speed of the storm, and the angle at which it strikes. The northeastern quadrant of a storm is the most intense quadrant of the system (Palmen, 1941) due to the wind velocity that is compounded with the forward velocity of the hurricane. For example, the Hurricane of 1938 made landfall as a category three storm, however maximum sustained winds at the Blue Hill Meteorological Observatory in Milton Massachusetts, roughly 65 miles from the storm center that was making landfall, recorded a gust of 186 miles per hour, and sustained winds of 140, which is well above what a category three storm would contain (Brooks 1939). Many of the anemometers and instruments used to measure wind speeds in New England were destroyed during the Hurricane of 1938, making recordings of actual wind gusts sparse (Palmen 1941).

A storm that hits a coastline head on (considered coast normal) will cause more damage than a storm that skirts the coast (Masselink and S. van Hereten 2014). In New England, because of its geographic orientation, storms that hit the coast are likely to have coast-normal landfalls. Storms that skirt the coast are on a track that will take them into the North Atlantic, where they will lose energy and eventually turn into a remnant low-pressure system, losing their warm water energy source. At this point they will only be a nuisance to fishermen and shipping traffic in the North Atlantic, rather than a major devastating storm that struck land. However storms that skirt the coast can produce waves that erode beaches dramatically, even if the storm itself does not make a direct landfall. The waves and swell associated with offshore storms that do not have a direct impact on land can cause erosion and movement of large volumes of sediment along a particular stretch of coastline, including barrier overwash and breaching (Masselink and S. van Heteren 2014).

2.7 Nor'easters

Another type of storm that commonly affects the eastern seaboard is the nor'easter. A nor'easter is a mid-latitude low pressure system that is positioned off the coast of the New England and Mid-Atlantic regions of the United States, causing the general wind direction to be from the eastern quadrant (Hirsch et al., 1991). Figure 2.1 is a satellite image of a nor'easter that affected most of New England in December of 2010. A strong, well-developed nor'easter can cause damage comparable to that of a hurricane, and can even exceed the damage that could be caused by a hurricane (Davis and Dolan 1999). Nor'easters are much more common in the northeast than are tropical systems. They are slow moving, and have the potential to be massive. They are named for the direction of their predominant winds which blow from the eastern quadrants. Unlike tropical systems, these storms can last for many days, causing waves with longer periods that have the potential to do significant damage on a particular stretch of coastline (Zhang et al. 2001). Major nor'easters to affect the east coast over the past 100 years have been winter storms in 1969, 1978, 1991 and 1992. All four of these storms caused significant damage to the coasts of Massachusetts, Rhode Island, and Connecticut (Davis and Dolan 1999).

Much like hurricanes, nor'easters arise where the atmosphere is unstable. The storms tend to form along fronts and further develop along these boundaries between warm and cool air. Nor'easters predominantly form between the months of October and March, with February being the peak of the storm season (Hirsch et al 1991). Unlike hurricanes, these storm systems do not need a warm water source for energy. Many nor'easters form hundreds of kilometers inland and move towards the coast on frontal boundaries. It is difficult to directly compare the potential for coastal damage from hurricanes versus Nor'easters. Hurricanes occur less often than nor'easters but when they do occur, they release a great deal of energy in the form of waves and storm surge. Hurricanes and tropical systems also focus their energy, having the well-defined eye and closely packed thunderstorm convection that a nor'easter lacks. For this reason, nor'easters can affect most of the eastern seaboard at once and can hover over a coastline for days.

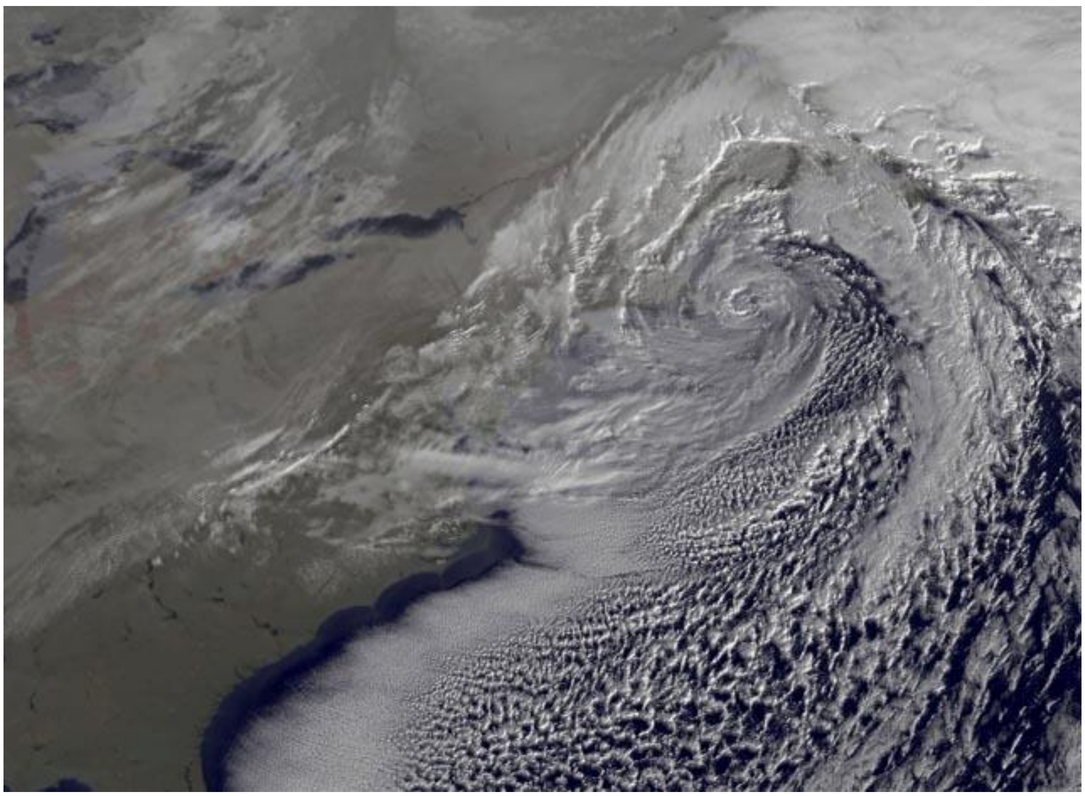

Figure 2.1: An Image of a well-organized nor'easter on December 27, 2010 as it sits over New England (NOAA).

The March 7th, 1962 storm (locally known as the Ash Wednesday Storm) contributed to an expansion of research regarding coastal responses to storm energy (Davis and Dolan 1999). This one storm was predicted to have ocean wave heights topping 10 meters well offshore. When considering large-scale winter storms that affect the east coast, Hirsch (1991) discovered that ocean wave heights of 1.6 meters or greater off the coast of New England have the potential to cause some degree of erosion to vulnerable coastlines. Waves and storm surge associated with winter storms cause the greatest potential for damage along the east coast (Zielinski, 2002).

Due to the shape of Long Island Sound and its effect on fetch, nor'easters have the potential to dramatically impact Connecticut beaches. Large swell, driven by winds from the eastern quadrant take a path through "The Race" or the channel between the western tip of Fishers Island and the eastern end of Long Island. Bushy Point beach is, for the most part, protected by the positioning of Fishers Island. However it is still impacted by the swell and storm tide created by nor'easters. This is evident by the fact that most barrier spits in Connecticut develop from east to west, and longshore drift on area beaches is predominantly from east to west (Ralph Lewis, Personal Communication 3/2014).

Ultimately, the physical characteristics of a coastline, coupled with the size and strength of the storm will determine the amount of damage received by a particular stretch of coast throughout the duration of both nor'easters and tropical systems. Different sections of a single barrier have the potential to be more vulnerable than other sections, depending on dune elevation and sediment composition. Low-lying barriers and low-relief coastal plains are more vulnerable to the wave and surge energy created by low-pressure systems than higher dunes. These vulnerable sections of barrier systems can be overwashed frequently causing a comparatively higher rate of erosion and inland movement (Williams et al., 2012).

2.8 Coastal Dynamics

Beaches are divided into a series of zones that are dominated by different energy sources (Figure 2.2). The highest elevation of the beach is called the dune, which is affected most often by aeolian (wind-driven) processes and features fine-grained sediment. Dune grass (*Ammophila breviligulata*) and sometimes salt-spray roses (*Rosa rugosa*) are commonly found on the dune and act as anchors to keep fine-grained sand in place, as well as to form dunes. Dunes on the Connecticut coastline commonly range from 50-150 feet in width, and are just over a meter in height, which are small in comparison to the widths and heights of dunes to the south of Long Island (Department of Environmental Protection, 2003). Dune height provides protection to infrastructure, lagoons and salt marshes that lie landward of the beach on the coastal plain. Lack of a pronounced dune on the east end of Bushy Point beach, closest to Bluff Point, has made this particular section of the beach vulnerable to overwash by storms (Serafin, 2009). The flattened dunes on the south coast of Long Island, New York have put many salt marshes and infrastructure at risk for inundation by storm surge (Coch, 1994).

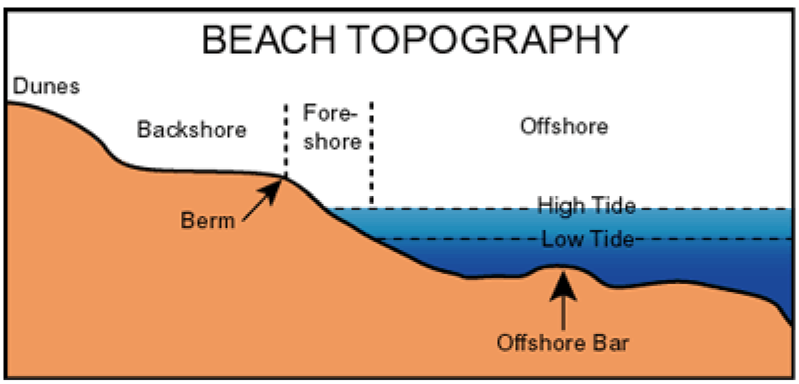

Figure 2.2 This diagram of beach topography features the dune, backshore and foreshore separated by a berm, and the offshore bar which occurs seasonally (Office of Naval Research, 2000).

The berm is the flat platform section of the beach just seaward of the edge of the dune. Berms are formed when waves transport sediment from the offshore tidal zone to the beach face (Davis and Fitzgerald, 2009). The berm separates the backshore area from the foreshore area (Figure 2.2). There can be multiple berms on a particular section of beach, separated by beach scarps. A beach scarp is a small, steep slope formed by a concentration in wave action on a particular section of beach (Masselink and Hughes, 2003). Following periods of higher wave energy, a wrack line can be found on the face of the beach, consisting of debris and larger-grained sediment that marks the high-water line of the previous high tide (Serafin, 2009). Further seaward of the berm is the beach face, which receives the brunt of the wave energy on the beach. The zone that contains the beach face, further seaward of the berm, is called the foreshore zone (Masselink and Hughes, 2003). The foreshore contains the beach face and the swash zone. The swash zone is a narrow region that extends from the edge of the offshore zone inland to the maximum point of wave action on the beach face. Further seaward is the offshore zone, which is the zone below the low tide line and can feature an offshore bar (Figure 2.2). The littoral zone is the area that encompasses the backshore, foreshore and offshore zones. The beach face is can often be steeper than the berm, depending on its sediment composition. Beach face slopes vary and respond to changes in wave energy, with steeper slopes observed during periods of high wave action and shallower slopes observed during periods of lesser wave action (Komar, 1998). The tidal zone and the breaker zone are the offshore sections of the beach which are dominated by wave and current action. Depending on the time of year, a longshore bar can be found just offshore of the tidal zone, being composed of sediment that has been transported from the beach face and foreshore to a location offshore by erosional wave action (Komar, 1998).

2.9 Beach Sedimentation

Sandy beaches are dynamic systems due to the granular nature of their sediments and the ability of water and wind to easily transport these sediments from place to place. Coastal systems are in a semi-state of equilibrium that is dependent on the grain size of the beach, the average wave height and the strength of longshore currents (Komar, 1998). Sediments can have both long-shore and cross-shore variations in size and shape. Sediment is coarsest in the swash zones, or zones where wave energy is the highest, and decreases significantly between the swash zone and the berm. The reason for this is that water is more likely to transport smaller sediments up the beach face and leave the larger sediments in the swash zone (Fox, et al., 1966 and Komar, 1998). Sediment size also decreases down the length of the beach in response to longshore currents. Similar to cross-shore variations, long-shore variations in sediment size are also wave driven. Longshore transport of smaller materials is easier than larger materials. Therefore the sediment size down the length of the beach will decrease in the direction of longshore drift (Lewis, 1938 and Komar, 1998).

Sediment movement in the surf zone on barrier beaches is determined by a series of currents that act on the near-shore environment. Currents are determined by the directions of waves along the length of a beach, and how that wave energy is passed to the beach face. Currents that act on the near-shore environment are known as longshore currents, rip currents and bed return flow. The combination of these three currents causes the majority of water and sediment movement laterally and across the shore (Masselink and Hughes, 2003).

Longshore currents (Figure 2.3) are flows of water that orient themselves parallel to the shoreline within the surf zone. These currents are responsible for the movement of sediment laterally across the beach face. As a wave approaches the beach at an angle and runs up the beach, it carries sediment with it. The return flow will also carry sediment along with the water rushing down the beach, and the angle of return flow will direct sediment movement across the beach laterally, represented by diagonal arrows in figure 2.3. Bed return flow currents occur in the surf zone as well, and pull sediment seaward in circulation. Finally, rip currents are channelized currents that pull sediment away from the shore. Wave height and surf zone energy levels strongly affect these three currents, and can in some cases create strong currents that can be hazardous to swimmers and lead to large amounts of sediment transport (Masselink and Hughes, 2003).

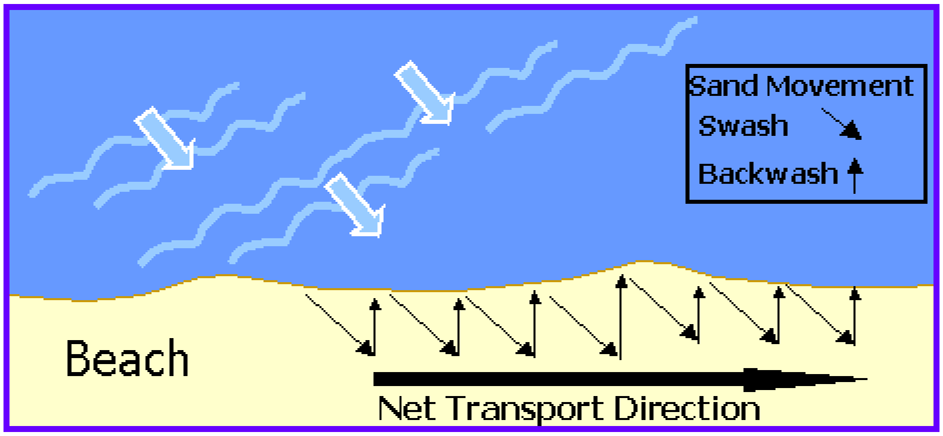

Figure 2.3: Longshore drift (longshore currents) is a wind and tide driven current that transports sediment along a beach face. The net direction of sediment transport is explained by diagonal arrows in the diagram (Texas A&M University 2014, Coastal Physical Processes)

2.10 *Seasonal and Storm-Related Profile Changes*

Barrier beaches have their own way of responding to higher energy waves that are associated with storm systems and high winds. Faced with increased wave heights, the beach responds by reducing its overall slope (Komar, 1998). This will shift the breaker zone further offshore and decrease the amount of concentrated erosion. Moving the breaker zone offshore causes waves to dissipate further offshore, so they are at their weakest state once they reach the beach face (Komar, 1998). Beach slope is determined by sediment grain size. Larger sediment sizes such as gravel-and pebble-sized sediments, will create a steeper beach face whereas smaller sediment sizes will create a shallower sloping beach face. When waves rush up a beach, there is a certain amount of energy associated with initial uprush of the wave and the return backwash, which is when the water rushes back down the beach face back to the ocean. Return backwash is weaker than the initial uprush of a wave because some of the water from the initial uprush is lost to the beach as it percolates through the sediment (Komar, 1998). Larger sediments will allow for more percolation, whereas smaller sediments will allow for less water movement through the sediment due to less space between the granules (Komar, 1998). This is essentially how wave energy is dissipated by a beach face in coastal environments.

Beach morphology is not only altered during individual storm events, but also changes seasonally. An example of an offshore bar can be seen in Figure 2.2. The presence of an offshore bar causes the beach to flatten and reduce steepness, because most of the sediment is stored offshore at that point. During these periods of time, the profile will contain very little indication of berm formation. In some cases, higher wave action will lead to cusp formations on the beach face associated backwash currents (Figure 2.4). Due to the fact that the summer weather patterns generally are indicative of lesser wave heights than the winter weather patterns, the profile of the beach will tend to flatten in the winter with the formation of the offshore bar. When the wave action settles, the offshore bar will then re-deposit during the relatively calm spring and summer months (Serafin et al, 2011). In Long Island Sound, wave action increases in the winter and decreases in the summer (Serafin et al., 2011). This is due to a difference in fetch with certain wind directions that are associated with storm events occurring in the time period from October to May, known locally as Nor'easters. In times of higher wave action, the foreshore will lose sediment and the transported material will be stored in the form of an offshore bar (Campbell, 2004).

Figure 2.4: This image shows the beginnings of cusp formation due to wave energy on a beach. Directly on the beach face, cusps are crescent shaped deposits of larger sediments (exemplified in this photograph by the darker sediments) caused by wave action. (Photograph Taken by Doug Thompson).

The height of barrier islands and barrier spits is the determining factor whether or not the system is over-washed during storm surge events. Barrier systems retreat inland and change their location significantly in response to rising sea level and storm surge. This process is called barrier rollover (Ritter, 2002). Figures 2.5 and 2.6 give an example of overwash (2.5) that leads to barrier rollover (2.6) and a net movement inland. Barrier systems have the ability to migrate over different lengths of time. This can be caused by heightened wave and surge action on the beach face that have the ability to overwash the barrier. Inland movement and change in location of the beach is associated with overwash events rather than seasonal, natural changes in the beach or the normal stresses of tide and longshore currents. These rollover events are driven by sea-level rise, but are punctuated by storm surge events. One strong storm that causes enough overwash on a barrier beach can cause meters of shoreline retreat within a short period of time (Masselink and van Hereten 2014).

Figure 2.5: A diagram of a process called overwash, which occurs when a storm surge is high enough to overtop a barrier system (University of Maryland Center for Environmental Sciences).

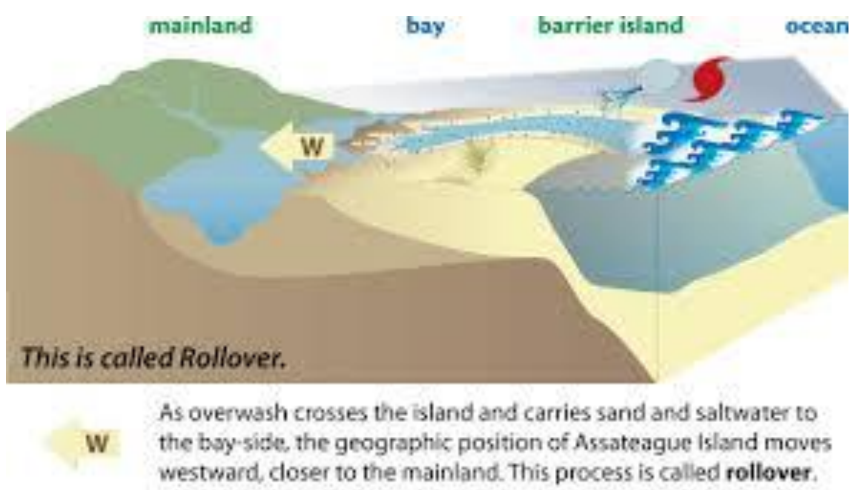

Figure 2.6: A diagram of a process called rollover, which occurs when a barrier system is overwashed. During barrier rollover, sediment from the front of the barrier is transported to the back of the barrier, causing the whole beach to physically change location (University of Maryland Center for Environmental Sciences).

2.11 Climate Change and Sea-Level Rise

Transgressive sea-level rise began after the most recent glacial advance, the Wisconsinan glacial period. This glacial period reached its peak roughly 24,000 calendar years ago and at that point began to melt off the continent as it retreated. This new freshwater source introduced enough water into the world's oceans to increase sea level roughly 100 meters on average in the past 18,000 years (Michener et al., 1997). Thermal expansion of the earth's oceans is also partially to blame for the global rise in sea level. Thermal expansion is a change in the density and volume of seawater associated with slight changes in temperature. Even if global temperatures stabilized this second, the sea level will continue to ride for the next 100 to 200 years, as thermal expansion reaches the deepest parts of the ocean due to natural ocean circulation (Michener et al., 1997).

Beaches have responded to Holocene era sea-level rise by migrating landward across the coastal plain rather than becoming submerged (Komar, 1998). This process will continue to happen as sea level continues to rise and there is still sediment to be worked and reworked in a landward direction, as long as sea-level rise does not accelerate past the point barriers cannot keep up (Serafin, personal communication 4/2015). At the beginning of the Holocene era, sea level was rising rapidly and has since slowed its rate of rise. During the time of accelerated sea-level rise, most sections of coast were moving inland rapidly through the process barrier rollover due to sea-level rise and were considered erosional, or transgressive. More recently, sea-level rise has reduced its rate, and a few sections of coast that were once transgressive have converted to regressive sequencing (Komar, 1998).

The IPCC (Intergovernmental Panel on Climate Change) estimates that mean global sea level has risen on average about 1-2 mm per year in the 20^{th} century alone, and will continue to rise due (Van Alast, 2006). At New London Ledge Light (roughly 1.5 km west-southwest of the study area), the tidal gauge indicates that the mean sea-level in this area of Connecticut has risen 2.25 mm/yr +/-0.25 mm at a 95% confidence interval between 1938 and 2014 (Connecticut Department of Energy and Environmental Protection 2013). Recent studies indicate that sea-level rise is beginning to accelerate and may approach rates experienced in the early and mid-Holocene periods (Masselink and S. van Hereten, 2014).

Worldwide climate change is expected to have a significant impact on sea surface as well as on land temperatures in many parts of the world, which many believe could potentially cause an increase in both sea level and the frequency and intensity of tropical systems (Michener et al. 1997). Ocean and atmospheric circulation are extremely fragile and complex systems. Increases in temperature and CO_2 even in small increments can have significant altering effects on atmospheric and ocean circulation (Masselink and S. van Heteren, 2014). Since ocean temperatures of at least 26 degrees centigrade are required for tropical system formation and intensification (Palmen, 1948), the argument is made that a global rise in temperature will directly correlate with an increase in the frequency and intensity of tropical systems (Michener et al., 1997) Nevertheless, recent global climate models often conclude mixed results in regards to whether or not hurricane frequency and intensity will actually increase, or remain the same (Masselink and S. van Heteren, 2014). Exactly how a global increase in temperature will adjust the intensity of tropical systems is a complex question, involving many constantly changing variables. What has been determined from recent climate models however is that slight changes in atmospheric and ocean circulation driven by temperature increases will change how meteorologists study and understand these complex weather systems (Masselink and S. van Heteren 2014).

3.0 Study Area: Bluff Point, Bushy Point Beach and Local Geologic History

Previous studies by Campbell (2004) and Serafin (2009) explain that Bushy Point Barrier beach responds naturally to seasonal as well as storm-driven changes in waves and surge heights. The spit has a specific morphological response to these events due to its orientation as well as its ability to move freely, being an unconstrained system. The previous studies by Campbell (2004) and Serafin (2009) will be referred to for their repeated transects taken at a site called Orange Stake (OS), the same site that will be used in this study.

Bushy Point barrier spit in Groton, CT has undergone a history including tectonic events, glaciation, transgressive sea-level rise, and most recently storm events that have caused coastal erosion and barrier spit development. An understanding of the site's geologic and glaciated history is necessary to make conclusions about the changes Bushy Point barrier spit is undergoing in response to wave and surge energy.

3.1 Bluff Point and Bushy Point Barrier Spit

Bushy Point barrier spit (Figures 3.1, 3.2) is one of five barrier spit formations in the area. The other three barrier systems are Groton Long Point in Groton (CT), Griswold Point in Old Lyme (CT), Napatree Point in Westerly (RI), and Long Beach near Bridgeport (CT). Bluff Point and Bushy Point barrier beach are both part of Bluff Point State Park Natural Preserve, part of a system of Connecticut state parks that features walking trails and wildlife protection areas. Before the hurricane of 1938, 104 privately owned beach cottages could be found both on the Bluff and on the barrier beach (Rafferty, unpublished). Following the Hurricane of 1938, the houses that were destroyed were not allowed to be rebuilt, and the land has remained absent of residential houses since. In 1975, almost fifty years after the September storm in 1938, the coastal reserve was purchased by the state of Connecticut as a park for public use. The Bluff Point State Park and Coastal Reserve is comprised of roughly 800 acres of protected woodland and marsh. The walk out to the beach is roughly 1.5 kilometers, mostly on trails through a wooded area alongside a saltwater lagoon (Rafferty, Unpublished). Along the trail there are many glacial boulders that were dropped by the most recent glacial advance, most of which are part of the Mystic Moraine. The Mystic Moraine runs through Southeastern Connecticut, and terminates at Bushy Point and Pine Island in the vicinity of the study area (Stone, 2005). The point is a comprised of a long, streamlined section of bedrock that has been modified by the most recent glacial period. Towards the end of the point, the path opens up to a rocky bluff at the point of the bedrock promontory, with Bushy Point barrier beach to the west of the bluff, running East-Southeast to West-Northwest ending in Bushy Point and Pine Island.

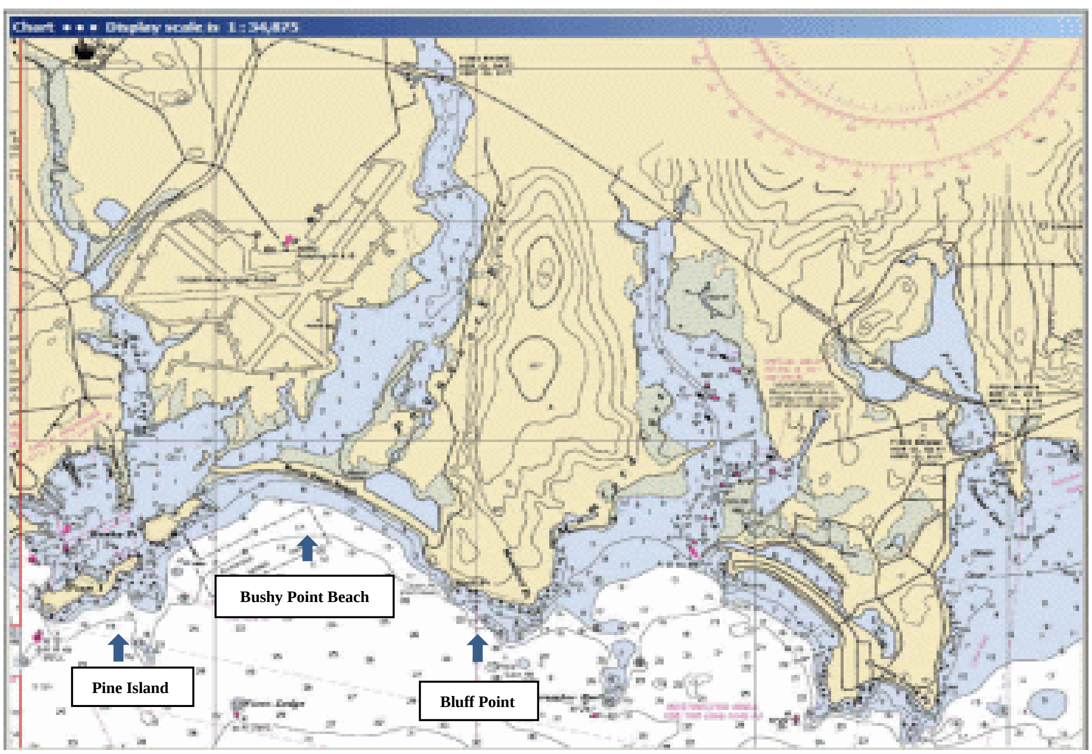

Figure 3.1: Nautical chart of the south coast of Groton, CT shows Bushy Point Beach, with Bluff Point to the east and Pine Island to the southwest on the southwest (Connecticut Department of Energy and Environmental Protection 2014).

Figure 3.2: A satellite image of Bushy Point Beach taken in 2014. To the left in the photograph is the west end of Bushy Point barrier spit and to the right in the photograph is Bluff Point. The body of water in the bottom of the photograph is Long Island Sound and the Poquonnock River can be seen in the top and top left of the image. Source: Connecticut Department of Energy and Environmental Protection.

The Poquonnock River runs north to south in southeastern Connecticut, and the river valley is only a few miles long. The river empties into Long Island Sound between Avery Point, Bushy Point and Pine Island, with Bluff Point and Groton Long Point to the east. Bushy Point barrier spit and Bluff Point lie just to the east of the mouth of the river. The Poquonnock River Valley is a south draining bedrock valley that acted as a pathway for glacial meltwater to reach Glacial Lake Connecticut. For this reason, the area to the north and surrounding Bushy Point barrier beach is a fluvial glacial delta (Lewis and DiGiacomo-Cohen, 2000). The sediment at Bushy Point barrier beach came from a variety of glacial and terrestrial sources. Glaciers brought with them the types of sediment that make up the majority of the coastline. Fluvial glacial materials (materials that were transported by glacial meltwater) and glacial till (material that was ground up and dropped by receding glaciers) are both found on area beaches. The larger types of sediments were dropped in long lines of boulders called moraines. Gravel-sized sediment beaches like Bushy Point barrier beach are common along glaciated coasts, with their sediment sources being glacial or fluvial glacial in origin (Williams et al., 2011). Other sediment sources feeding the supply on gravel sized barriers come from the erosion of nearby cliffs or headlands.

The Poquonnock River is a flood-tide dominated system (Malone and MacBroom, 1995) evidence of which is visible in a flood-tidal delta just to the north of the Poquonnock River Inlet. The amplitude of tides changes throughout Long Island Sound, in addition to resonance around the tidal node at The Race. The Race is the space between the eastern tip of Long Island to the south and Fishers Island to the north, forming a deep, narrow entrance into Long Island Sound. Due to its oblong, narrowing shape, water that is funneled in from the Atlantic Ocean builds up in the western edge of Long Island Sound at high tide. This causes the amplitude of tides to increase by almost three times as you travel from The Race at the entrance of Long Island Sound to Kings Point just outside of New York City (O'Donnell 2014). The shape of Long Island Sound makes the coastlines of Connecticut and eastern New York vulnerable to highly destructive storm surges, because water funnels into the narrow parts of the sound and is forced ashore in the densely populated New York City metro area.

Bushy point barrier beach is surrounded by two rocky headlands on both ends, one being Bushy Point and Pine Island to the west and Bluff Point itself to the east. The beach was once described as a welded barrier (Campbell 2003), but has since broken through at the western headland, causing the system to attain the characteristics of a barrier spit. The barrier-beach system protects a brackish-water lagoon, which lies just to the south of the marsh area on which the Groton-New London Airport is built. The lagoon behind the beach is partially composed of organics mixed or interbedded with estuarine silt and fine grained sand that extends to the backside of the barrier. The salt marsh organics and Poquonock River deposits that make up this lagoon extend roughly a 0.8 km inland, forming in part the flat area on which the Groton-New London airport is situated (Stone, 2005). Glacial boulders can be found on the trails leading to along the coast of Bluff Point, and especially further inland of the coastline. Glacial striations can be seen on the low lying flat rocks on the Bluff, the striations oriented perpendicular to Fishers Island, which can be viewed from Bluff Point if the observer faces south- southeast. To the south of Bluff Point is Long Island Sound, Long Island, and to the southeast directly off the coast is Fishers Island.

Figure 3.3: An image of Bushy Point beach facing Bluff Point. Photograph was taken facing southeast, with Long Island sound to the right of the photograph. Fishers Island can be seen in the distance.

3.2 Local Bedrock Formations and Quaternary Geology

Bluff Point is a bedrock promontory that strikes north to south and projects into Long Island Sound. Bluff Point and adjacent Bushy Point beach is underlain by both Alaskite gneiss and New London gneiss (Avalonian terrane), both of which are common to the surrounding bedrock geology. Alaskite gneiss is an orange pink, light tan to white gneiss, which is locally stained with iron. It is mostly fine grained, indistinctly foliated granite gneiss locally containing muscovite and sillimanite-quartz (Goldsmith, 1967). New London gneiss is light grey in color, medium to fine grained gneiss with black biotite and scattered magnetite grains. New London gneiss is found throughout the Poquonock River valley extending over into the local towns of New London and Waterford to the west (Goldsmith, 1967).

The Alaskite and New London gneisses are mantled by a layer of glacial till, deposited by the most recent glacial period (Goldsmith, 1965). Till is generally poorly-sorted sediment that is dropped directly off a glacier as it moves across a landscape, consisting of crushed rock and solid material picked up and deposited by advancing ice (Ritter, 2002). The Poquonock River deposits are ice marginal fluviodeltaic deposits in the Poquonock River valley, where small tributaries grade southward to create an extensive delta just south of the Interstate 95 Bridge in Groton (United States Geological Survey and Stone 2005). The barrier itself is composed of relatively well-sorted sand and gravel deposits that are glacial in origin and constantly being worked and reworked by current and wave action in Long Island Sound (Goldsmith 1965).

3.3 Glaciation

At least four ice sheets have overridden New England and have terminated as far south as Long Island, Martha's Vineyard, Nantucket and George's Bank south of Nova Scotia (Lewis, 2014). Glaciation produces many of the dominant features present along the Connecticut coastline. Glaciers are large bodies of ice that are formed through the layering of snow and compaction of that snow over a long period of time (Ritter, 2002). The most recent period of glaciation to affect temperate areas of the northern hemisphere was the Wisconsinan Glaciation Period, which reached its peak roughly 24,000 calendar years ago (Lewis, 2014). This paper will primarily focus on this recent glacial advance and retreat. The origin of this glacier was the region of the present-day Hudson Bay, which is around 60° N latitude. Glaciers in most cases do not originate from the poles, due to the lack of precipitation in those areas. Due to Hadley Cell and Ferrell Cell circulation, the 60° N latitude areas receive higher amounts of precipitation and would be where glaciers are more likely to build. Glaciers need this constant supply of precipitation in the form of ice or snow in order to advance (Ritter et. al, 2002).

Moraines are formed during periods of glacial recession, and at the edge of an advancing glacier (Ritter et. al, 2002). Moraines in eastern Connecticut are parallel to the larger terminal moraine that comprises Long Island and the smaller recessional deposits that make up the Charlestown Moraine (Rhode Island), the Fishers Island Moraine (New York) and the Mystic Moraine (Connecticut into Rhode Island) (Stone, et. al, 1988). Recessional Moraines are made up of stratified sand and gravel deposits that underlie dense areas of large boulders on the surface. Boulders were deposited in east-west striking lines that range from 3-18 meters in thickness and have a tendency to follow narrow zones that progress from southwest to northeast in the state of Connecticut (Stone, et.al, 1988).

The most recent glacial period has its terminal moraine along the south coast of Long Island, called the Ronkonkoma-Amagansett-Shinnecock terminal moraine (Lewis, 2014). Just to the north of the terminal moraine, the recessional moraines known as the Roanoake Point-Orient Point-Fishers Island-Charlestown moraine and the Mystic moraine orient themselves in east-west lines that trail north into Connecticut and Rhode Island (Lewis and DiGiacomo-Cohen, 2000). Since glaciers have the ability to strip sediment from the underlying sediment, the coast of Connecticut is unlike the coastline to the south of Long Island as it is relatively sediment starved in comparison to the rest of the east coast of the continental United States (Lewis, 2014). If glaciers did not travel as far south as they did, the coast of Connecticut would look much like the sediment abundant shorelines south of Long Island. Glaciers acted like a conveyor belt to strip the coast of its sediment. This is also the reason why soils in the Northeast are relatively young in comparison to the rest of the continent (Thompson, Personal Communication 10/2013).

The Mystic Moraine starts in eastern Connecticut and western Rhode Island and runs northeast to southwest, striking through the western length of Bushy Point beach, ending in the larger deposits of Bushy Point headland and Pine Island. Boulders associated with the Mystic Moraine can be found on the walking trail that leads to Bluff Point and Bushy Point beach (Stone, 2005). The Mystic Moraine runs parallel to larger recessional moraines to the north and south of it, that were formed during the ice retreat following the Wisconsinan Glacial period.

While the glaciers acted to strip the area of sediment, they also acted as a source for sediment (Lewis and DiGiacomo-Cohen, 2000). Most of the sediment on the Connecticut coastal plain is glacial in origin. Following the long period of glacial advance was a shorter period of glacial recession. Beneath the glacial boulders that form moraines is a layer of ablation till which melted directly off the glacier as it receded to the north. Additional sediments came from sources further upstream, as the glaciers continued to melt and recede. Meltwater carried with it fluvial-glacial sediments downstream. This formed a series of glacial sediment deltas along the coast of what was once Glacial Lake Connecticut (Lewis, 2014). North-south oriented bedrock valleys acted as basins for meltwater from the receding ice. For this reason, south draining bedrock valleys feature glacial material that was deposited by meltwater streams (Lewis and DiGiacomo- Cohen, 2000). River deposits tend to be more rounded rather than angular, and are well sorted in comparison to glacial till or ablation till which is dropped directly off the ice surface (Ritter, 2009). This type of glacial meltwater deposited sediment makes up a great deal of the coastal plain today (Lewis and DiGiacomo-Cohen, 2000).

3.4 Long Island Sound

Long Island Sound is an estuary that stretches from east to west and is 182 km long and 32 km wide. The long horizontal east-west orientation of the Long Island Sound makes it unique in its sedimentation and draining patterns (Lewis and DiGiacomo-Cohen, 2000). The Sound forms the boundary between glacially modified bedrock to the north and the relatively sediment abundant coastal plain to the south (Lewis, 2014). The south coast of Connecticut is primarily a rocky coastline with barrier spits forming where sediment is locally abundant (Lewis and Stone, 1991). Bushy Point barrier beach is one of these barrier spits. Barrier systems on the southern coast of Connecticut occur in small pockets, because glacially deposited beach sediments are only locally abundant. Locations much like Bushy Point beach are Griswold Point in Old Lyme, Napatree Point in Westerly RI, and Long Beach near Bridgeport, CT.

Long Island sound began its life as a freshwater body called Glacial Lake Connecticut. Glacial Lake Connecticut was once part of a chain of glacial lakes that included Rhode Island and Block Island Sounds, stretching as far east as Narragansett Bay in Rhode Island and

Buzzards Bay in Massachusetts (Lewis and DiGiacomo-Cohen, 2000). Sea level rose when the glacier continued to recede, and the dam was eventually overtopped, causing the sound to take on characteristics of a mixed estuary (Lewis, 2014).

With the exception of large storms, the previous studies of Campbell (2004) and Serafin (2007) have shown that predominant wind directions for this area are from the westerly quadrant. The predominant wind direction in the winter is from the Northwest, and the predominant summer direction is from the Southwest. Keeping fetch in mind, which is the available distance wind can travel over open water (Fitzgerald and Davis, 2004), there will be a large amount of energy coming from the southwest in the summer, a direction with a longer fetch than to the southeast, limited only by the positioning of Long Island to the south. Wind generated waves are considered the most erosive waves that occur in Long Island Sound. Energy from wind is directly transferred into the waves as the wind moves over the surface. Waves that are associated with storm activity are influenced by the duration of the storm, wind velocity and direction, and fetch. Although Long Island Sound is fetch limited, storm waves can be refracted around both Fishers Island and Long Island through The Race and Fishers Island Sound, preventing energy loss as the waves enter the Sound. For this reason, it is possible for Connecticut's beaches to receive the impact from Atlantic Ocean sourced storm waves and swell despite their relatively sheltered location (Personal communication, Ralph Lewis 2/2014). A longer fetch directly corresponds with wave height (Figure 3.4). If a strong wind has a larger distance it can travel over open water, this will correspond with higher wave amplitudes and longer wave periods (Davis and Fitzgerald 2004).

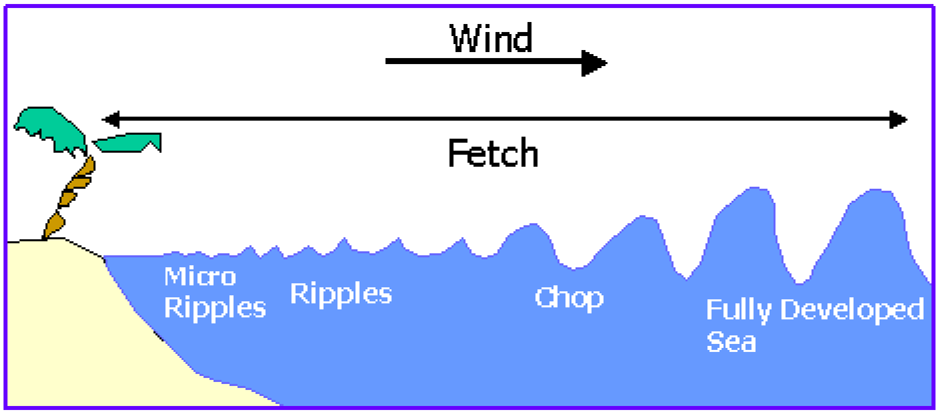

Figure 3.4: Fetch, as described by the distance of open water that wind has an effect on. A larger fetch will increase the height of wind-produced waves (Texas A&M University 2014, Coastal Physical Processes)

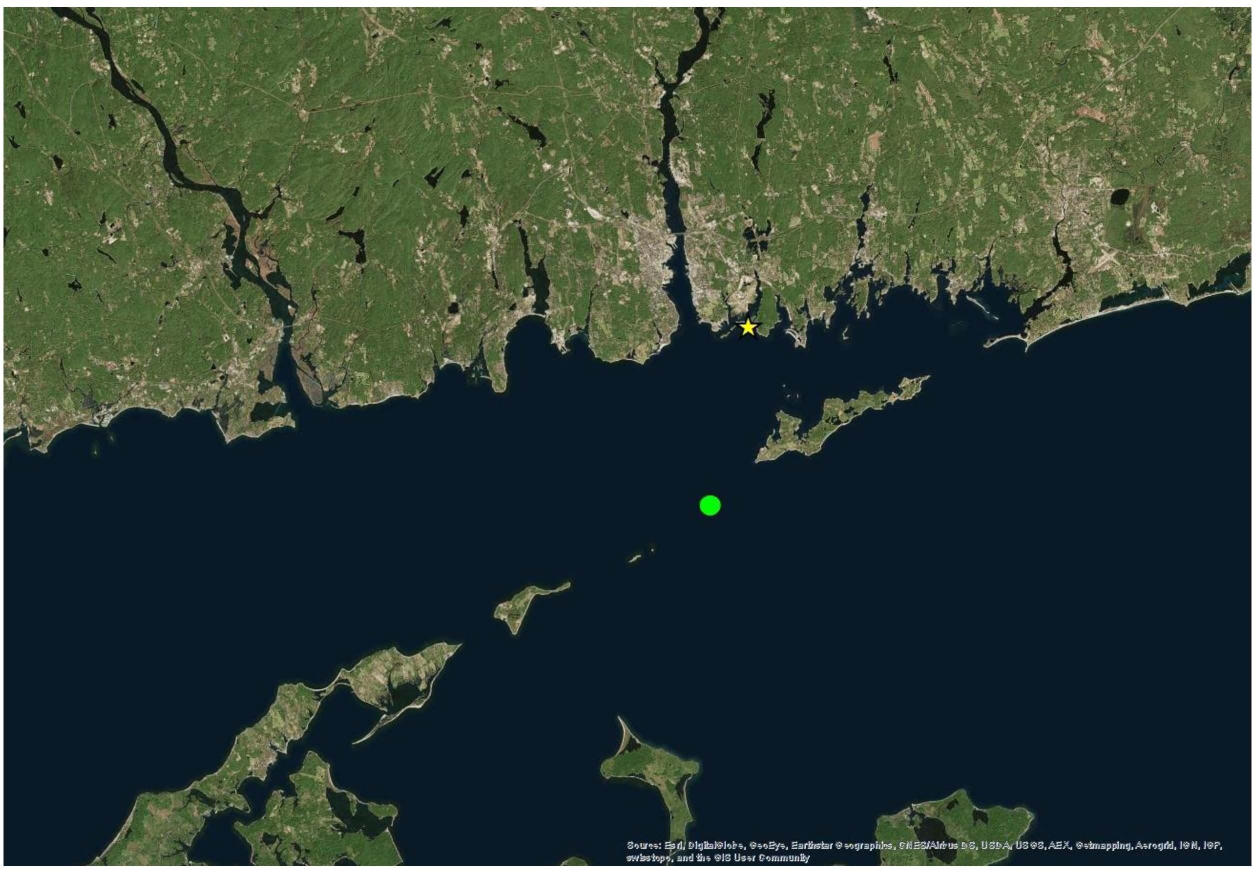

Figure 3.5: A map of eastern Long Island Sound. The yellow star on the map represents the location of Bushy Point beach. Notice the positioning of Long Island and Fishers Island (just to the south of Bushy Point Beach) which provides a breakwater effect, causing Long Island Sound to be a low energy wave environment. Wind driven waves from easterly directions can be refracted through The Race (green circle on map), making eastern long island sound's beaches vulnerable.

Because fetch from certain directions will directly affect the height of waves, the energy of the waves that strike the beach will change down the length of the barrier system from west to east. The furthest west tip of the barrier is shielded by southwest wind driven wave energy because of the positioning of Groton's Avery Point and both Bushy Point and Pine Island. For this reason, the section of the barrier closest to the bluff will exhibit the most change in response to a strong southwest wind. Additionally, an east wind can produce the same effect because of a phenomenon called wave refraction. Erosive waves from an easterly direction can strike the east side of the beach because they are refracted, or curved around Bluff Point headland (Campbell 2003). When this process occurs during a storm, the energy associated with erosive storm waves can be transferred directly to the beach.

3.5 The Hurricane of 1938

On September 21, 1938, a category three hurricane made landfall in southern New England and devastated many southern-facing beach dwelling communities. This highly unanticipated storm raced up the mid-Atlantic seaboard as a category four storm, and would strike the coast of Connecticut as a category three storm with a force not yet seen by that generation (Boothroyd, Klinger and Galligan, 1989). The storm surge completely overtopped the dunes at Bushy Point barrier beach where the small summer houses were built, and left nothing but rubble on the beach face. Before 1938, there were houses and development along the stretch of the beach. The storm surge on the morning of September 21, 1938 was estimated to be 10-15 feet at the mouth of Long Island Sound, and arrived at high tide in certain areas (Brooks, 1939).

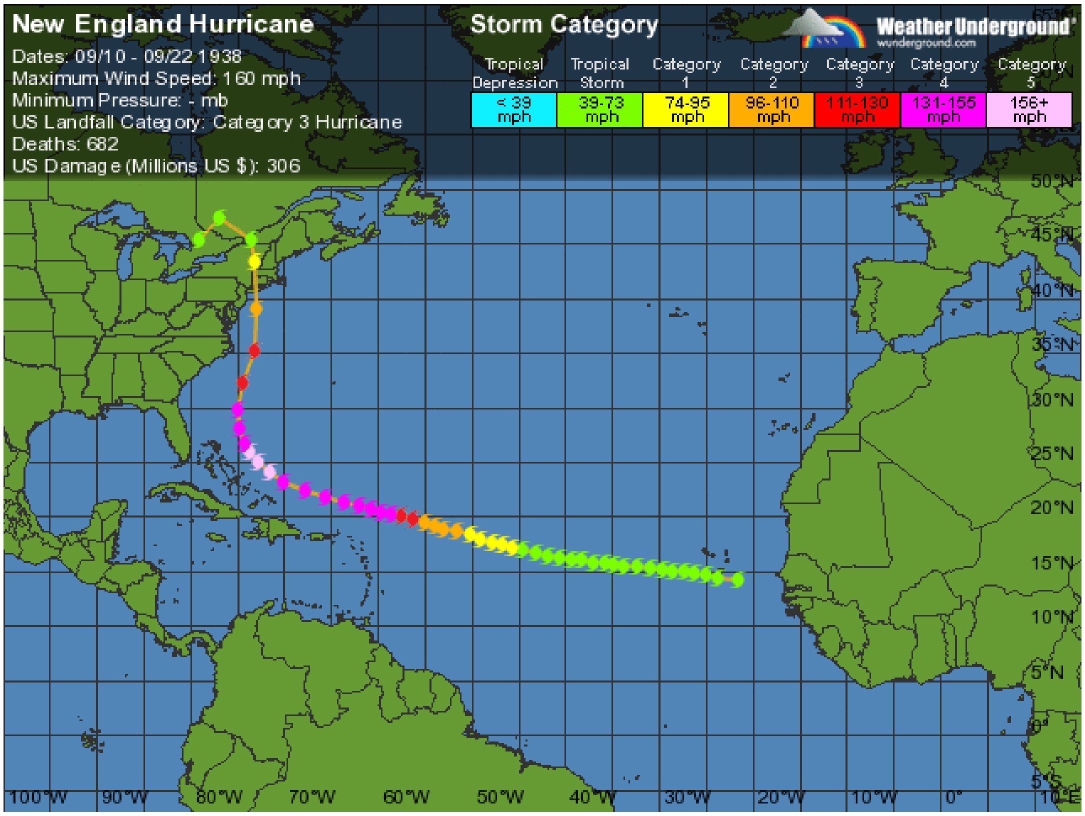

Figure 3.6: An Image of the estimated track of the Hurricane of 1938 from September 10, 1938 to September 22, 1938 (wunderground.com)

The weather conditions that are necessary to steer a storm up the eastern seaboard are surprisingly common. The weather patterns of mid- September 1938, featured a high pressure system that was centered over eastern Newfoundland, which provided a general pressure gradient from east to west (Brooks, 1939), as well as a low pressure system centered over the great lakes. The space between these two pressure systems created a corridor where a storm of high magnitude could race up the eastern seaboard at an unprecedented speed (Pierce, 1939).

The top wind gust recorded in the Hurricane of 1938 was 186 mph, recorded by the Blue Hill Meteorological Observatory in Milton, MA (Iacono 2001). The storm surge for this particular storm reached heights of 3-5 meters at the mouth of Long Island sound, and the south coast of Rhode Island in Narragansett Bay (Brooks 1939). The storm surge in many areas was compounded by an astronomical high tide in most areas, causing significant coastal flooding in

Southern New England, and inundation of barriers from the south coast of Long Island, NY to Cape Cod, Massachusetts. These widespread over-wash scenarios caused significant coastal modification in the Northeast following the storm (Ashton, Donnelly and Evans 2007).

3.6 Sandy

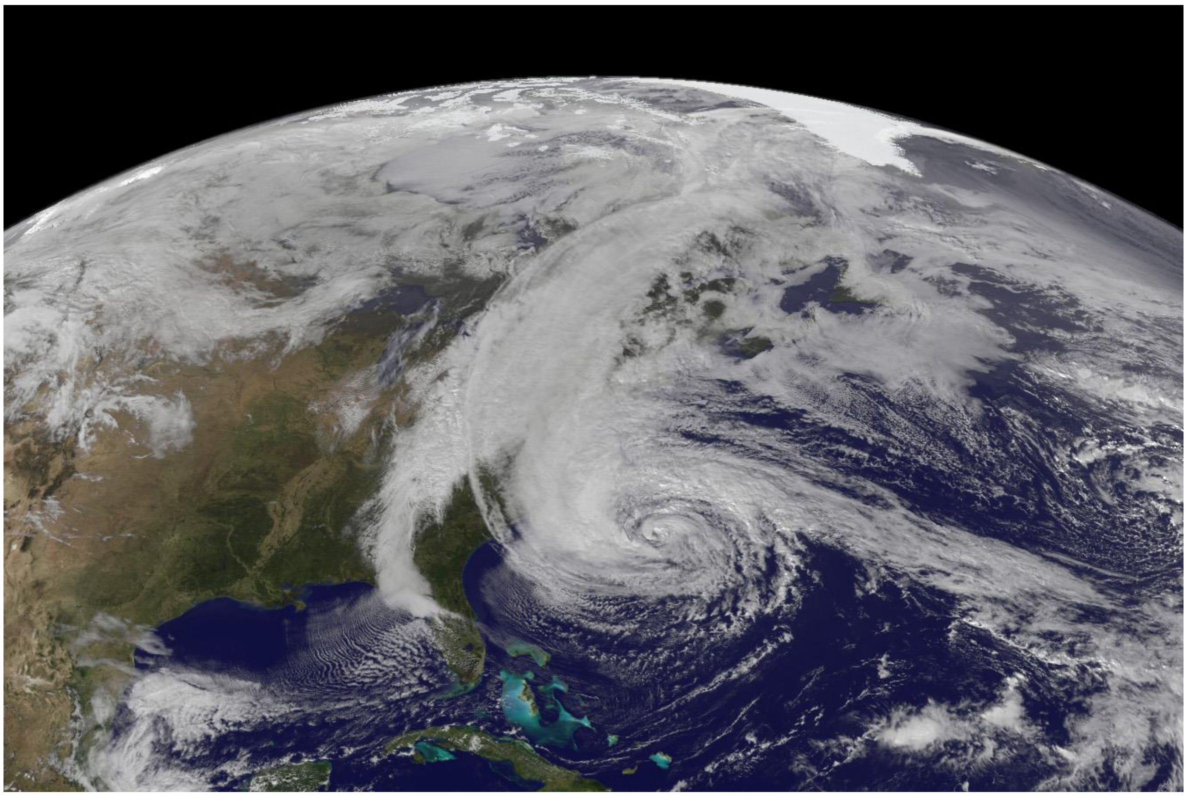

Figure 3.7: This image of Hurricane Sandy was taken on October 29th, 2012 when it was still off the mid-Atlantic coast. (earthobservatory.nasa.gov)

New England had gone roughly 75 years without encountering a major storm that took a destructive track. In late 2012, a category one storm made landfall off the coast of New Jersey. Hurricane Sandy was the first incidence in the Northern Hemisphere where blizzard warnings and hurricane advisories were issued for the same storm (Halverson and Rabenhorst 2013). "Superstorm" Sandy made landfall on the coast of New Jersey after starting off as a tropical depression in the Caribbean a few days before. The tropical system strengthened and was given the name “Sandy” on October 23rd, 2012. Sandy crossed over Cuba a few days later. The landfall weakening the system slightly, before it made a turn to the North and began to enter the cooler waters of the mid-Atlantic seaboard. At this point, Hurricane Sandy grew in size to become the largest tropical system in Atlantic basin history, at 1,700 km in diameter (Halverson and Rabenhorst 2014). Storm surges for this storm in Long Island Sound peaked at 3.5-4 meters in the lower New York Metro Area. The storm surge recorded for New London Ledge Light tidal station, roughly 1.5 km from Bushy Point barrier spit, was 2.1 meters (Figure 3.8).

The predominant weather patterns in the northeast at the time Sandy was making its way up the eastern seaboard created a situation where the storm would travel to the north, encounter colder air masses, and take a turn towards the New York City metro area. A dip in the Jetstream created a barrier between colder air from Canada and warmer air from the tropics. Sandy brought with it tropical moisture, which created this worst case scenario of storm systems. A blocking high over Newfoundland rotating clockwise acted as a barrier to push the storm towards the Mid Atlantic rather than letting it bend out to sea. Because of the storm’s counterclockwise spin, warm air was being funneled up the east side of the storm while colder air was being pushed southward in front of the storm. This provided the conditions necessary for a temperature drop that caused snow to fall in inland areas of the mid-Atlantic, while hurricane and tropical storm conditions persisted to the north (Halverson and Rabenhorst 2013).

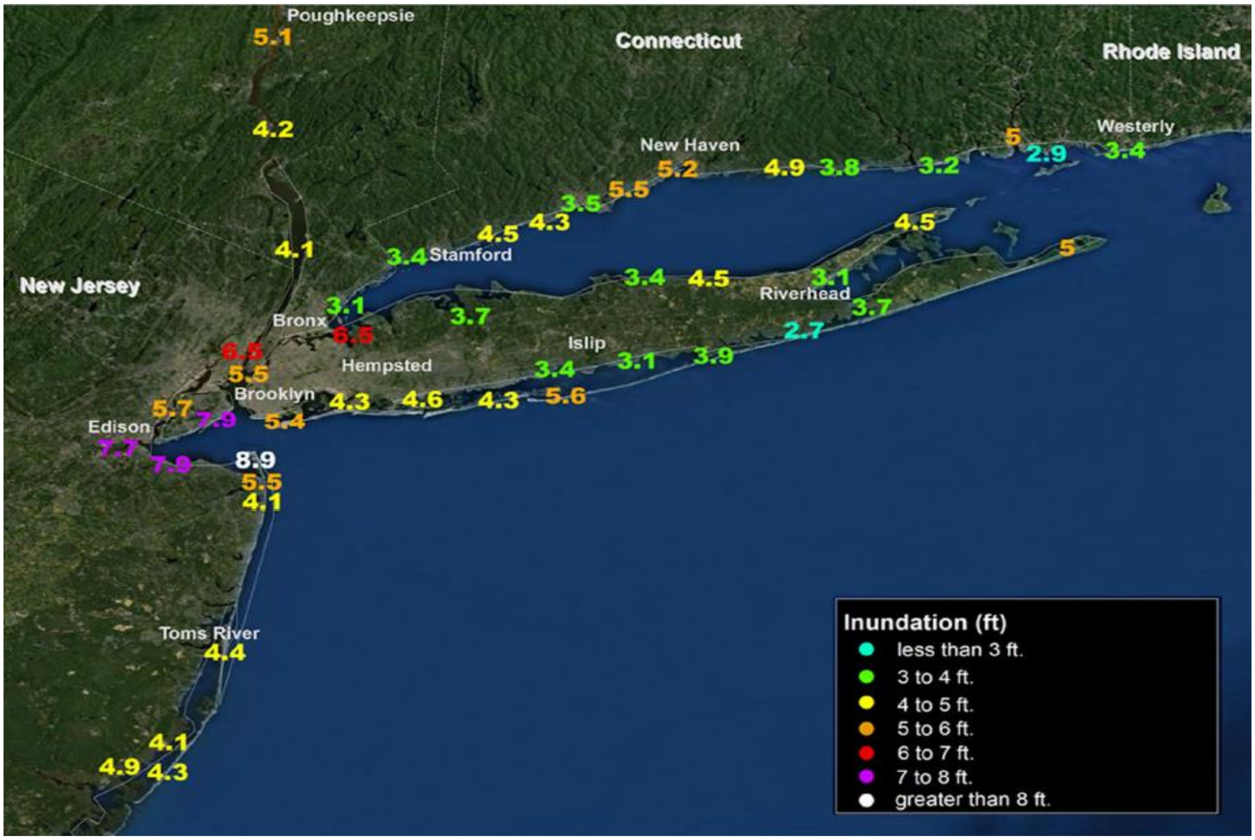

Figure 3.8: An image of a location based map of maximum storm surge heights that occurred during Hurricane Sandy on October 31, 2012. Numbers were taken from tidal buoys at each location. The New London tidal buoy indicated a storm surge height of 2.9 feet while the tidal buoy at nearby Napatree Point in Westerly, RI indicated a storm surge height of 3.4 feet. (NOAA 2012)

4.0 Methods

This study is comprised of the analysis of Bushy Point barrier beach through elevation profiling, sediment sampling, and Geographic Information System (GIS) mapping. Elevation profiles were performed at multiple locations along the barrier to gain insight to beach morphology down the length of the barrier, as well as repeated in one location in order to monitor changes in one section of the barrier. Repeated elevation surveys were performed at a location labeled Orange Stake (OS) previously used in studies by Campbell in 2003 and Serafin in 2007. Elevation surveys were performed to show changes in the morphology of the beach. Sediment sampling at stations down the length of the barrier was used to determine direction of longshore drift. Geographic Information Systems (GIS) mapping was used to show changes and long-term movement of the barrier.

4.1 Elevation Profiling, Orange Stake

The elevation profiling consisted of a series of repeated topographic elevation surveys on a reference point known as Orange Stake (Global Positioning System (GPS) Coordinates: N 41 19.025 W072 02.061). Elevation surveys at Bluff Point barrier beach were accomplished by a two-person survey team, and were taken using an auto level, stadia rod and tape measure. In this two person team, one of the surveyors held the stadia rod while the other surveyor read the value on the stadia rod through the auto level. Measurements were taken at one-meter increments across the surface of the beach from the lagoon to the sound, and care was taken to note the locations of water's edge, dune crests, berm and dune grass locations across the profile. The starting point near the dune crest was labelled "0 meters" and the survey continued in both directions from there to the water's edge. The surveys were taken at varying distances into the Long Island Sound depending on tide, wave height and the comfort of the surveyor. Positive values were given to the Long Island Sound side of the barrier, whereas negative values were given to the lagoon side of the barrier.

At Orange Stake (OS), five profiles perpendicular to the shore were taken in 2003 on September 5th, September 19th, October 3rd, November 7th, and December 12th (Campbell, 2004), and five profiles were taken in 2007 on May 15th, September 28th, November 8th and November 25th (Serafin, 2009). The November 8th profile was completed immediately following tropical storm Noel. In the modern study, one profile was completed on November 28th, 2012 immediately following Hurricane Sandy. Additionally, three profiles were completed between June of 2013 and May of 2014. Table 4.1 lists the Orange Stake profiles taken for this study. These profiles, along with the profiles taken in 2003, 2004 and 2007 were graphed on the same axis in order to track changes in the beach at this particular profile over a ten-year period.

Table 4.1: Orange Stake Elevation Profile repeated survey dates, 2012-2013.

Orange Stake Repeated Surveys	
Date	**Location**
11/16/2012	N 41 19.025 W 072 02.061
5/20/2013	N 41 19.025 W 072 02.062
6/19/2013	N 41 19.025 W 072 02.063
11/13/2013	N 41 19.025 W 072 02.064

In the fall of 2014, it was discovered that Orange Stake had been pulled up and removed from its location most likely by beachgoers. For that reason, continued elevation profiling at the OS site officially ceased in the fall of 2014. Profiles can still be collected from the site using the GPS coordinate for the stake, however it was determined that these surveys will most likely vary roughly +/- 0.5m in location due to the level of GPS accuracy.

Analysis of profiles began by entering the numbers into an Excel spread sheet and using a correction factor of 150 cm, which was added to the benchmark elevation at OS. Because there was no reference point, this factor represented a distance above sea level, determined and kept constant for this site by Campbell (2004) and Serafin (2009). This corrected benchmark elevation was subtracted from each of the measurements taken along the beach in order to provide an accurate picture of the beach profile above sea level. The profiles were compared by overlaying the profile graphs on the same axis, and determining the difference using subtraction of the corrected values.

4.2 Elevation Profiling, Stations 1-5

Five additional topographic profiles were taken in the fall of 2014 down the length of the barrier beach, perpendicular to the shore (Figure 4.1). These included a stake near the end of the spit with the inscription “402” (Labeled station #1) and four subsequent points going west to east down the length of the barrier (Labeled Station #2, Station #3, Station #4 and Station #5 for convenience). Locations of each survey station are as follows: Station 1: "402" Stake N 41 19.179 W 072 02.912, Station 2: N 41 19.187 W 072 02.774, Station 3: N 41 19.097 W 72 02.415, Station 4: N 41 19.042 W 072 02.297, Station 5: N 41 18.993 W 072 02.206 (Table 4.2). These five points started at the end of the spit, and were spaced further down the beach towards the Bluff, sectioning off the barrier. These five surveys cannot be used to view historical changes in the beach, but rather used to see differences in the morphology along the length of the barrier. Race Lighthouse and the United States Coast Guard Navigation buoy at Vixen Ledge (N28VL) on the Long Island Sound side were used as stable reference points to align the profile for the surveys.

Table 4.2 : List of the dates and locations of five new survey stations established in 2014.

Station	Location	Date
1	N 41 19.179 W 072 02.912	9/19/2014
2	N 41 19.187 W 072 02.774	9/19/2014
3	N 41 19.097 W 072 02.415	10/14/2014
4	N 41 19.042 W 072 02.297	10/15/2014
5	N 41 18.993 W 072 02.206	10/15/2014

Figure 4.1: A map of the station locations chosen for profiling in order to represent the elevation and shape of at different locations down the length of the beach. The location of Orange Stake is also present in this image.

These surveys were taken using the same elevation profiling method, using a stadia rod, auto level, tape measure and two surveyors. Much like the OS survey, measurements were taken at one-meter increments across the surface of the beach from the lagoon to the sound, care being taken to note the locations of water's edge, dune crests, berm and dune grass locations across the profile. The starting point, taken at an arbitrary point just seaward of the dune crest was labelled "0" and the survey continued in both north and south directions across the width of the beach from there. The survey distance taken into the Long Island Sound depended on tide, wave height and the comfort of the surveyor. Positive values were given to the Long Island Sound side of the barrier, whereas negative values were given to the lagoon side of the barrier, to add ease in graphing.

In the Fall of 2014, a final elevation survey was taken using a laser total station. This survey was performed in order to connect the five survey stations to the National Geodetic Survey marker on the Bluff. By connecting the survey stations to this marker, true elevations above sea level for each station could be established. The laser total station was positioned within sight of the National Geodetic Survey marker, marked by a small brass plate embedded boulder off a trail on the Bluff. The elevation from the shooting point was established, the laser total station was moved to a point closer to the beach. It took two "steps" to get from the survey marker in deep brush to the barrier beach. Once the laser total station established the true elevation of the beach using the national geodetic survey marker as a reference, the elevation of every point on the beach could be determined. The elevation of each of the five survey stations was found using the laser total station, and then was used as a reference value to create each beach elevation profile. In Serafin (2009) and Campbell's (2004) surveys on the beach, they used a value of 1.5 meters to represent a value above sea level in order to create the Orange Stake (OS) profiles.

4.3 Sediment Analysis

Three sediment samples were collected at the five different survey stations down the length of the beach, one taken from the berm, one taken from the beach face and one taken from the dune at each station. GPS coordinates were noted at the collection point of each sample. After the samples were collected, sediment analyses for size and sorting indices were performed in the Sediment Analysis and Hydraulics lab at Connecticut College. The most commonly used method for the analysis of sand to gravel sized particles is dry sieving (Gordon et al., 1992). Individual sediment samples were dried completely before sieving to avoid adhesion between particles. A set of sieves was stacked together, with the largest aperture size on top, and decreasing in size downwards by ½ ϕ intervals. Roughly 100 grams of each sample was run through the sieve separately, and the sample was shaken for 15 minutes to ensure proper time for separation of particles. After the fifteen minute shaking period, the contents of individual sieve was transferred to a weighing tray, and care was taken to brush the excess particles from the sieve openings into the tray. The mass of fraction of sediment was recorded. Although some loss was expected, the total weight of the fractions was compared to the original weight of the sediment sample. This process was repeated for each of the fifteen sediment samples.

The data from the sieve analysis was inputted into the GRADISTAT v8, developed by Dr. Simon J. Blott of the Royal Holloway University of London, UK (2010). It is the most widely used sediment analysis program for the United States Geological Survey. The individual sediment sizes were graphed in order to find the d_{16}, d_{50} and d_{84} values. The variable d refers to the particle diameter in mm, given by the material present in each sieve. By taking the negative log base two of the size in mm, a phi unit was calculated in order to better describe the sediment sizes.

$$\phi = -\log_2(sediment\ size\ in\ mm) \qquad \text{[EQ 4.1]}$$

From the sieving, the numbers were used in order to find a sorting index for each sample. A sorting index gives the measure of the spread of sediment sizes in a given sample (Gordon et al., 1992).

$$Sorting\ Index = \frac{1}{2}\left(\frac{d84}{d50} + \frac{d50}{d16}\right) \qquad \text{[EQ 4.2]}$$

This will indicate how well the sediment is sorted at particular points on the beach. Sediments that are better sorted will be down current of sediments that are less sorted, indicating the direction of longshore drift across the barrier.

4.4 Historic Storm Analysis

Storm tracks for significant hurricanes and Nor'easters to strike New England from 1934 to 2014 were collected using the National Oceanic and Atmospheric Administration's (NOAA) Historic Hurricane Tracking tool, as well as historical written accounts of storm landfalls for storms that predated tidal gauges and tracking systems (Ludlum, 1963 and Donnelley et al. 2001). Heights of storm surges dating back to 1936 that were measured by nearby tide gauges at Newport, Rhode Island, and New London, Connecticut by NOAA/ NOS/CO-OPS, (2000) and the United States Army Corps of Engineers (1962) were put together to list and compare hurricane and Nor'easter driven storm surges that made landfall at or around the study area. For more recent storms, wave and surge height data was collected directly from the NOAA's National Data Buoy Center, using Station 44039 which is located at the mouth of Long Island Sound. This buoy is maintained by the research staff at the University of Connecticut at Avery Point.

4.5 Geographic Information Systems

GIS was used for historical data on the movement of the beach further back in history than the elevation profiles. GIS was particularly useful in analyzing changes in spit morphology from 1934 to 2014. Aerial photographs were uploaded into GIS, digitized and overlapped in order to map physical changes in the location of the beach as a whole. Aerial photographs at equal year intervals were difficult to find, therefore a best effort was made to focus on major storm events as reference points. Additionally, maps were created using GIS and input data from the GPS device used in this project that showed the locations of transects and sediment sampling performed along the length of the barrier.

Table 4.3: Aerial Photographs Analyzed and Sources. Sources include: MAGIC Index Image (University of Connecticut's Map and Geographic Information Center Index), NAIP Imagery (National Agricultural Imagery Program), and CT DEEP Archives (Connecticut Department of Energy and Environmental Protection Archives).

1934 MAGIC Index Image
1951 MAGIC Index Image
1968 CT DEEP Archives
1986 CT DEEP Archives
1991 MAGIC Index Image
2010 NAIP Imagery
2012 NAIP Imagery
2014 NAIP Imagery

GIS was used in two ways: to find a rate of retreat of the beach for each year-interval, and to find area changes over three sections of beach for each year-interval. After the photographs were uploaded, overlain and digitized, transect lines were digitized at each of the five survey stations and at Orange Stake. Georeferencing accuracy was determined to be within 1 meter. The rate of retreat was found by overlapping the transect lines with the digitized outlines of the beach, intersecting the two sets of data, and finding the distance between the intersection points. Since the digitized polylines were taken directly from georeferenced images using the same coordinate system, the digitized outline of the beach can be considered to be the location of the beach in each aerial photograph. This method was based on a method for measuring shoreline retreat in GIS by Chaaban et al. (2012), with an error margin estimated at +/- 5 meters based on errors in shoreline digitization, georeferencing and rectifying photographs, and photograph resolution. Figure 4.2 is an image of the transect lines and the digitized beach outlines. The distance between the points on the transect lines that intersect the digitized beach locations in different years will represent the amount of retreat during that increment. This was done by using the intersect tool in GIS, and then the measuring tool to find the distance between each location where transect lines intersected digitized beach outlines.

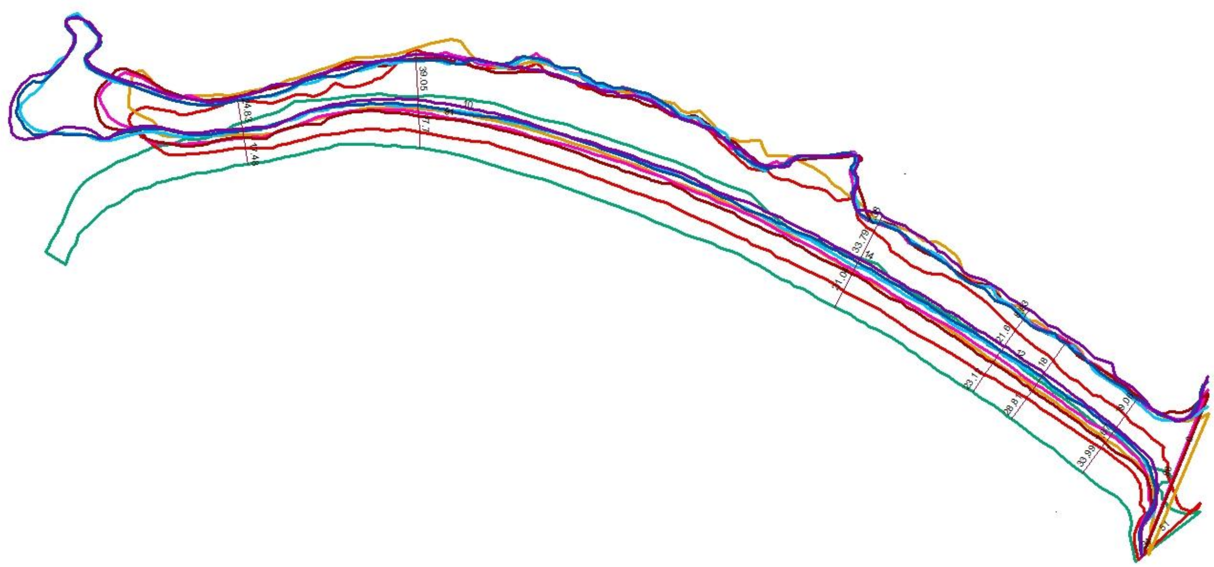

Figure 4.2: An image exported from GIS featuring digitized outlines of the beach in each year and the 5 transect lines. Transect lines were drawn at Stations 1-5 as well as at Orange Stake. Retreat at each location was found using GIS measuring tools.

To simplify matters, the assumption was made for overwash situations that the area of sediment lost from the beach face was roughly equal to the volume of sediment gained on the lagoon side of the barrier, exemplifying retreat inland. A rate of retreat (m/year) was found for each station location by dividing by the number of years in the increment. Added to this set of data, area changes for three sections of beach, the eastern section, middle section and western section were determine. This was done by first sectioning off the beach into three sections (Figure 4.3), and then by using the feature to polygon tool in GIS. Area changes were then determined by overlapping polygons to find changes in overall area. Since a depth of sediment cannot be determined from an aerial photograph, area changes based on the photographs were used to characterize coastal change.

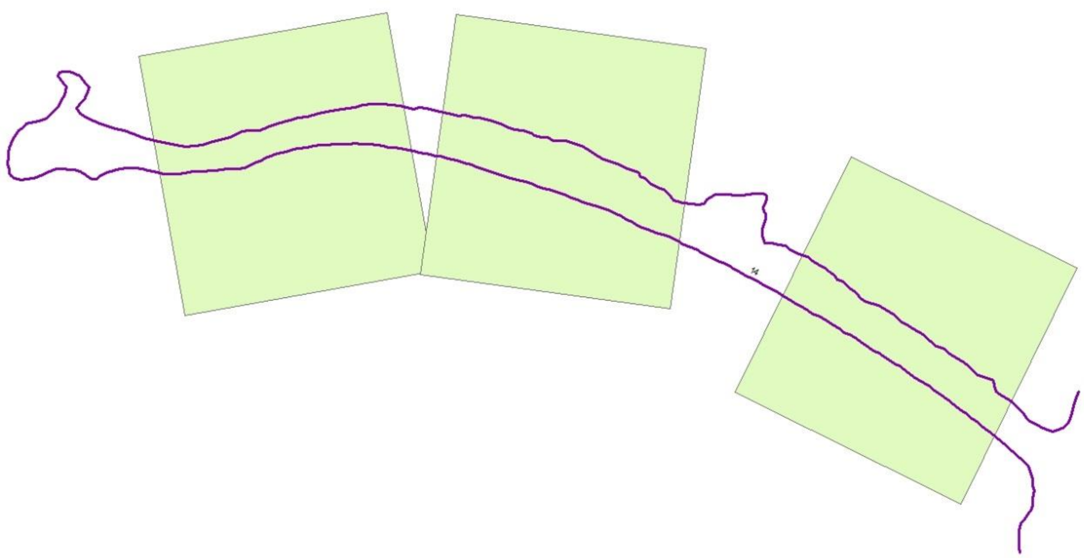

Figure 4.3: Image exported from GIS showing the digitized outline of the 2014 aerial photograph of the beach, sectioned into three parts. Two sections of beach were left out of area change calculations; the end of the spit, because of its constantly changing nature and the center of the barrier, because of its attachment to land behind it.

Each of these methods can be used individually and collectively to provide insight to how the beach is behaving both in the short term and long term. Elevation profiles give information about beach slope and dune height, and repeated elevation profiles show small changes in slope, elevation as well as larger changes such as beach retreat. Sediment analysis gives information about longshore drift direction and can provide evidence for steeper sloping beach faces, paired with elevation profiles. Finally, aerial photograph overlay and GIS analysis of digitized beach locations gives information about longer term movement of the beach changes in overall shape of the spit.

5.0 Results

The results for this project are divided into four parts. The first is the elevation surveys taken at Orange Stake from 2012-2014. These surveys were compared to surveys taken in 2003, 2004, 2007 and 2008 by Cat Campbell (2004) and Katherine Serafin (2009) focusing primarily on position and shape of the beach. The second part of the results focuses on the profiles and sediment samples from the five new survey stations that were established in the Fall of 2014. The third part of the results is an overview of surge heights for particular storms that affected the study area over the 80 year period from 1934 to 2014. The final section of the results provides an analysis of historical photographs of the beach using Geographic Information Systems (GIS). Through GIS locations of the beach were digitized and overlain, and a rate of retreat was determined for yearly increments.

5.1 Elevation Surveys

In this study, profiles were taken at Orange Stake (Figure 5.1, 5.2) in November of 2012 and then again at roughly 6-month increments until 2014 (Table 4.1). In November 2012, the profile changed significantly from the 2007 profile following Hurricane Sandy (Figure 5.4), which came ashore in southern New Jersey on October 30th 2012. Overwash fans (Figures 5.3, 5.5a, b) were present on the beach a few days following the storm, and significant elevation changes at Orange Stake (OS) indicated partial to complete overwash of the barrier system. Further evidence found on the beach included a lack of vegetation, the dune grass (*Ammophila breviligulata*) and beach roses (*Rosa rugosa*) being mostly washed away due to inundation by salt water or burial by transported sand. The removed vegetation was deposited in the lagoon on the back side of the barrier during the overwash. Figure 5.4 shows a few selected surveys from previous research in 2003 and 2007, as well as three surveys taken in 2012-2013. The previous surveys showed little change in beach elevation or location between 2003 and 2007. Evidence from the new profiles suggests that the top of the dune at the Orange Stake (OS) was flattened and in some cases has disappeared altogether. The first survey taken immediately following the storm indicates flattening of the beach, a response to high water levels, and the two subsequent surveys taken in 2012 and 2013 demonstrate the re-formation of berms on the beach face. The new location of the beach is evident in all profiles after November of 2012 (Figure 5.4), indicating a landward shift in the location of the beach occurred between 2007 and 2012.Visual observations of the system suggest that most of the change was associated with Hurricane Sandy

Figure 5.1: This photograph depicts the Orange Stake (OS) survey site used in studies in both 2003-2004 and 2007. Photograph taken a few days following Hurricane Sandy in November of 2012 by Doug Thompson. This image is taken facing west, with Bushy Point visible to the left and Groton's Avery Point in the distance. The beach shows numerous overwash fans and salt inundated vegetation, along with a well-defined wrack line and flattened beach profile

Figure 5.2: The last image taken of Orange Stake (OS) before it was pulled up sometime over the summer of 2014. Image was taken in the spring of 2014, facing north.

Figure 5.3: This image, taken from the east end of the barrier facing northwest, shows lines of overwash fans and a flattened dune. Photograph taken in early November of 2012 by Doug Thompson near the location of station 4 on the east end of the barrier.

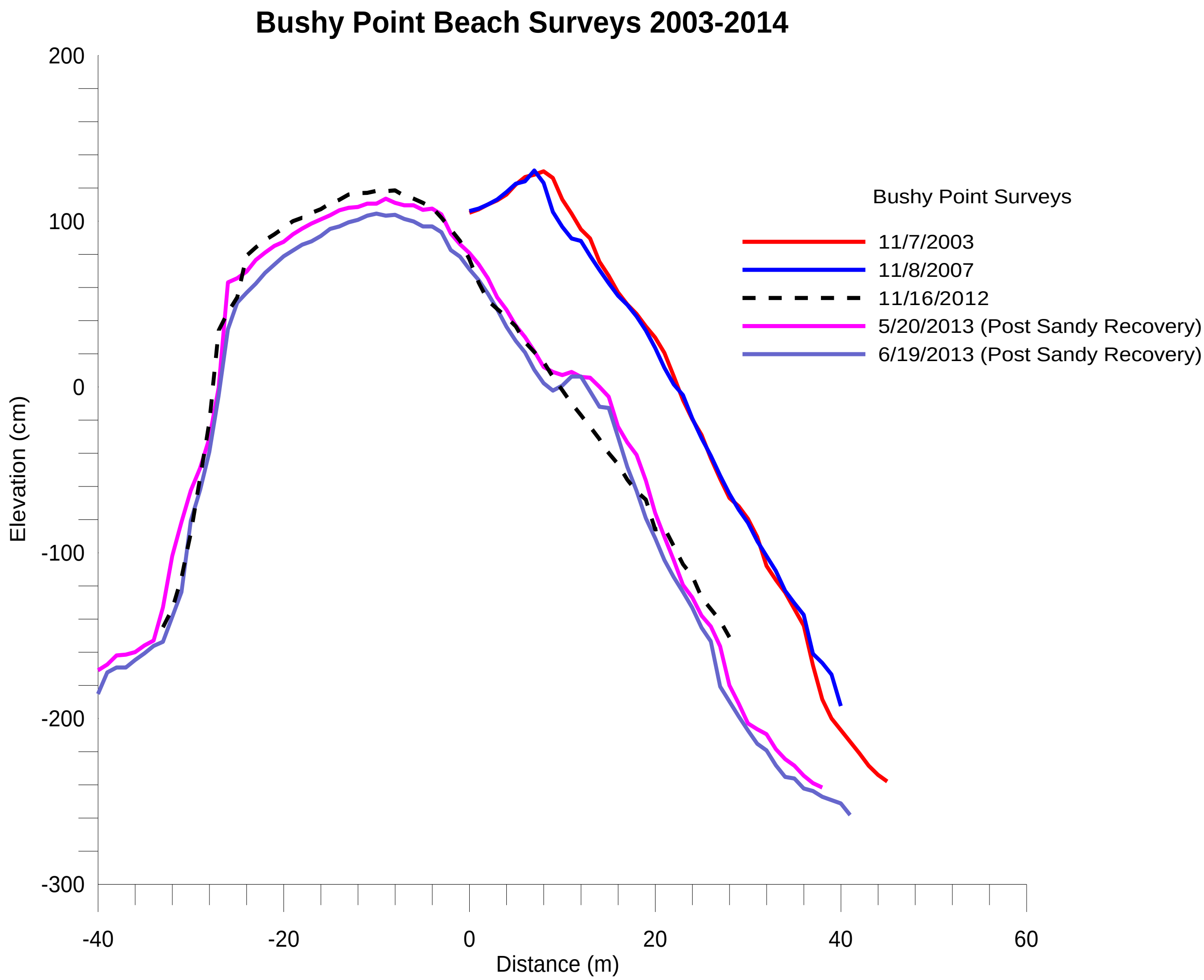

Figure 5.4: This figure of Bushy Point beach elevation surveys shows five elevation profiles, one taken in 2003, one taken in 2007, one taken in 2012 immediately following Hurricane Sandy, and two in the late spring of 2013 to track how much the beach recovered in the 6 months following the Hurricane. In the two 2013 spring profiles there are signs of a re-developing berm. Resurveyed transects were assumed to have a vertical error margin of +/- 0.5 cm for the OS benchmark, therefore any differences between profiles that are greater than +/- 0.5 cm completed at OS can be considered accurate representations of profile change.

Before the 2012 overwash on Bushy Point barrier beach, the beach responded naturally to seasonal changes in wave height. Profiles taken in 2003 and 2007 following smaller storm events show alternating periods of beach face flattening and berm formation. In the winter months, which tend to be associated with higher wave heights, the beach face is flattened and a bar of sediment is stored offshore. In the relatively calm summer months, this offshore bar of beach sediment is re-deposited on the beach face and berms are formed. The elevation profile taken on November 8, 2007 by Serafin immediately following Tropical Storm Noel indicates a flattening of the beach and net movement of sediment from the beach face to the tidal zone (Serafin 2009).

The beach tends to be highly cuspate following moderately stormy weather on Long Island Sound. These patterns were seen following minor storms in 2003, 2004 and 2007, and were observed again in 2013 and 2014 following windier days and rougher weather on Long Island Sound. This is another natural morphological response to higher energy wave action, dependent on the local conditions of sediment size and beach slope. Figure 5.6 shows a cuspate eastern end of Bushy Point Beach following Hurricane Irene, which made landfall on August 28th, 2011. This particular storm caused changes along the front of the beach including a steepening of the beach face, a well-defined wrack line and a cuspate beach, however there were no signs notable of overwash following the storm (Doug Thompson, personal communication, 2/2015).

Figure 5.5a

Figure 5.5b

Figures 5.5a and 5.5b: These photos of overwash effects on the back of the barrier taken late in November of 2012 represent the barrier spit's natural response to storm surge, sediment from the front of the barrier is deposited on the inland side of the barrier, changing its location. Photographs taken by Doug Thompson 11/2012.

Figure 5.6: An image of the eastern end of Bushy Point beach following Hurricane Irene. The beach is highly cuspate and has a well-defined wrack line. The storm surge was 1.1 meters high and arrived at low tide, therefore it is highly unlikely that it overwashed this section of beach (Connecticut Department of Energy and Environmental Protection)

5.2 Stations 1-5

Following the removal of Orange Stake, five survey stations were set up at different locations across the length of the barrier (Figure 4.1, Table 4.2). Elevation profiles from surveys taken at stations 1, 2, 3, 4 and 5 were graphed for comparison (Figure 5.7). Station 1 (closest to Bushy Point) has a pronounced dune crest however its elevation is significantly lower than Stations 4 and 5 towards the bluff. Station 2 has the lowest average elevation, with a pronounced dune on the Sound side. Stations 1, 3 and 4 are about even with station 4 having a higher elevation beach face and lower dune, and Station 3 having a higher elevation dune, and a lower beach face. Station 5 (closest to Bluff Point) has the highest elevation of all five stations. Station 3 (symbolized by the dotted line) is the widest part of the beach while Station 1 lies on the narrowest section of barrier.

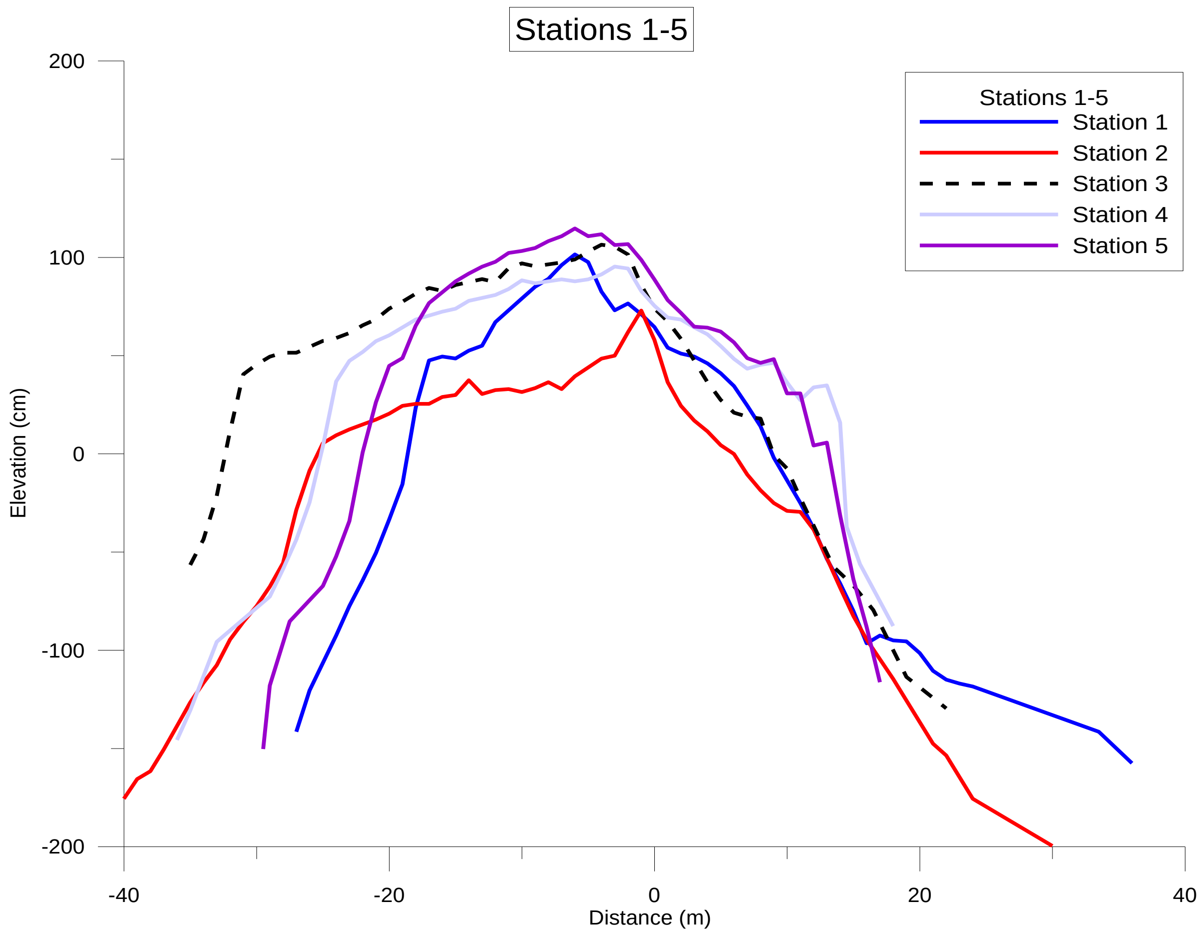

Figure 5.7: A graph of all five stations' profiles graphed on the same axis to show width and shape changes down the length of the barrier spit. Station 5 is at the eastern most end of the barrier and Station 1 is at the western end of the barrier at the end of the spit.

5.3 Sediment Analysis

Sieve Data indicates that sediment size from the samples taken at the berm, beach face and dune at each of the stations increases moving east to west, from Bushy Point to Bluff Point. Sediments are the largest on the berms and beach faces of Stations 4 and 5, which are the closest stations to Bluff Point (Figure 5.9). The smallest sediments on the beach are found at the berms and dunes of Stations 1 and 2, which are closest to Bushy Point and the end of the spit, near the inlet

(Figure 5.9). Stations 1 and 2 were comprised of fine sand to medium-coarse sand, whereas stations 3 and 4 and 5 transitioned from fine sand to medium-coarse sand to coarse sand containing larger pebble sized material, indicating an increase in sediment size between Station 1 and Station 5. Closest to Bluff Point, Station 5 was comprised of gravel, pebbles with traces of sand and fine sand. The largest clasts found at stations four and five reached 16+ mm in diameter. Sieve data ranged from 0.0% to 1.9% error, which is acceptable for this type of sediment analysis.

Table 5.1: The sorting index values are found in the far right column of the table, and the components to finding the sorting index are found in the far left tables. The highest value for sorting index is 6.884 and is found at the dune at Station 5. The lowest value for sorting index is 1.473 and is found at the dune at Station 1. Stations are separated by zone for sediment analysis.

Station	d16 (mm)	d50 (mm)	d84 (mm)	Sorting Index
1 Berm	0.153	0.307	0.329	1.539
1 Face	0.159	0.307	0.595	1.934
1 Dune	0.164	0.307	0.330	1.473
2 Berm	0.267	0.570	0.659	1.645
2 Face	0.287	0.536	0.659	1.549
2 Dune	0.154	0.307	0.329	1.533
3 Berm	1.031	1.234	2.832	1.746
3 Face	0.249	1.000	1.510	2.763
3 Dune	0.149	0.297	0.330	1.552
4 Berm	1.053	8.000	18.38	4.947
4 Face	0.154	1.000	4.930	5.712
4 Dune	0.165	2.000	2.640	6.721
5 Berm	4.287	5.278	10.20	1.581
5 Face	1.035	2.378	4.000	1.990
5 Dune	0.159	2.000	2.378	6.884

Using the samples from each station, a sorting index was calculated for each part of the beach (Table 5.1). The sorting index values are higher at Stations 3, 4, and 5, and therefore are higher in closer proximity to Bluff Point. The dune at Station 5 had the highest sorting index value of 6.884, indicating very poorly sorted sediment. The dune at Station 4 also had a relatively high sorting index value at 6.721. The lowest values for sediment sorting index were found at stations 1 and 2, the lowest value being found at the dune at Station 1. The sorting index value of 1.473 at Station 1's dune indicates the presence of sediments that are relatively sorted in comparison to higher values. Most of the values for the three zones of each station were relatively close in value, except for Station 5. Station 5's dune had the highest sorting index value of 6.721, however the berm and beach face had much lower values of 1.990 and 1.581. The range of values for each Station increases between Stations 1 and 5, moving west to east along the barrier spit (Figure 5.8).

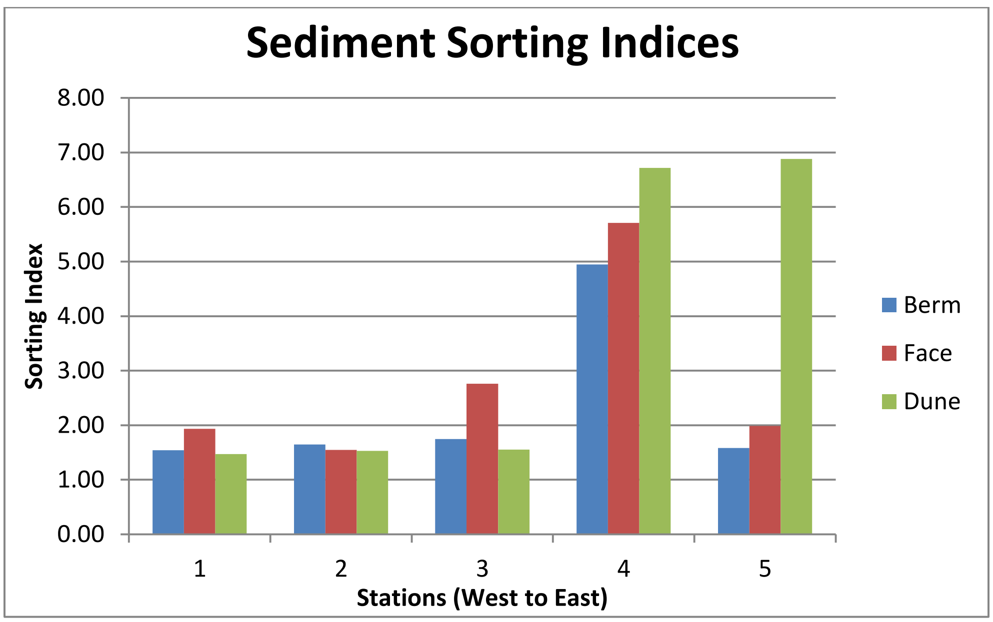

Figure 5.8: A graph of sediment sorting index values at the berm, dune and beach face at each station

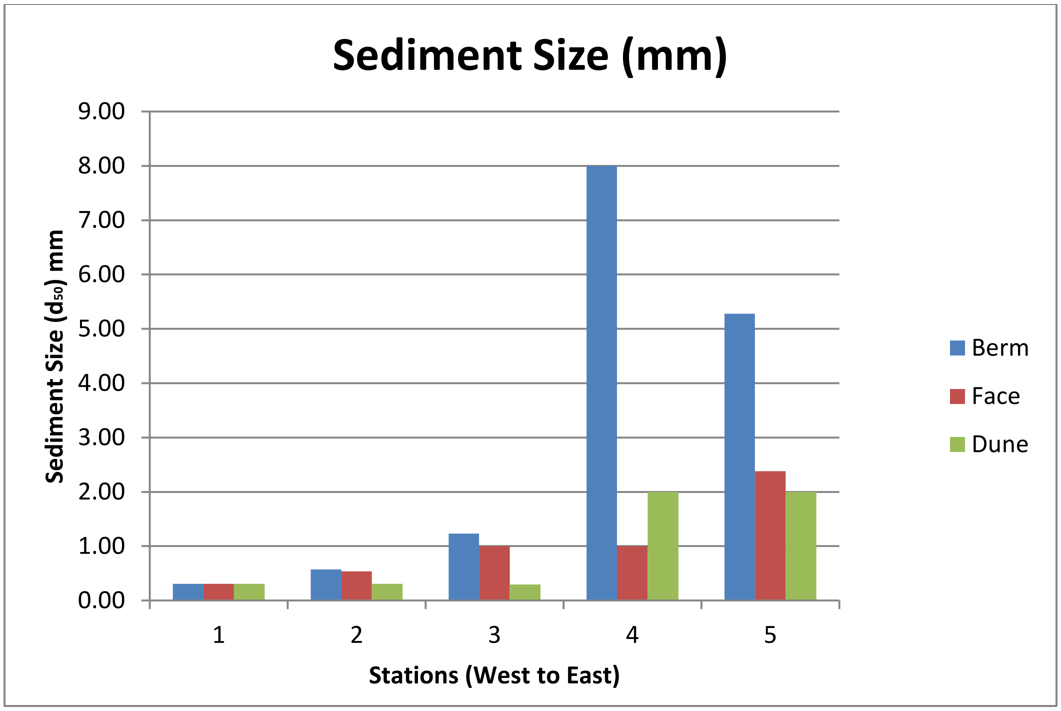

Figure 5.9: A graph of the sediment sizes at the berm, dune and beach face at each station

5.4 *Storm Data*

In general, there was a 40-year period of relaxed storm activity in the Northeast from the 1970's to the present. A few storms have come close to having a significant impact on the Northeast, but have arrived at low tide or have taken tracks that brought them too far to the east to have a strong effect. During this time of reduced storm activity, beach retreat is minimal if existent, and the barrier system only responds to natural seasonal changes in profile, keeping its relative location static. There was morphological response to both Hurricane Isabel in 2003 and Tropical Storm Noel in 2007. However there is little evidence that the storm surge in either storm overtopped the beach and caused further retreat. According to previous studies completed in 2004 and 2009, there was very little change in dune elevation between profiles, evidence that points to a lack of overwash on Bushy Point barrier beach during the four year period between 2003 and 2007 even with tropical systems Noel and Isabel.

Table 5.2: Storm data covering winter storms and tropical systems that produced storm surges of significance at the study area (Donnelley et al. 2001, NOAA).

Type	Date	Name (If Applicable)	Surge Height at High Tide (m above MSL)
Winter Storm/Nor'easter	10/1/1936		1.2
Tropical System	9/21/1938	Great New England Hurricane	3.8*
Winter Storm/Nor'easter	3/3/1942		1.2
Tropical System	9/14/1944	Atlantic Hurricane of 1944	2.1*
Winter Storm/Nor'easter	11/30/1944		1.5
Winter Storm/Nor'easter	3/3/1947		1.3
Winter Storm/Nor'easter	10/22/1949		1.2
Winter Storm/Nor'easter	11/25/1950		1.4
Winter Storm/Nor'easter	11/7/1953		1.5
Tropical System	8/31/1954	Carol	3.7*
Winter Storm/Nor'easter	10/16/1955		1.6
Winter Storm/Nor'easter	4/3/1958		1.3
Winter Storm/Nor'easter	11/29/1959		1.2
Tropical System	9/12/1960	Donna	1.2
Winter Storm/Nor'easter	3/7/1962		1.8
Winter Storm/Nor'easter	2/7/1978		1.4
Tropical System	9/27/1985	Gloria	1.4
Tropical System	8/19/1991	Bob	1.2
Winter Storm/Nor'easter	3/14/1993		2.3*
Tropical System	8/28/2011	Irene	1.1
Tropical System	10/30/2012	Sandy	2.1*

5.5 Geographic Information Systems Analysis

Geographic Information Systems was used to analyze the location changes of the beach between 1934 and 2014. Beach locations from aerial photographs were digitized and overlain from the following years: 1934, 1951, 1968, 1986, 1991, 2010, 2012, and 2014.

The image of the overlain photographs, digitized in Geographic Information Systems (Figure 5.9) shows the overall retreat of the beach over the 80 year interval. One of the most important features in the photograph is the breaking through of the beach at the Bushy Point headland, marking the transition of the barrier from a welded barrier to a barrier spit. Sediment buildup due to longshore drift is clearly visible in the 2014 aerial photograph taken by the USGS in this study. The end of the spit has grown to the west and northwest as longshore drift deposits and continues to deposit sediment on this section of the beach.

Figure 5.10: An image of digitized beach outlines representing locations from 1934 to 2014. The beach outline from 1934 is pictured in *green*, 1951 in *red*, 1968 in yellow, 1986 in *pink*, 1991 in *maroon*, 2010 in *light blue*, 2012 in *dark blue* and 2014 in *purple*.

5.6 Beach Retreat

Beach retreat is clearly visible in Figure 5.10. The location of the beach is shown through aerial photographs to be moving inland from 1934 to 2014. The spit' width and length has also evolved, and has shown through examination of aerial photographs to be lengthening and decreasing in width. Since exact volumes of sediment lost and gained per interval is difficult to obtain from aerial photographs, area changes over three sections of beach were calculated in order to represent coastal change at the east, middle and western sections of beach (Figure 4.3). The beach increased in width between 1934 and 1951, increasing in width by 1160 meters at the east end of the beach, 8075 meters in the middle section of beach and increasing by 1963 meters at the west end of the spit. The barrier sharply decreased in width and lengthened between 1951 and 2010, decreasing in area by 3229 meters at the east end, 8766 meters in the middle section and 6023 meters at the west end. The beach area increases dramatically at the eastern portion of beach between 2012 and 2014.

Table 5.3: Area change per interval. The table depicts the area lost and gained during each year interval. It is important to note that the very end of the spit was not included in this determination of area change, because it is not visible in every photograph and is changing rapidly. The spit began to lengthen and decrease in width after 1951, which provides an explanation for extremely high area losses in area between 1951 and 2010.

Area Change Per Interval (East, Middle, West) in M^2				
	1934-1951	1951-2010	2010-2012	2012-2014
EAST	1168	-3229	-768	1328
MIDDLE	8075	-8766	365	-2623
WEST	1963	-6023	-174	712

Table 5.4: Retreat for each interval. The amount of retreat was found for each interval through GIS analysis. Negative values are assigned to values of inland retreat (to the north) while positive values are assigned to accretion (south). Using the values for each station, an average was taken to represent the average amount of the retreat for the beach as a whole. Values are in meters.

	Amount of Retreat Per Interval (m)						
	1934-1951	1951-1968	1968-1986	1986-1991	1991-2010	2010-2012	2012-2014
Station 1	-17.5	-11.8	3.7	0	-8.1	0.7	-2.6
Station 2	-18.2	-25.8	3.62	4.51	-10.9	-0.8	-5.3
Station 3	-21	-24.1	3.2	2.8	-7.8	-5.5	-3.9
Station 4	-23.1	-16.5	-6.2	5.9	-11.1	0	-6.1
OS	-28.9	-13.7	2.5	5.5	-11.1	0	-4.9
Station 5	-33.9	-8.1	-7.7	-9.2	-13.1	0	-2.5
Whole Beach=	-23.8	-16.7	-0.1	1.6	-10.4	-0.9	-4.2

The amount of retreat at each station varies depending on which year-interval is studied. The retreat value for the 1934-1951 interval is much greater than retreat calculated for the 1951-1968 interval. At the western section of the beach, the retreat values were calculated to be 17.5 meters of retreat at Station 1, 18.2 meters of retreat at Station 2, and 21 meters of retreat at Station 3.The eastern section of the beach features a 23.1 meter retreat at Station 4, and a 28.9 meter retreat Orange Stake. Station 5 (furthest east) showed the value for beach retreat between 1934 and 1951, at 33.9 meters (Table 5.4). There was dramatically less beach retreat between 1951 and 1968. During the time period between 1951 and 1968 Station 5 furthest east) had the lowest value for beach retreat at 8.1 meters of retreat. The 1934-1951 and 1951-1968 intervals are the same length, both being 17 years long.

Accretion is observed at Stations 1, 2, 3, 4, and Orange Stake from 1968 to 1991 (Table 5.4), with only Station 5 showing actual beach retreat during this period. The amount of retreat at all stations increases again from 1991 to 2014. The highest amount of retreat on the beach was during the two year timespan from 2012-2014, at -4.22 meters. Station 5 (furthest east) is the only station showing negative (retreat) values or no change for the entire 80 year time span.

Table 5.5: Rate of retreat per year over year-intervals. A rate of retreat was calculated for each interval by dividing the value for retreat by the number of years in that interval. Negative values are assigned to values of inland retreat (to the north) while positive values are assigned to accretion (south). Using the values for each station, an average was taken to represent the average amount of the retreat for the beach as a whole. Values are in meters/year.

	Retreat Per Year (m/year)						
	1934-1951	1951-1968	1968-1986	1986-1991	1991-2010	2010-2012	2012-2014
Station 1	-1.03	-0.69	0.21	0	-0.43	0.35	-1.3
Station 2	-1.07	-1.52	0.20	0.90	-0.57	-0.4	-2.65
Station 3	-1.24	-1.42	0.18	0.56	-0.41	-2.75	-1.95
Station 4	-1.36	-0.97	-0.34	1.18	-0.58	0	-3.05
OS	-1.7	-0.81	0.14	1.1	-0.58	0	-2.45
Station 5	-1.99	-0.48	-0.43	-1.84	-0.69	0	-1.25
Whole Beach =	-1.40	-0.98	-0.01	0.317	-0.54	-0.47	-2.11

The rate of retreat per year also varies between intervals as well as stations. The greatest value for rate of retreat is in the interval between 2012 and 2014 at -2.1 m/year. The years between 1934 and 1951 also had a high rate of retreat at -1.4 m/year. Other, much lower values occurred between 1968 and 1986, and there was accretion at .317 m/year between 1986 and 1991. The rates of retreat at Stations 4, OS and 5 (east end of the beach), are higher on average than the retreat rates at Stations 1 and 2 (west end of the beach). The highest rates for the early years were calculated at Station 5, whereas the highest rates of retreat for more recent years were calculated at Station 4. During a few increments the beach shows slight accretion at certain stations, however overall the beach has a net movement inland.

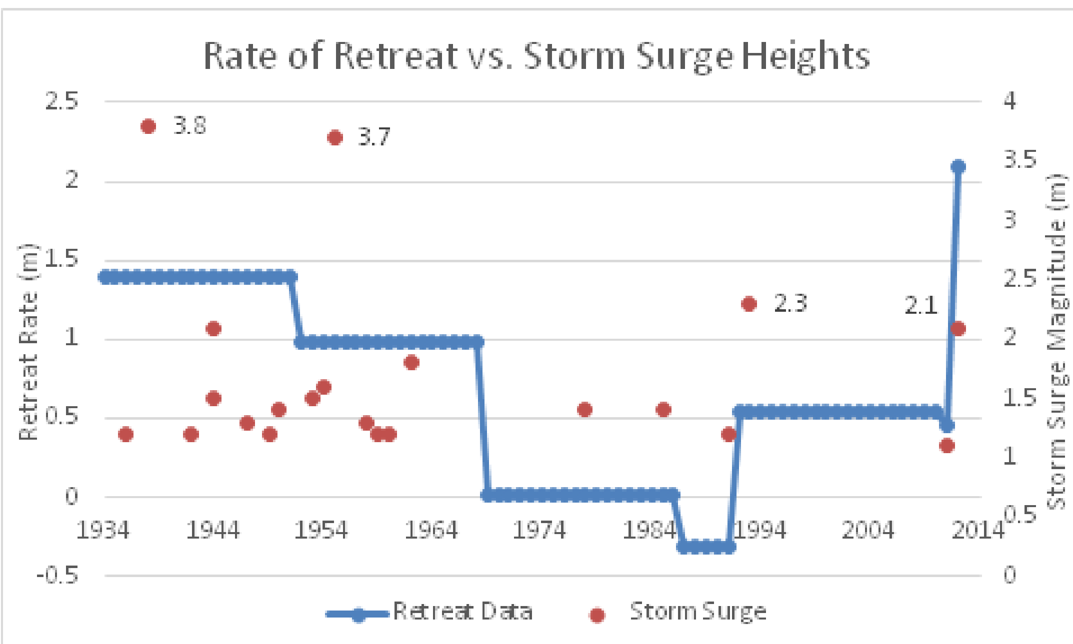

Figure 5.11: Graph of retreat rates (m/year) vs. storm surge heights (m) from 1934-2014

The high rate of retreat rate between 1934 and 1951 corresponds with one category 3 hurricane that featured a storm surge height of 3.8 meters (1938) and one nor'easter that featured a 1.2 meter storm surge (1936). Rate of retreat decreases between 1968 and 1991, and the beach on average is accreting between 1986 and 1991. This corresponds with a decrease in storm activity in the study area. Between 1991 and 2014 two surge heights of significance were observed in 1993 (Nor'easter) and 2012 (Hurricane Sandy) at 2.3 meters and 2.1 meters, respectively. This correlates with an increase in the amount of beach retreat during this time period.

6.0 Discussion

Beaches respond to both daily variations in wave height and tidal levels as well as severe overwash associated with major storm events. Masselink and S. van Hereten (2014) explain that barrier erosion and retreat on mixed-energy barriers is not a gradual process, but an event driven process that is compounded over time. Bushy Point barrier beach's response to storm surge overwash is to retreat inland, and it has been doing so for many years as relative sea-level rose and waves continued to erode the available sediment from the deltas of Glacial Lake Connecticut. Sea-level rise will accelerate this process and intensify coastal vulnerability by increasing the likelihood for overwash scenarios.

Previous studies completed in 2004 and 2009 demonstrate that Bushy Point barrier spit is free to respond naturally to storms and seasonality, because it is an unconstrained system. In comparison to nearby Groton Long Point which is a similarly oriented barrier system that is constrained by a sea wall. Bushy Point beach has been shown in these past studies to respond to increases in wave energy in specific ways.

Bushy Point beach is likely migrating inland via barrier rollover processes caused by partial to complete overwash. In November 2012, the profile changed significantly following Hurricane Sandy (Figure 5.4) which came ashore in southern New Jersey on October 30th 2012. Overwash fans were present on the beach a few days following the storm, and the significant elevation changes at Orange Stake (OS) indicate partial to complete overwash of the barrier system (Figure 5.5a, 5.5b). Figure 5.4 shows a few selected surveys from previous research in 2003 and 2007, as well as three surveys taken in 2012-2013. Evidence from the profiles suggests that the top of the dune at the Orange Stake (OS) lowered in elevation significantly. The profiles also suggest that the beach showed little to no change in location following the 2012 survey at

OS, indicating that a significant event occurred between the years of 2007 and 2012 that led to beach retreat. This permanent shift in the location of the beach occurred during the overwash caused by the storm surge brought with Hurricane Sandy as it made landfall on October 31, 2012.

Retreat rates obtained by photograph overlay and analysis in GIS indicates that barrier retreat has been occurring over the 80 year period from 1934 to 2014. The image of the overlain photographs, digitized in GIS (Figure 5.10) shows the overall retreat of the beach from 1934 to 2014. One of the most important features in the photograph is the breaking through of the beach at the Bushy Point headland after the 1938 hurricane, marking the transition of the barrier from a welded barrier to a barrier spit. This breach is evident in a comparison between photographs taken in 1934 and 1954. Even further back in history, two maps created by NOAA and the USGS in 1848 and 1890 (respectively) show a land connection between the barrier and Bushy Point that was above the high tide line (Figure 6.1, 6.2). In the aerial photographs from 1954 to present day, it is easy to see a rough submerged outline of the location of the breach, signified by a shallow section of rocky sediments and small boulders connecting Bushy Point spit to Bushy Point. Since the breach, the tip of the spit has been the most dynamic section of beach. Sediment buildup at the end of the spit due to longshore drift (determined from previous studies as well as sediment analysis to be traveling from east to west) is clearly visible in the 2014 aerial photograph.

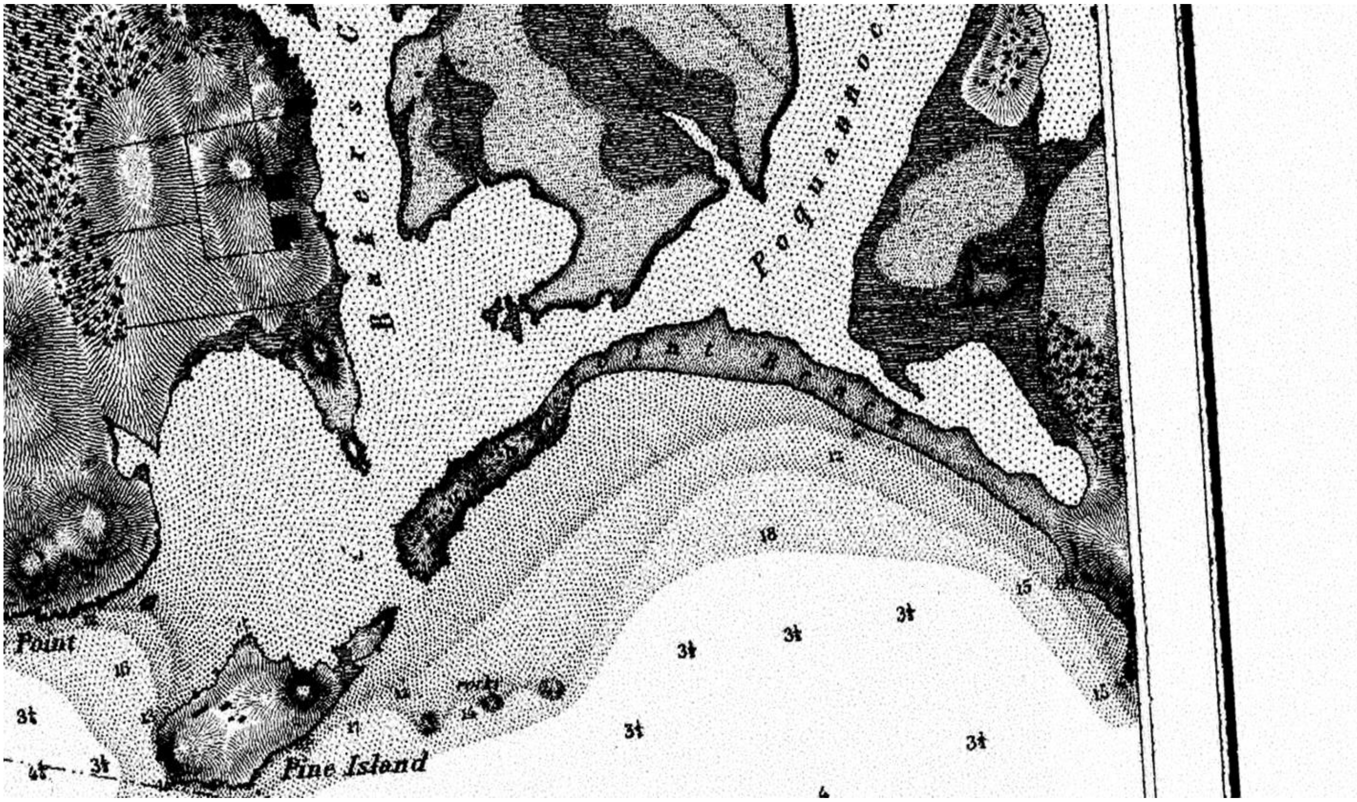

Figure 6.1 is a photograph of a map created by the NOAA of the Connecticut coastline in 1848. This map shows a land connection between Bushy Point and Bushy Point beach that no longer exists. This map could not be georeferenced and overlain in GIS due to a lack of referencing landmarks present in both this image and 2014 aerial photographs.

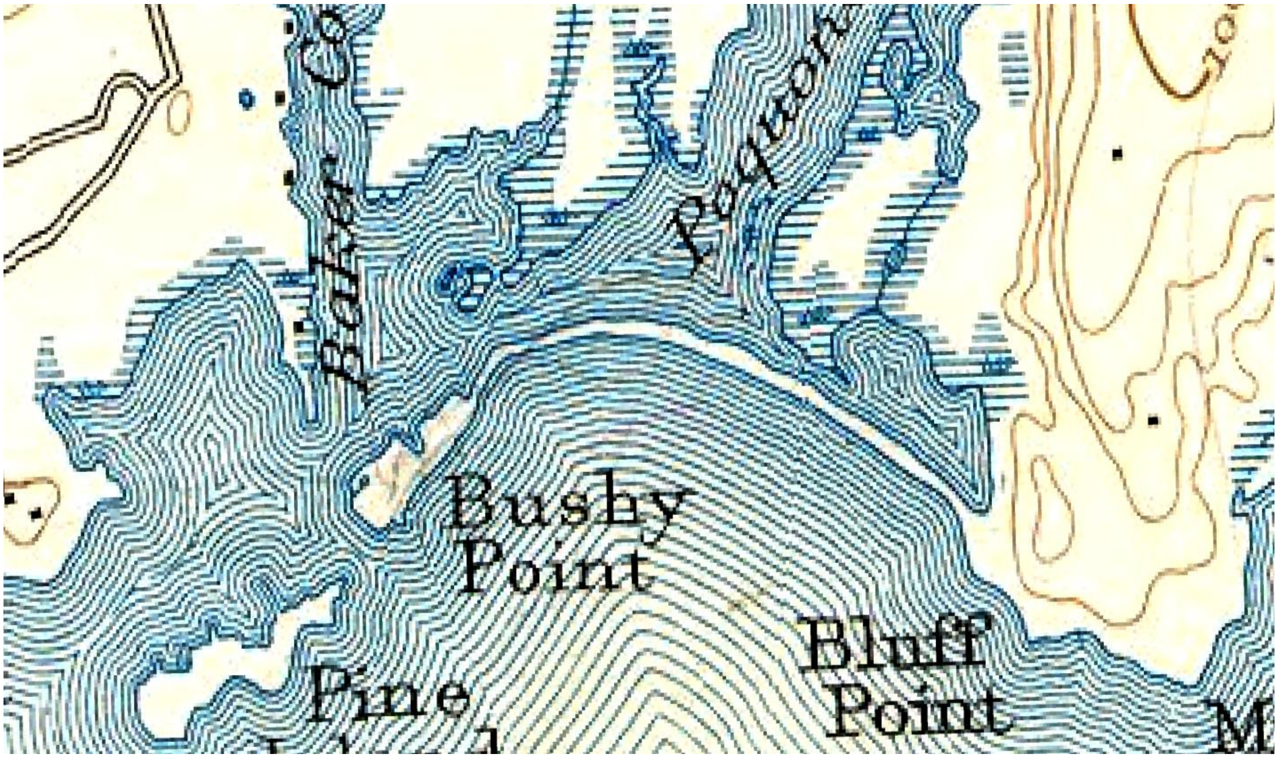

Figure 6.2 is an early United States Geological Survey map of Bushy Point beach from 1890. Much like the map image in figure 6.1, a land connection is evident in this depiction of the beach. This map could not be georeferenced and overlain in GIS due to a lack of referencing landmarks present in both this image and 2014 aerial photographs.

Overwash associated with storm surges accompanying strong tropical systems and nor'easters is the direct and only cause of landward barrier movement. Although a rise in sea level is the main cause of barrier migration inland, and is the cause of Bushy Point beach's migration to the North, during storm events is when this change in the beach morphology takes place as the sand is moved from the seaward side to the landward side in a surge that overwashes the beach. Barrier beaches in the Northeast will not disappear in response to storm surge and relative rise in local sea level, but will instead change its location (Ashton et al., 2007), unless sea-level rise accelerates to a rate at which the beach cannot keep up. What will be lost, rather than the beach itself, is the man-made infrastructure on the beach as it takes on natural changes.

The storm events that affect the study area can be separated into two categories: tropical systems, and nor'easters (Table 5.2). Tropical systems have the potential to cause partial to complete overwash of the beach, which would cause lateral movement inland. However tropical systems are not the most common storm system to affect the study area. Nor'easters are far more common, larger, and are slower moving in comparison to tropical systems (Zhang et al. 2001). Figure 6.4 and Table 5.2 indicate storm surges in southern New England occurring from both tropical systems and nor'easters from 1635 to 1993. The height of storm surges dating back to 1936 has been measured by nearby tide gauges at Newport, Rhode Island, and New London, Connecticut (NOAA/ NOS/CO-OPS, 2000; USACE, 1962). Historical written accounts of storm surge heights were used for storms that predated the tide gauges (Ludlum, 1963) (Donnelley et al. 2001). Data from Hurricane Sandy was not included in this graph at the time, but the surge height at the New London tidal buoy during Hurricane Sandy was determined to be 2.9 meters and 3.4 meters at nearby Napatree Point in Westerly, RI (NOAA 2012). These two values exceed the storm surges that occurred in southern New England during Hurricane Gloria in 1985, Hurricane Donna in 1960 and Hurricane Bob in 1991 (Figure 6.4). The combination of effects of these systems' energies along with tidal forces and longshore drift causes barrier spits in Connecticut to grow in a westward direction and shift inland with each subsequent overwash event.

The longest period of time without a hurricane in the Northeast was 22 years (between 1916 and 1938). Coming in at a close second was the 18 year time period between 1991 and 2009, and the 16 year period between 1960 and 1976 (Iacono, 2001). During these hurricane "dry seasons" and periods of time where storm activity is relatively minimal, barrier beaches will take on a relatively stable state that features short lived changes in the beach face due to tidal and

seasonal wave energy patterns. This is when barrier beaches become home to beach dwelling communities. The last major storm to strike New England before the Hurricane of 1938 was the Great September Gale of 1815, occurring over 100 years before (Donnelley et al. 2001).
It was in the period between 1815 and 1938 when beach communities on Bushy Point barrier spit and nearby Napatree Point in Westerly, Rhode Island were developed and thrived (Coch, 1994). Since the Hurricane of 1938 overwashed both beaches and destroyed both communities, houses were never again built.

The storms that contain enough energy to overwash the beach follow a certain formula, with tracks that are specific. The storm tracks that will bring about strong southeasterly winds or strong southwesterly winds as well as a large storm surge will cause the beach to migrate on large scales, with energy being driven into the most vulnerable parts of the barrier. Additionally, storms that caused the greatest surge in eastern Long Island Sound were storms that made landfall that coincided with high tide. The Hurricane of 1938, Carol in 1956 and Hurricane Sandy all made landfall at around high tide. Donna, in 1980 took a similar track and had comparable wind velocities to Carol however it arrived at low tide, changing the surge height significantly. More recently, the peak of Hurricane Sandy's storm surge arrived at high tide, whereas Hurricane Irene's storm surge arrived at low tide. The beach was overtopped during Sandy and shifted inland significantly. Large scale overwash was not seen during Hurricane Irene.

Rates of retreat for set intervals of time show correlations with storm surge heights (Figure 5.11). The rates of retreat at Bushy Point Beach were highest during two intervals: 1934-1951 and 2012-2014. It is difficult to compare these two values with the highest level of accuracy because of the difference in the number of years in each interval. However the values are important when compared to other intervals in this study. The 1968-1986 (18 years) interval showed an average accretion rate of 0.3 meters per year (Table 5.5). 1968-1986 was also a relatively quiet period storm-wise. The 1934-1951 interval had two major storms with significant storm surges: The Hurricane of 1938 and the Atlantic Hurricane of 1944, with surges of 3.8 meters and 2.1 meters, respectively. Looking at 2012-2014 compared to the rates of retreat for 2010-2012, the numbers more than double. The 2012-2014 interval featured one major storm, Hurricane Sandy which had a storm surge of 2.1 meters that was significant enough to overtop the beach. While the 2010-2012 interval contained Hurricane Irene, sources as well as figure 5.6 indicate that the storm surge associated with Irene did not overtop the beach. The two storms that occurred during the 1934-1951 interval were most likely the cause of the beach's migration. Looking at the year interval as a whole, the entire beach retreated 23.8 meters. If the beach retreated only during storm events with significant storm surges, each event would have pushed the beach an amount that corresponds with the surge height for that particular storm event. However since the interval analyzed is 17 years long, the beach had time following these two major storm events to recover, and may have even begun to accrete seaward at parts of the beach much like in the 1986-1991 interval. Since there was one storm during the 2012-2014 interval it is likely that the beach experienced roll over, was pushed back and had not yet had the time to recover within the two year interval.

The eastern section of barrier spit is particularly vulnerable to overwash, and is moving inland at a rate that is comparatively higher than other points on the beach. Evidence of this vulnerability can be traced from a number of sources. First, the Orange Stake profiles taken in 2003, 2004, 2007 and 2012 (Figure 5.6) show a dramatic change in location of the beach that occurred during Hurricane Sandy in 2012, along with the absence of a dune system, suggesting partial to complete overwash of this section of beach. The beach in the Orange Stake (between Stations 4 and 5 at the eastern section of the beach) profiles shows a 7 meter change in location between 2007 and 2012 (post-Sandy). Additionally, historical retreat values per interval from GIS analysis demonstrate increased movement on the eastern section of the beach, 33.9 meters of retreat at Station 5 (furthest east) during the 1934-1951 interval versus 17.5 meters of retreat per year at Station 1 (furthest west), 7.7 meters of retreat at Station 5 versus 3.3 meters of accretion at Station 1 during the 1968-1986 interval, and finally 13.1 meters of retreat at Station 5 versus 8.1 meters of retreat during the 1991-2010 interval (Table 5.4).

Arguably there is an imbalance of concentrated energy striking the length of Bushy Point beach. Due to the oblong shape of Long Island Sound, there is limited fetch in certain directions. Therefore, only certain wind directions will correspond with significant wave building. For example, a strong west-southwest wind will cause larger, more erosive waves than a straight southerly or straight northerly, because of the distance the wind can travel over the water causing wave buildup (O'Donnell et. al 2014). Seasonal prevailing winds lie primarily in the western quadrants, coming from the northwest in the winter and south-southwest in the summer. Storms that are common to the area are nor'easters, with prevailing winds in the easterly quadrants, and occasionally tropical systems, whose wind direction varies due to positioning of the storm. This fetch from the west will increase activity on the eastern end of the barrier, making it vulnerable to increased wave energy and storm surge. Because it is the positioning of large storms that affect the wind directions that dominate a certain area, it is entirely possible that as a storm moved through the area, the winds shifted from the east-southeast to the west-southwest, changing the wave angle and focusing more energy onto the eastern side of the beach.

Additionally, the low elevation of the eastern-most section of beach will make it vulnerable to further overwash events, therefore increasing its rate of movement inland.

The eastern-most section of Bushy Point beach was overwashed completely during the storm surge associated with Hurricane Sandy in 2012, and retreated several meters during this event. This type of overwash has happened previous to 2012, evidence of which lies in a photograph of the eastern end of the beach immediately following the Hurricane of 1938 (Figure 6.3). This photograph clearly shows a breach in the barrier very close to Bluff Point on the eastern section of beach, near present day Station 4. This breach in the barrier was quickly filled in by the town of Groton following the storm, and has not broken through due to overwash since the 1938 storm. The photograph also is an indicator of the relative height of the storm surge, depicted by how much sand was transported from physical location of the beach to points on the Bluff. Visible in the center of the photograph is evidence of large amounts of sand being deposited just to the east of the barrier on the lowlands of Bluff Point, where there is presently a walking path. It is entirely possible that with enough storm-surge energy the section of beach could breach again, causing significant changes to the dynamics of the eastern section of this barrier beach.

Figure 6.3: A photograph of the eastern section of Bushy Point beach and Bluff Point immediately following the hurricane that made landfall on September 21st of 1938. A breach in the eastern section of the barrier is visible in the bottom left of the image.

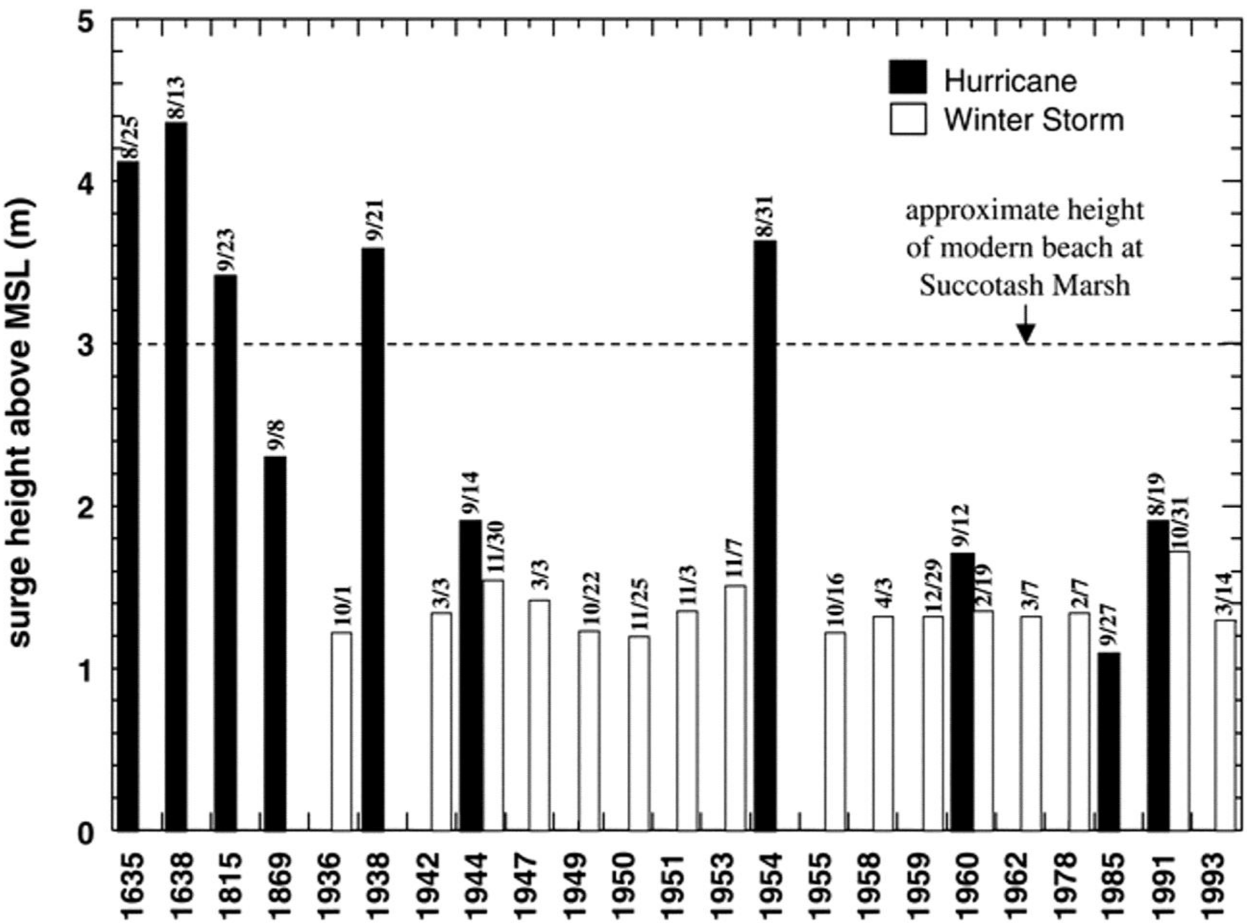

Figure 6.4: Storm surge heights in southern Rhode Island and Southeastern Connecticut relative to contemporary mean sea level (MSL). The height of storm surges dating back to 1936 has been measured by nearby tide gauges at Newport, Rhode Island, and New London, Connecticut (NOAA/ NOS/CO-OPS, 2000; USACE, 1962). Historical written accounts of storm surge heights were used for storms that predated the tide gauges (Ludlum, 1963) (Donnelley et al. 2001).

Lower dune heights visible in the 2012-2013 profiles (Figure 5.4) indicate that the entire beach is becoming more vulnerable to overwash scenarios. Coupled with a rising sea level, which is an estimated 2.25 mm/year between 1938 and 2014 at New London Ledge Light (Connecticut Department of Energy and Environmental Protection, 2013), a storm surge that was 3.8 meters in 1938 will have the same if not a greater effect on the beach as a 2.1 meter storm surge in 2012. Masselink and S. Van Heteren (2014) explain that the increase in mean sea level will increase the severity of storm surge impacts on beaches, and cause an upward shift in coastal flooding and barrier erosion. Sea-level rise increases Bushy Point beach's vulnerability to these types of severe overwash events, and impacts will increase as sea level continues to rise.

Sediment analysis indicates that longshore currents are moving from east to west. This supports Komar's (1998) definition of barrier spit growth as a function of sediment transport due to longshore currents. Sediment that has the time to be worked and re-worked by continuous wave action will be smaller in size than sediments are newly eroded, in this case off the bluff at Bluff Point. Further evidence of longshore drift is provided by the visible lengthening of the spit in aerial photographs taken between 1934 and 2014. Additionally, the sorting index values calculated at the five stations down the length of the beach (Table 5.1, Figure 5.8) acts as a further indicator of longshore drift. Poorly sorted sediments are found at the bluff whereas moderate to moderately-well sorted sediments are found at the far west end of the barrier. Since smaller sediments are more easily transported by water (Ritter et al., 2002), the smaller, sand sized sediments will move further laterally down the beach face than the larger gravel-pebble sized sediments. Water is an excellent at sorting sediments, which is why coastal sediments are very well sorted (Ritter et al., 2002). The more time water and waves can interact with sediment on the beach face, the better sorted the sediments will become.

Sorting index also gives insight to the wave energy along the length of the beach. Stronger more erosive wave energy will remove smaller sediments from the beach face while leaving the larger clasts. The sediment sorting indexes in general increase between Stations 1 and 5, indicating that the poorly sorted sediments are found near the Bluff Point end of the barrier spit and the best sorted sediments are found at the west end of the spit near Bushy Point (Figure 5.8). Looking at the specific stations themselves, Stations 1 and 2 have the same pattern of the dune having the lowest value of sorting index and the berms and beach faces having slightly higher sorting indices. For Stations 4 and 5, the two Stations closest to Bluff Point on the eastern section of the beach, the opposite is true. For these two stations, the dune has the highest sorting index value compared to the berm and beach face at each station. These values were unexpected and do not follow the pattern of the rest of the beach. If the dune had never been overtopped, it is unlikely that the sediment sorting indices would be this high. It is also important to note that this is the same section of beach that was breached after the 1938 hurricane, and was filled in by the City of Groton following the storm, and these high sediment sorting indices could be attributed to foreign sediment put into place to fill in the breach caused by the Hurricane of 1938.

The sharp increase in sediment sizes at the berm and beach face at Stations 4 and 5 is compliant with Komar's (1998) description of coarse sediments present in the swash zone of dissipative beaches. Accretion on the beach is caused by a period of less erosive waves leading to an increasingly depositional pattern, which is responsible for the formation of the pronounced berm near the Bluff. This section of the beach is not only coarse, but also significantly steeper than the beach at Stations 1, 2 and 3 (Figure 5.7). This is a direct response to wave action on this section of beach which is increased by the process of wave refraction around Bluff Point. This section of beach will have a steeper sloped beach face on windier days and a shallower sloped beach face on calmer days.

The beach has only slightly changed since Hurricane Sandy. The surveys taken from Orange Stake show a significant shift in beach location and change in beach elevation due to surge and overwash energy produced by Hurricane Sandy in October of 2012. The shape of the beach profile in the 2013 surveys shows the development of a berm. A well pronounced berm is a result of sediment being deposited on the beach face as the beach undergoes natural recovery following high wave energy events. This effect is also seasonal. What is also interesting about Station 4 is that it is has a relatively undeveloped dune crest in comparison to other points on the barrier spit. This could still be evidence of the overwash that occurred in October of 2012.

Why Study Bushy Point Beach?

A question that arises is what the migration of the barrier beach at Bushy Point would do to the inlet that allows for drainage of the Poquonnock River. The inlet has been narrowing since measurements were first taken on the inlet in 1934 through aerial photographs (Malone and MacBroom, Cook 1995). The strength of tidal ebb versus the strength of tidal flow is the main controlling factor for sediment transport through the inlet. Other factors include bay tidal prism, inlet geometry and the geometry of the back-barrier. Changes in sea level will affect the hydraulics of coastal inlets much like this one, adjusting levels of ebb dominance and flood dominance in these systems (Ashton, Donnelly and Evans 2007).

The inlet just to the west of Bushy Point and its adjacent barrier beach is a flood dominated system, and has been ever since creation of the Poquonnock Reservoir in Groton. The dam was built in 1902, and limited the amount of natural out flow from the river (Malone and MacBroom, Cook 1995). Because the system is now flood dominated, material from the front side of the barrier transported by longshore drift along the beach from east (Bluff Point) to west (Bushy Point, and the end of the spit) is being transported by the strong flood tide once it reaches the end of the spit. This creates a periodic, constantly changing delta just to the north and west of the barrier, being comprised of mainly beach face sediments from the barrier. This delta is visible in the more recent aerial photographs of the beach, due to an increase in photograph quality in more recent years. If the beach continues to migrate inland, it is logical to say that the inlet will continue to narrow, as it has been for the past century in response to the changing location of the beach. The inlet is still able to transport the necessary volume of water in and out of the inlet due to the tidal prism of the estuary. As the inlet narrows, the flood tide will become stronger and stronger eroding away at the end of the spit. If longshore transport is unable to replenish the eroded sediment at the west end of the barrier in a timely manner, this end of the beach will be unable to sustain itself with the strong flooding tide. This is to say that although the west end of the barrier is the most rapidly changing feature of the barrier, there is the possibility of a limit to its movement inland, because of the tidal inlet. If the inlet were to close due to the natural migration of the barrier in response to rising sea level and overwash events, the estuary (whose flow ebbs if the Poquonnock River dam overtops) would find another path for water drainage at a vulnerable location on the barrier beach.

Wind, Waves and Surge: The Future of Bushy Point Barrier Spit

The IPCC estimates that the mean global sea level has risen on average about 1-2 mm per year in the 20th century alone, and will continue to rise due to an increase in average global temperatures since the Industrial Revolution of the late 19th century (Van Alast 2006). Most recent studies indicate that sea-level rise is beginning to accelerate, and may approach rates experienced in the early and mid-Holocene periods (Masselink and S. van Hereten 2014). With roughly 55 percent of Americans living within fifty kilometers of the US coast (Lam et al., 2009), this change in sea level is an important factor affecting coastal processes, especially rates of barrier migration and erosion.

Major hurricanes that strike the northeast bring with them consequences similar to those that strike southern states (Coch 1994). A few factors control this. Hurricanes moving up the eastern seaboard usually pick up speed as they begin to interact with new air masses of the further north latitudes. Additionally, the slope of the continental shelf off the coast of Long

Island creates the potential for highly damaging storm surge. The narrowing width and gentle slope of the shelf allows for a greater amount water to be driven ashore both onto the western edge of Long Island and the New York City metro area. The lack of protective dunes in the northeast causes an even greater potential for coastal flooding, as the protective barriers the northeast once had have been either developed, or eroded back. Finally, the unprecedented increase of population on the coast puts the Northeast in an extremely vulnerable state (Coch 1994). Major cities include New York, Boston and many other cities and their suburbs.

It is difficult to predict exactly the scenario that will ensue if global temperatures keep increasing. Masselink and S. van Heteren (2014) briefly state that the connection between severe storms and an increase in average global temperatures is not straight forward. Future storms will be more difficult to model because of changes in the atmospheric conditions all over the world. There is little consensus amongst scientists regarding the increasing frequency and intensity of storms associated with climate change (Masselink and S. van Heteren 2014). However what is known is that storms like the Hurricane of 1938 and Hurricane Sandy are more than capable of striking an increasingly vulnerable Northeast corridor, and climate change will only add to the complexity of these systems.

Further Research

Bushy Point Barrier spit is a complex system that involves many constantly changing variables. In order to fully understand this system, repeated surveys would need to be done on a frequent basis at each of the five survey stations, keeping in mind the meteorological activity and wave heights. Taking elevation profiles before and after storms at each survey station would increase the confidence in the changes in the profiles caused by specific storms. Additionally, having tide, wind, wave and barometric pressure data for the specific site will provide insight to the exact combination of such necessary to provide significant changes in the beach.

In Geographic Information Systems, using smaller year increments would be useful for gaining more insight about how the beach behaves during active and relatively inactive storm periods. The aerial photographs of Bushy Point barrier spit used in this thesis were from a variety of different sources, taken at different times of year and at different tides. There is no way to determine what level the tide was at when the photograph was taken. When digitizing, the shoreline was determined by where the surf zone met the beach face, and that surf zone line was digitized in each photograph. Additionally, older photographs from 1934 and 1951 were difficult to digitize due to the low quality of the imaging during that time period. It is important to remember the issues of working with an imperfect system when making conclusions about Bushy Point barrier spit and its movement inland and response to storm activity. Finding high resolution photographs and focusing on statistical error associated with photograph overlay would be a logical extension to this project.

The beach was divided into three polygons in GIS in order to determine area changes for each section of beach. The very western tip of the barrier spit was not included in the calculations for retreat. There are a few specific reasons for this. First, the very end of the spit is the most dynamic section of beach and is in constant change on a very visible scale. Second, the spit is not necessarily retreating inland, but rather it is growing westward as sediment is added to it from the beach face through the processes of longshore drift. Finally, the end of the spit is highly influenced by the Poquonnock River inlet, which is a tidally influenced inlet just to the west of the barrier spit. These reasons make it necessary to omit the end of the spit from the calculations for barrier retreat.

7.0 Conclusion

Previous studies show that Bushy Point barrier spit is free to respond naturally to storms as well as sea-level rise, because it is an unconstrained system. In comparison to nearby Groton Long Point, which is a similarly oriented barrier system that is constrained by a sea wall, Bushy Point beach has been shown in the past to respond to increases in wave energy by changing its morphology. The results conclude that Bushy Point beach retreat is due to the frequency and intensity of over-wash events. This is considered a barrier system's natural response to a rise in sea level, according to research by Masselink and van Hereten (2014) and Komar (1998). Overwash events are not a daily occurrence on Long Island Sound but are driven by storm energy. The next major event to strike the northeast will bring with it the potential for severe coastal change. The highest rate of change in Bushy Point barrier beach was in the late 1930's, referring to the breach between Bushy Point and the barrier itself. Since that initial breach, the end of the spit has been in a state of constant change, lengthening and retreating with each overwash event. Although major events have a significant effect on the morphology of this beach, smaller events and every day weather activity that does not produce overwashing surge also have an effect on the longshore transport, which is producing changes to the end of the spit.

Bushy Point beach has shown changes in its location over the 80-year period from 1934 to 2014. Its vulnerability is increasing due to rising sea levels and changes in barrier morphology. The absence of the dune observed in the 2012-2013 profiles indicate that this system is more vulnerable to overwash scenarios due to the lowering of elevation of the beach itself, making it much closer to sea level.

Bushy Point barrier spit, like all barrier systems, is a highly complex system involving variables that are in a state of constant change. With the predicted rise in sea level and the potential for more intense storm activity, overwash potential and coastal vulnerability will increase. With continued sea-level rise the beach will continue to retreat to the north, working with the available sediment supply of the Poquonnock River delta. When the system runs out of sediment to work with, it will stop retreating and instead erode, much like what is happening at Groton Long Point beach.

Barrier systems are extremely important to study. These naturally changing systems act as protection for fragile ecosystems as well as coastal infrastructure. These ecosystems and infrastructure are put into jeopardy when these systems are overwashed, their dune system is flattened and the barrier migrates inland. The interface between land and sea is an extremely chaotic interaction of systems and is a challenging topic of study. Additional research is necessary to be able to accurately describe how these systems act naturally and the variables interact. This information needs to be taken into account when attempting to effectively provide coastal management solutions.

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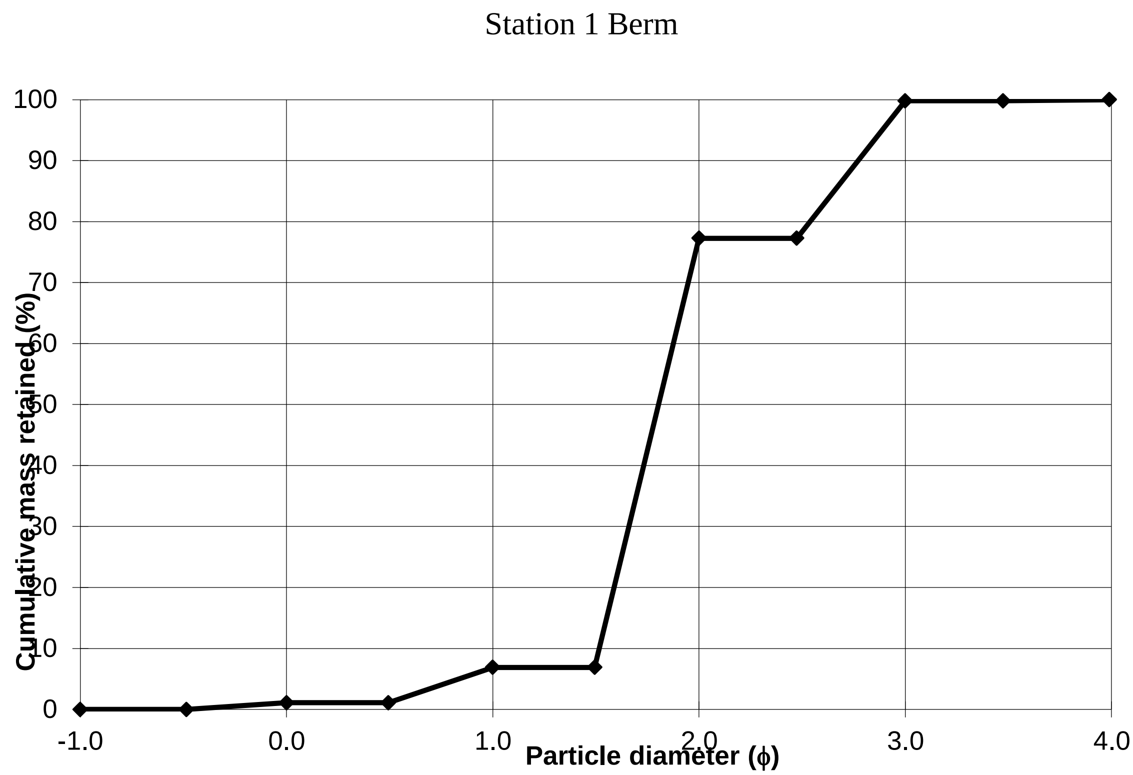
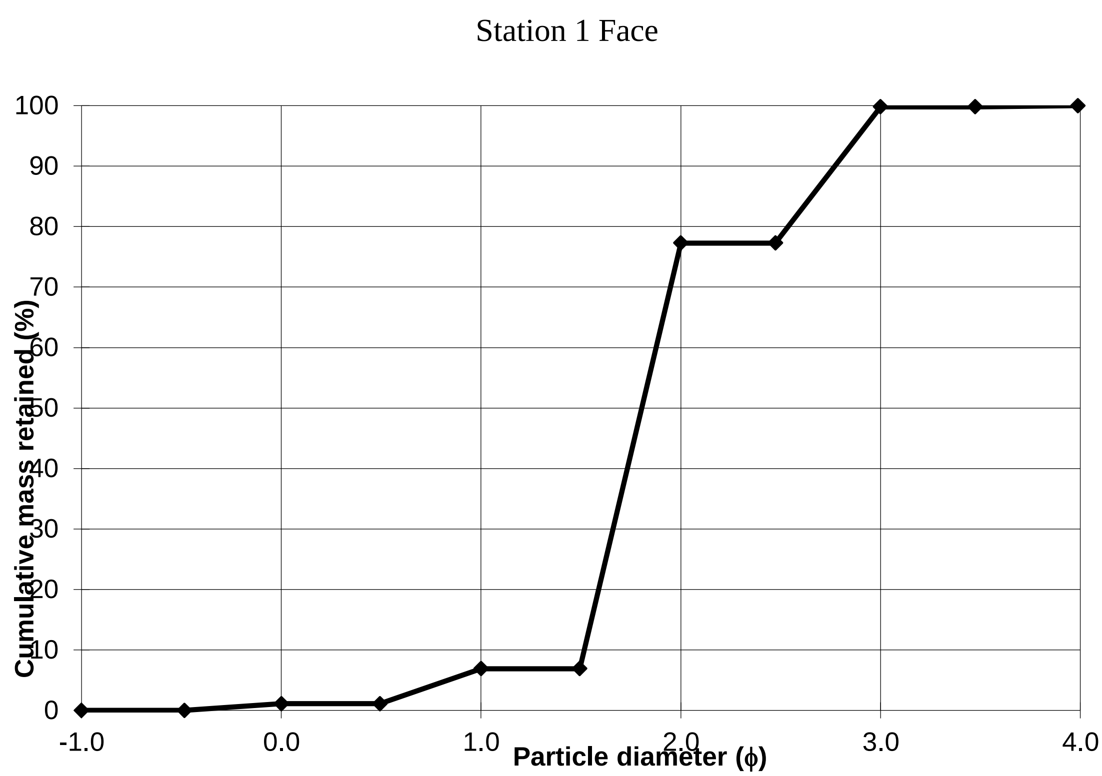
Appendix A

SEDIMENT ANALYSIS





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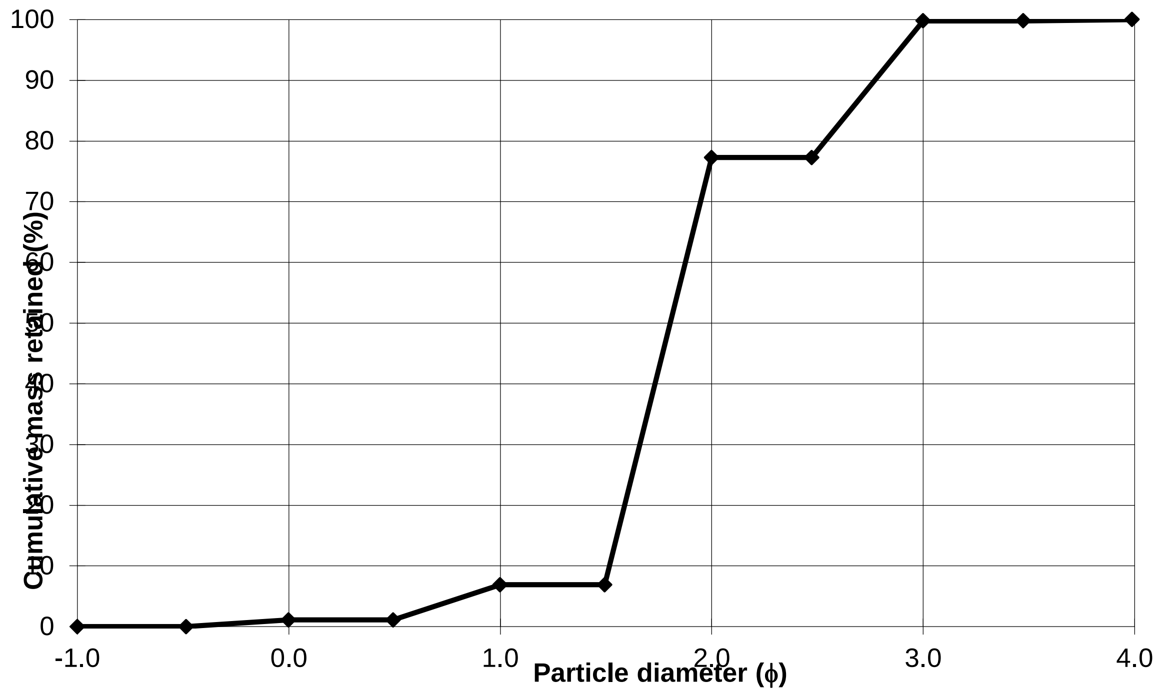

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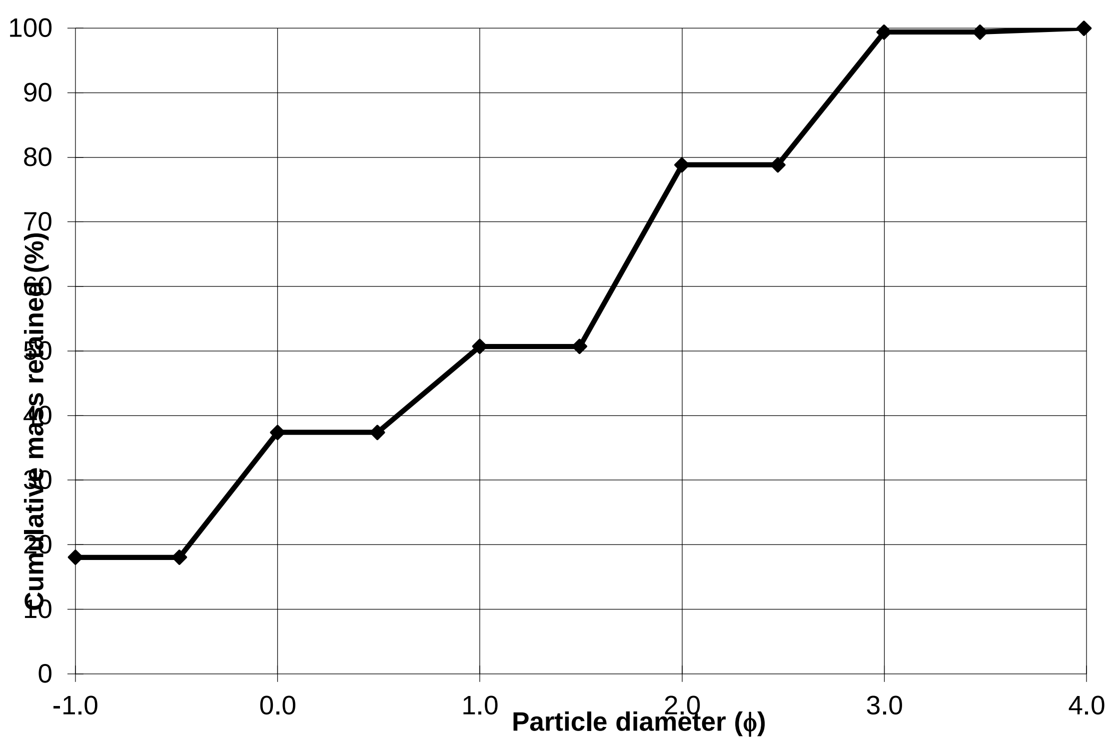

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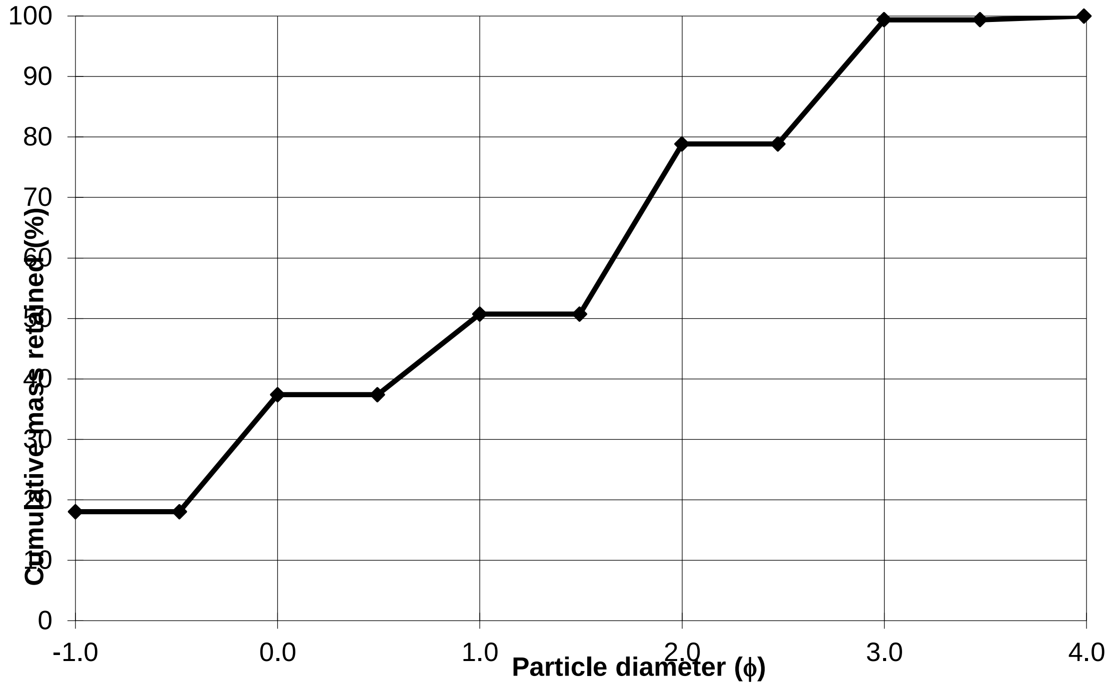

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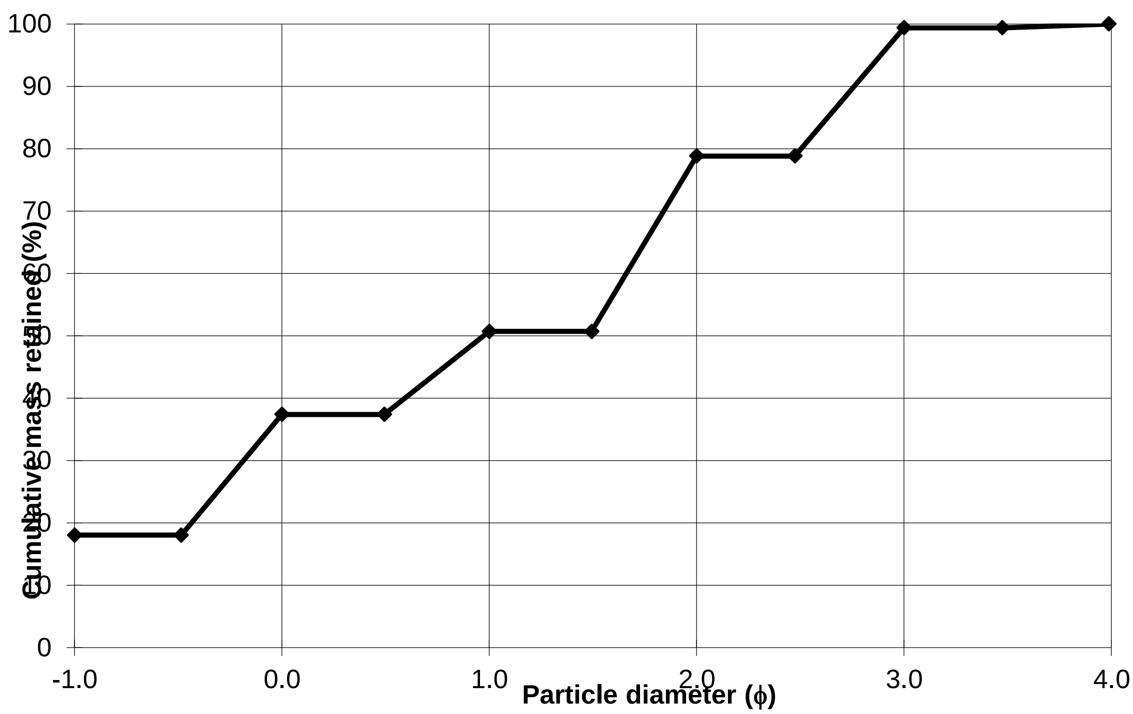

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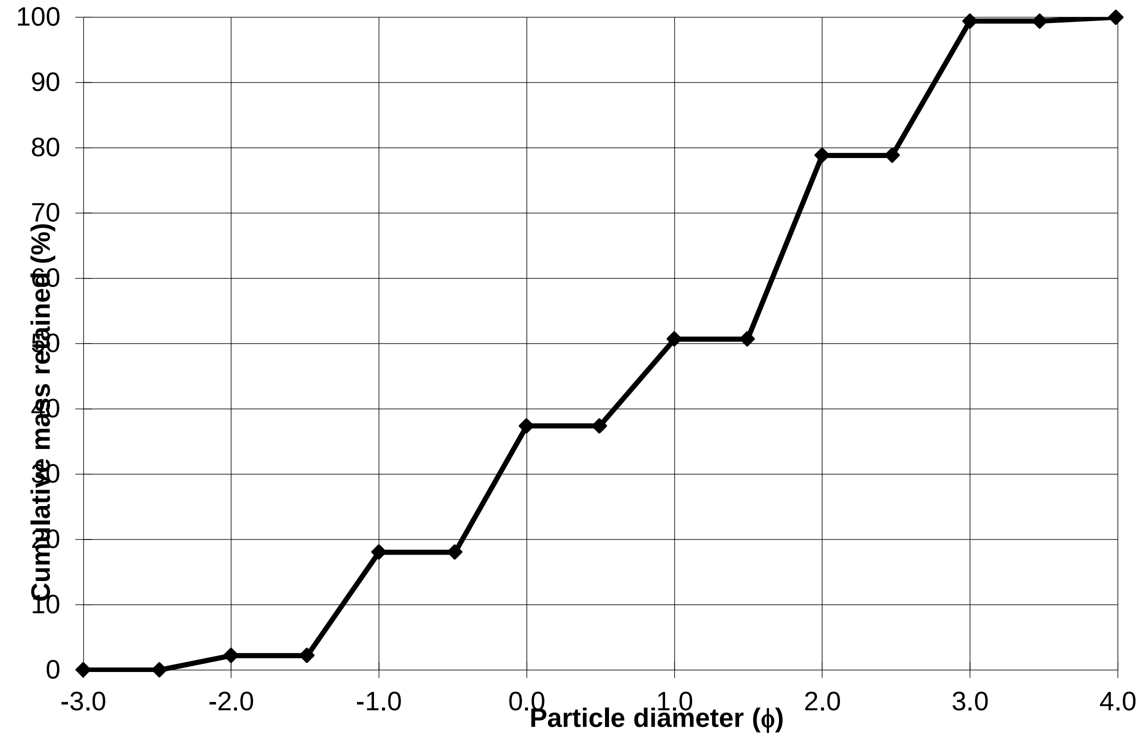

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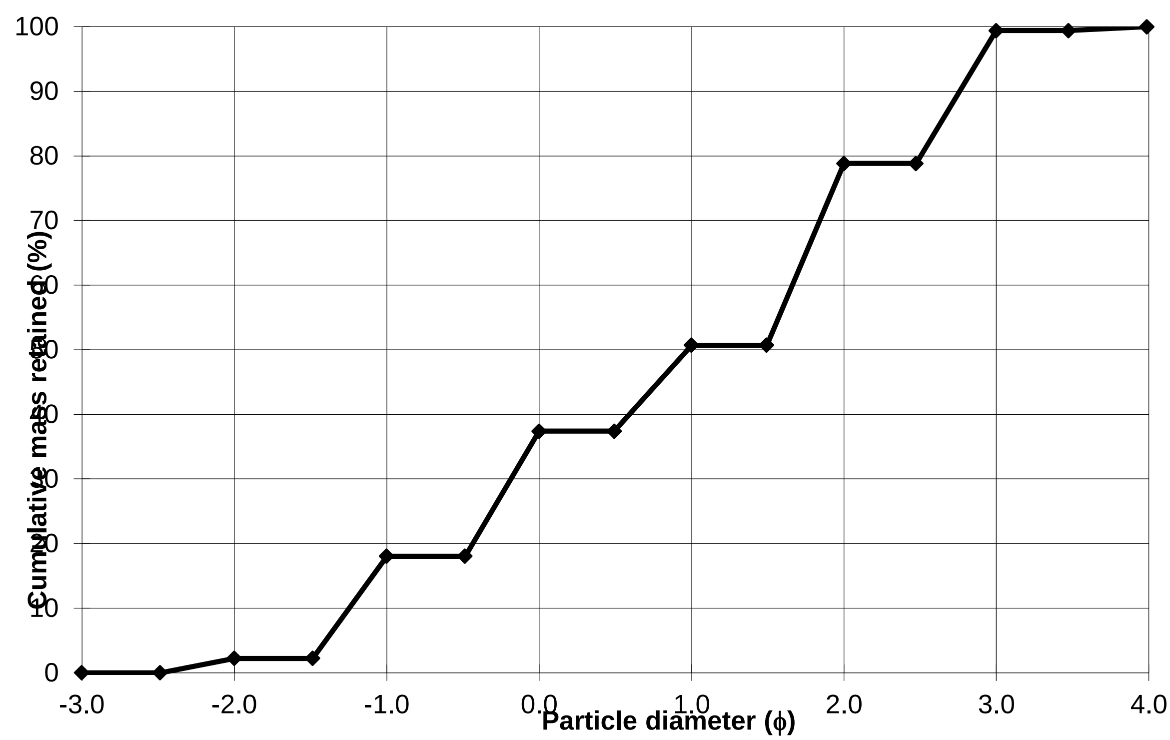

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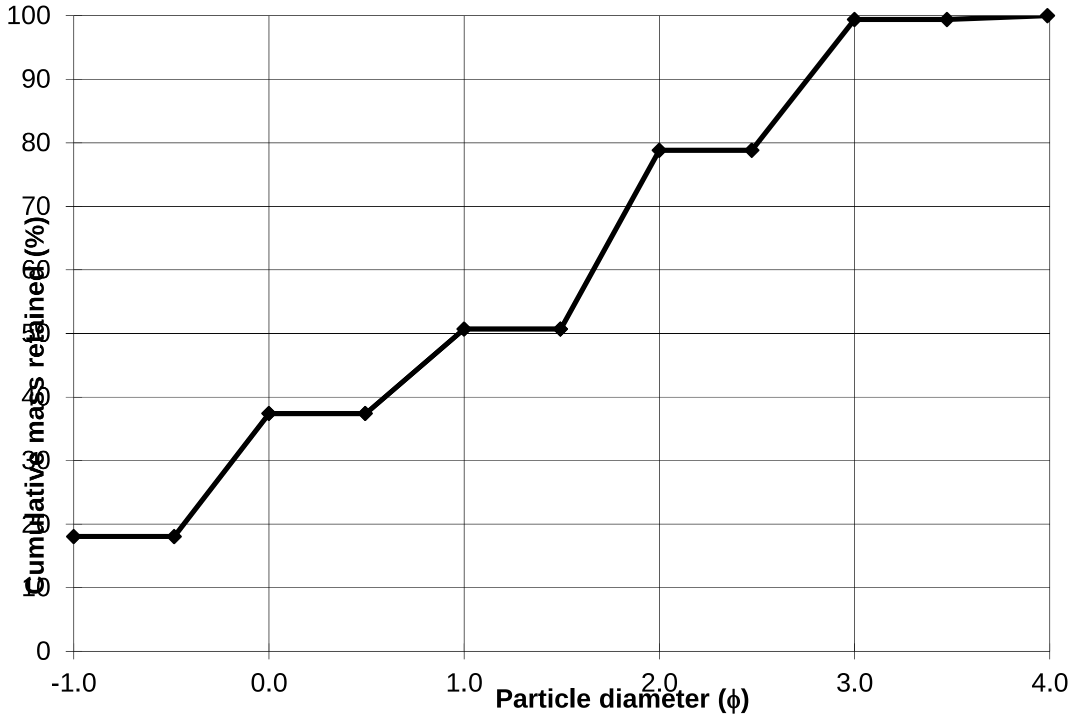

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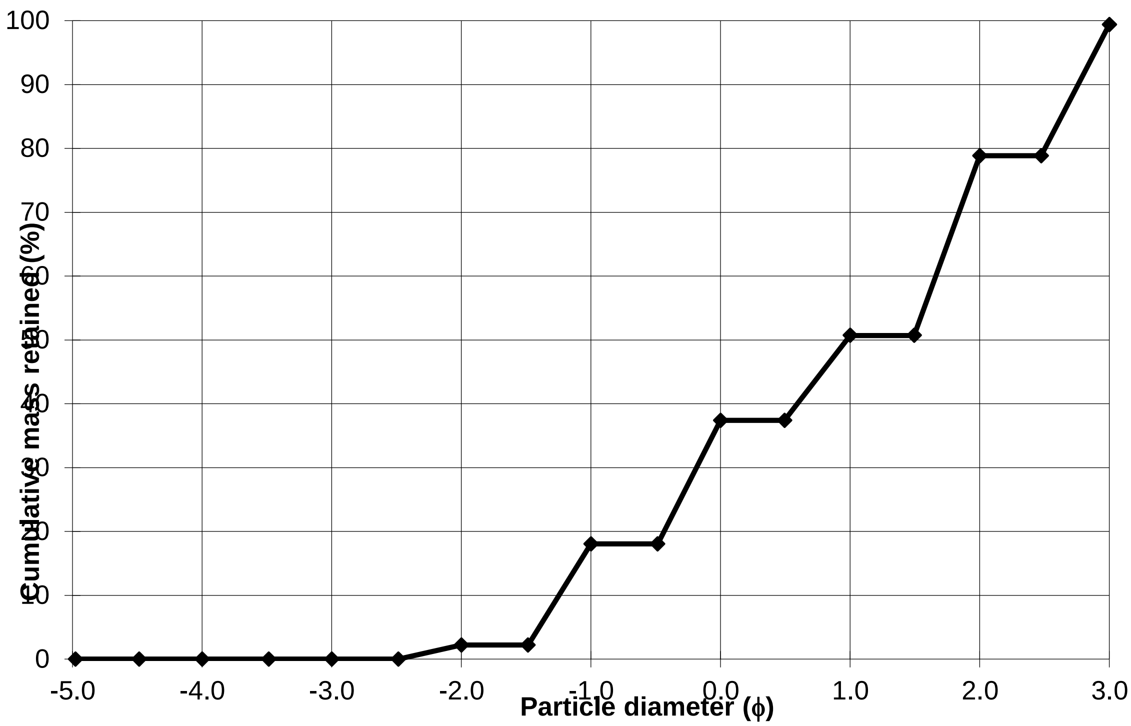

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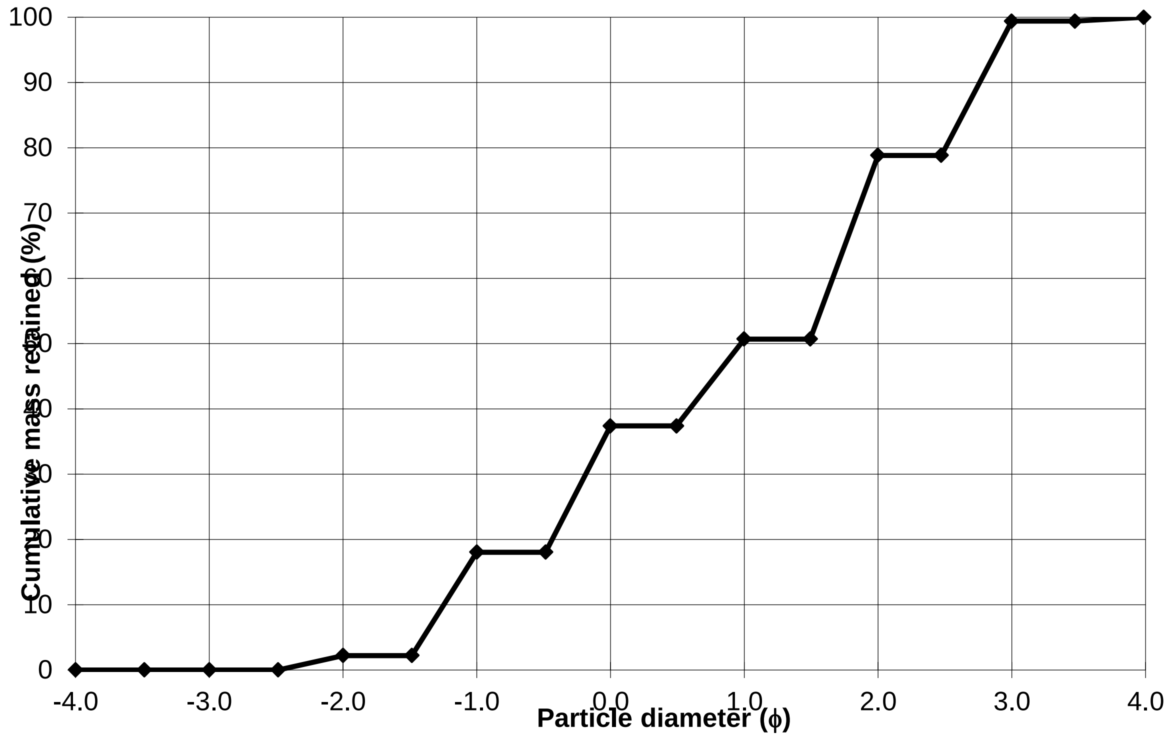

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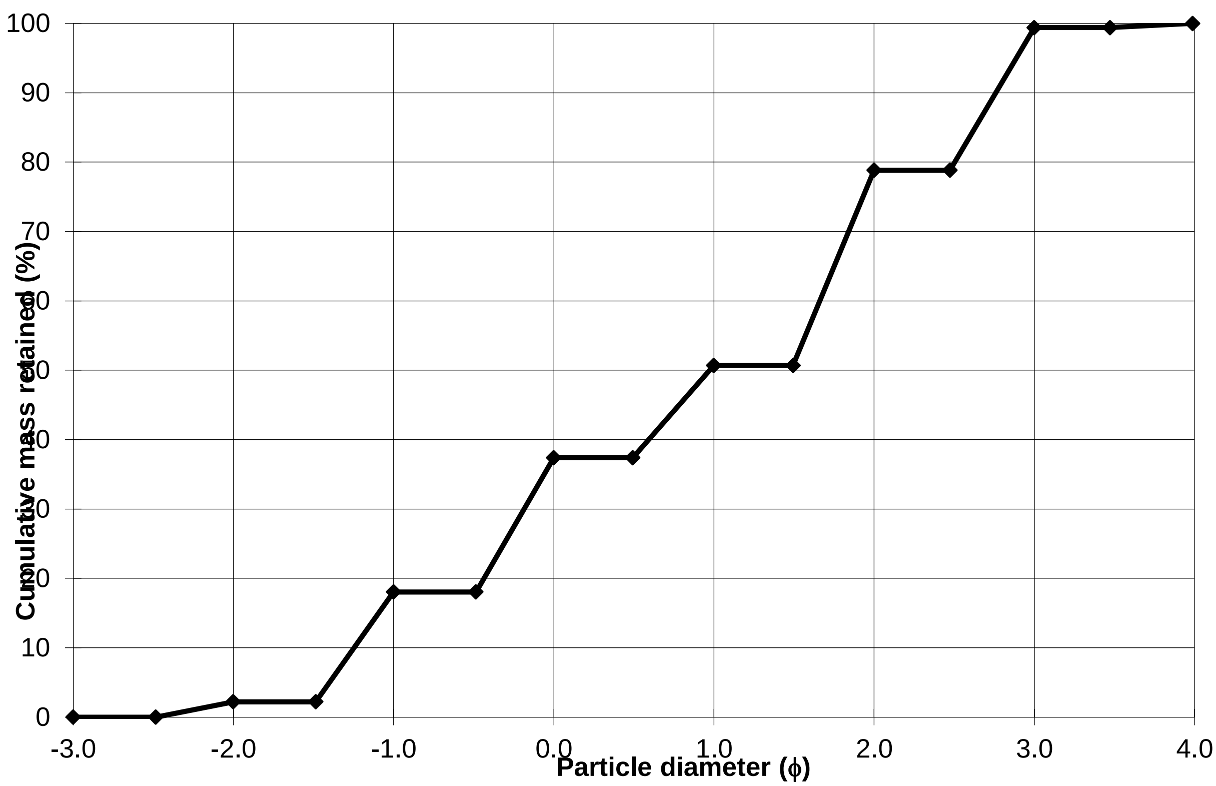

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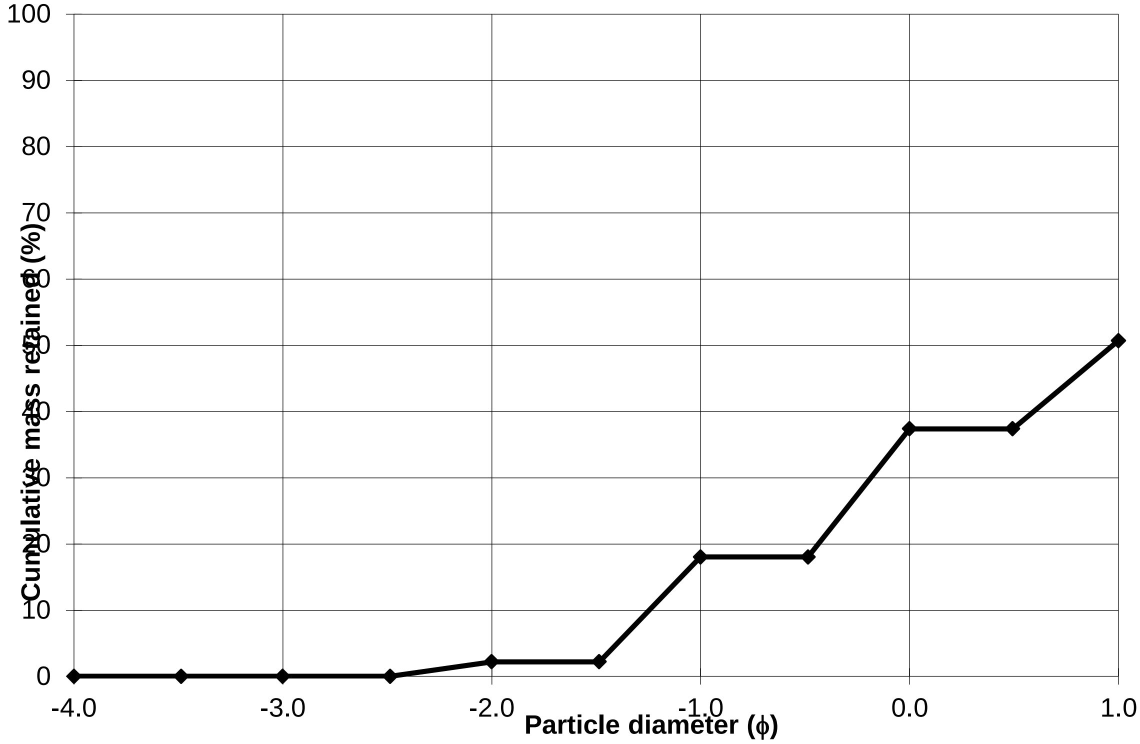

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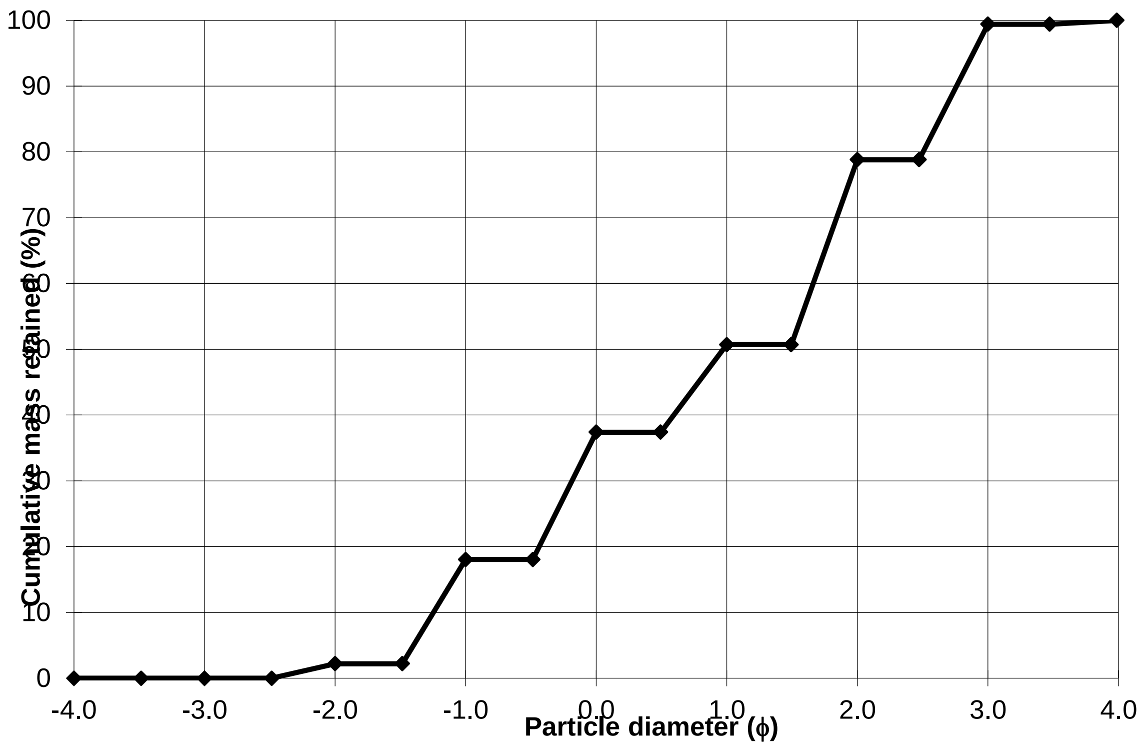

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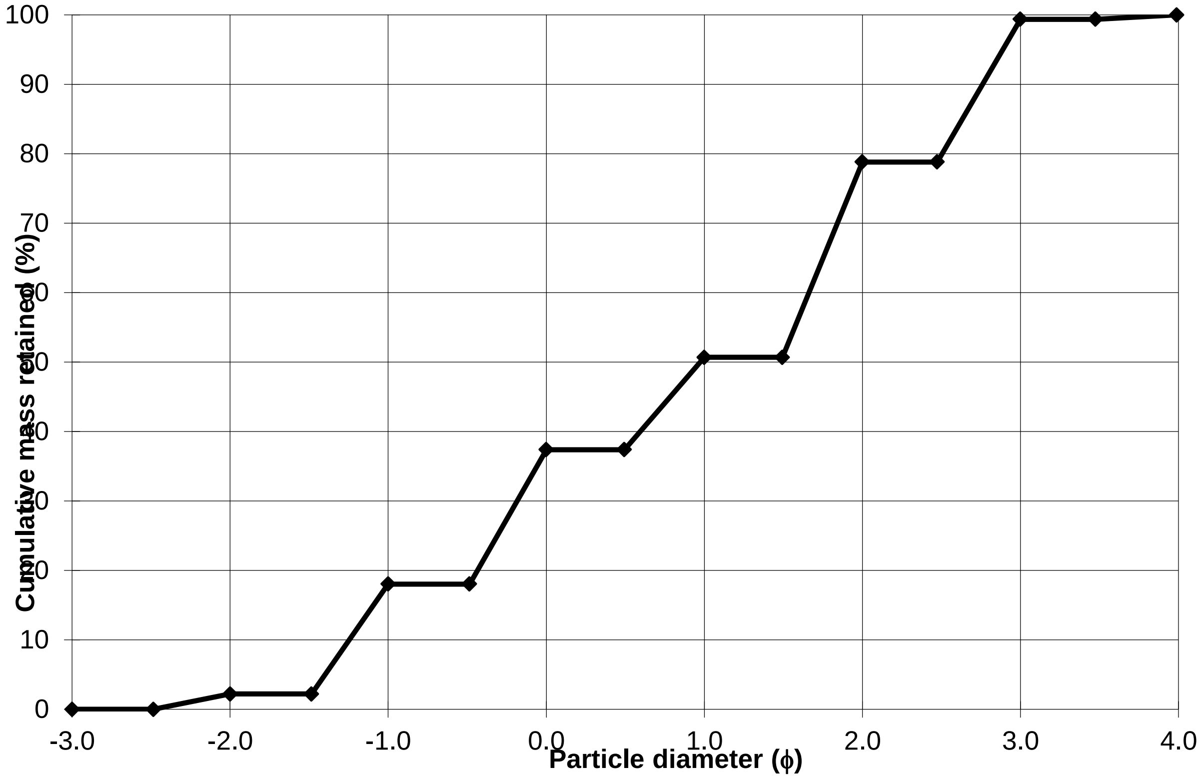

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#1 Berm** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#1 Face** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
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D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
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(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

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SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#1 Dune** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#2 Berm** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#2 Face** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#2 Dune** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#3 Berm** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#3 Dune** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#3 Face** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#4 Dune** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#4 Face** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SAMPLE STATISTICS

SIEVING ERROR: 1.2%

SAMPLE IDENTITY: **#4 Berm** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (*Sk*):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (*K*):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SIEVING ERROR: 1.2%

SAMPLE STATISTICS

SAMPLE IDENTITY: **#5 Berm** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	μm	μm	φ	μm	φ	
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SIEVING ERROR: 1.2%

SAMPLE STATISTICS

SAMPLE IDENTITY: **#5 Dune** ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	μm	μm	φ	μm	φ	
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

SIEVING ERROR: 1.2%

SAMPLE STATISTICS

SAMPLE IDENTITY: **#5 Face** ANALYST & DATE: ,

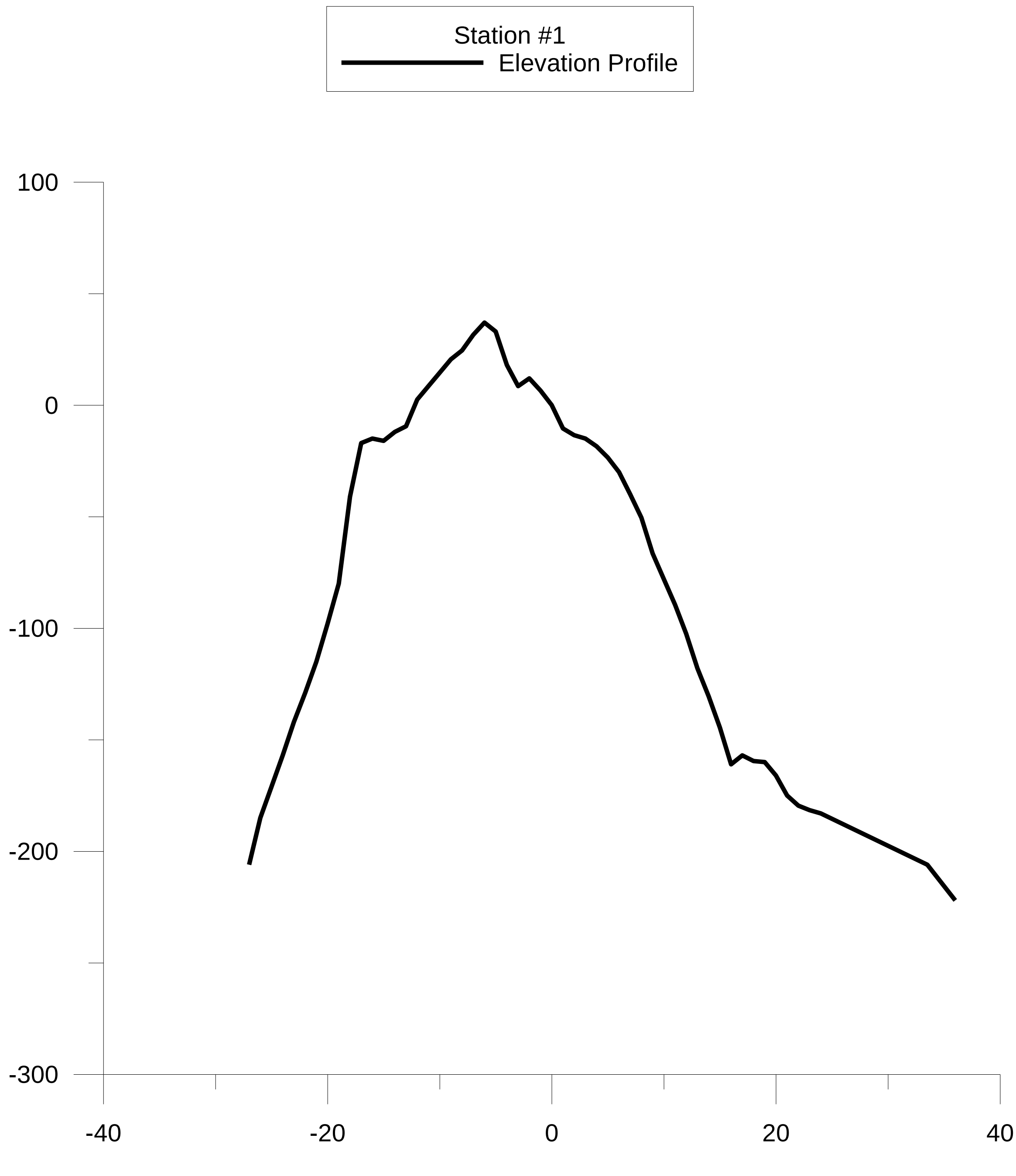
SAMPLE TYPE: Trimodal, Poorly Sorted TEXTURAL GROUP: Sandy Gravel

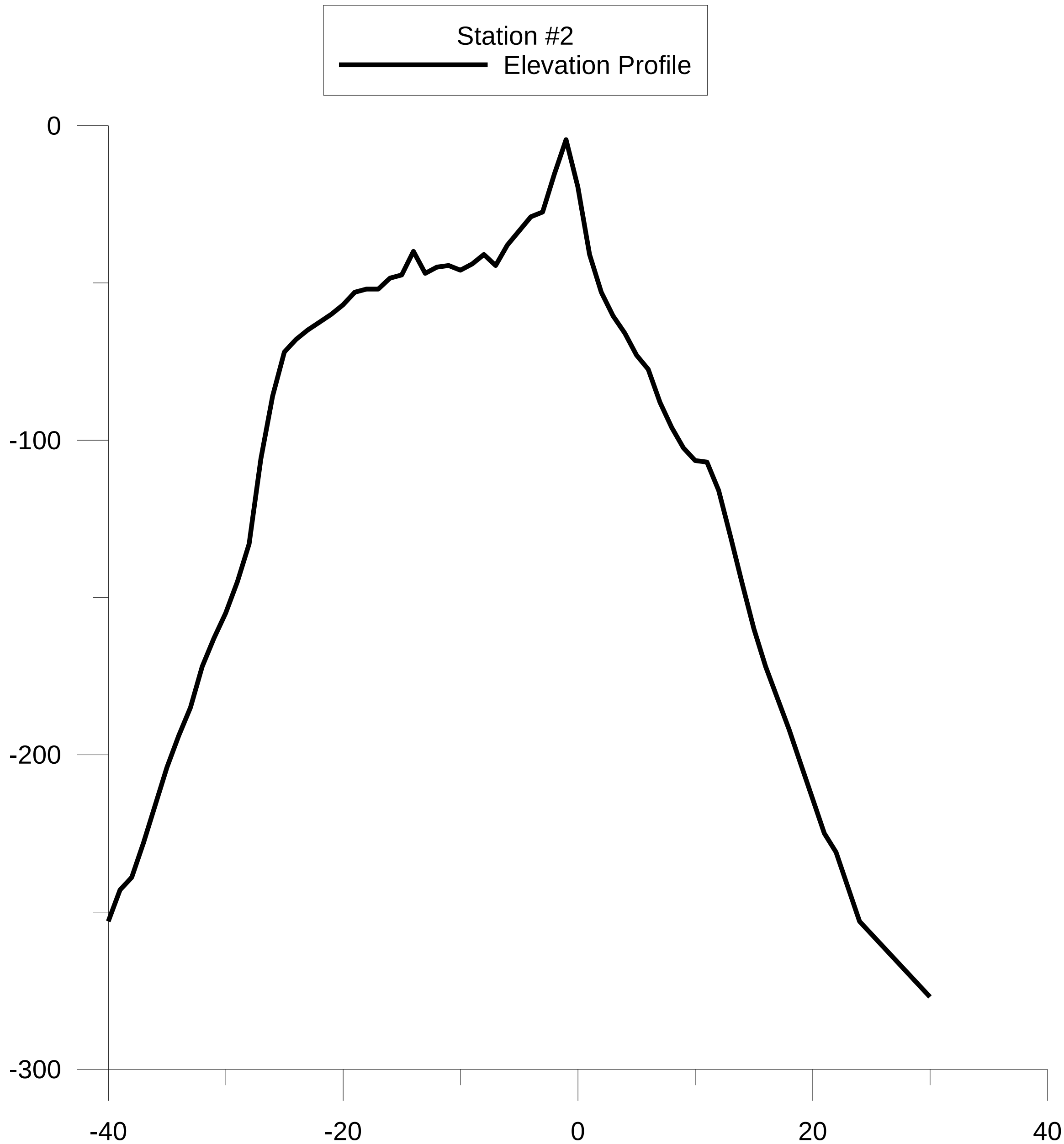
SEDIMENT NAME: Sandy Very Fine Gravel

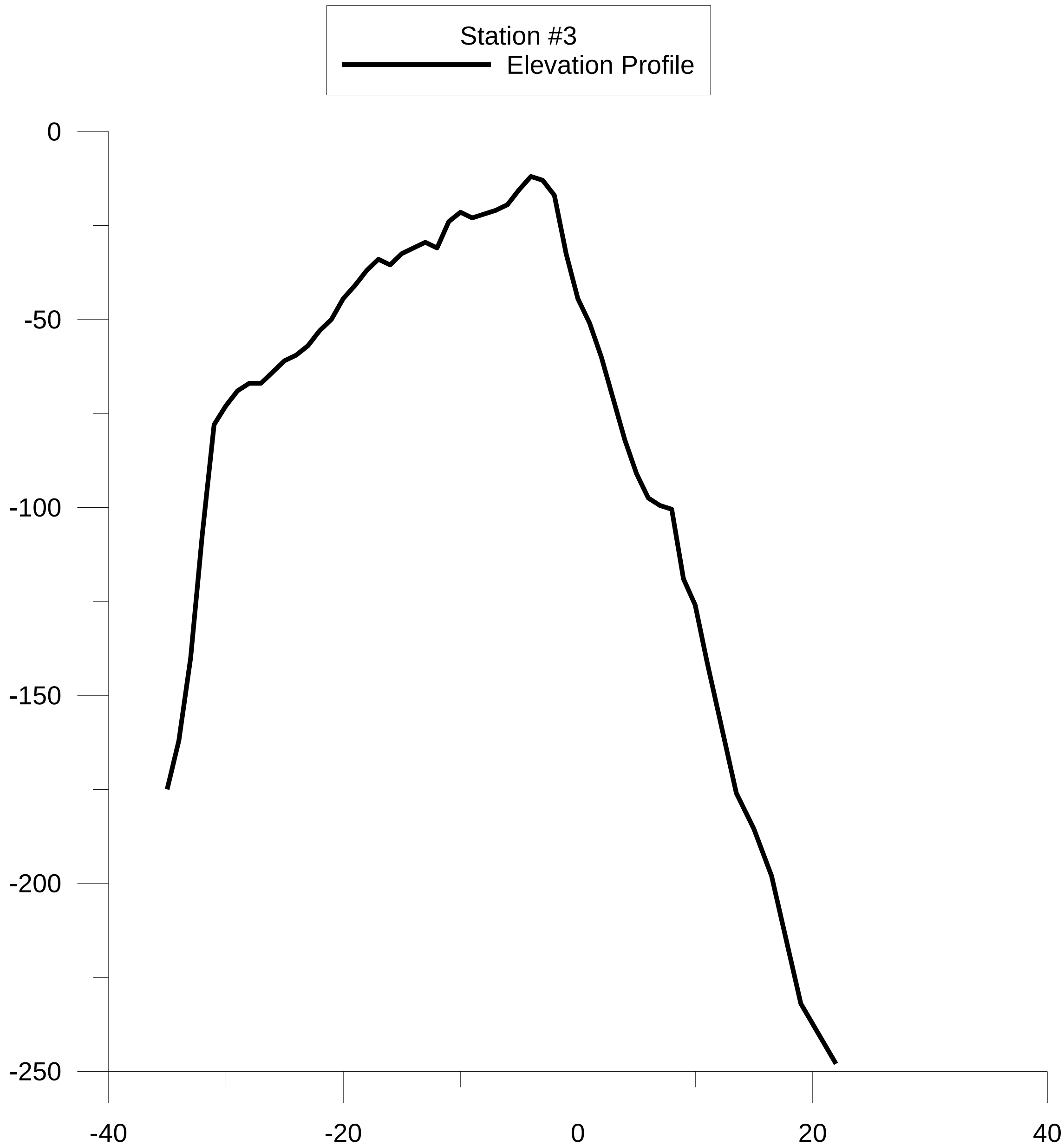
	μm	φ	GRAIN SIZE DISTRIBUTION	
MODE 1:	2400.0	-1.243	GRAVEL: 70.1%	COARSE SAND: 0.1%
MODE 2:	1200.0	-0.243	SAND: 29.9%	MEDIUM SAND: 1.5%
MODE 3:	4800.0	-2.243	MUD: 0.0%	FINE SAND: 6.1%
D_{10}:	1018.0	-2.291		V FINE SAND: 1.2%
MEDIAN or D_{50}:	2271.5	-1.184	V COARSE GRAVEL: 0.0%	V COARSE SILT: 0.0%
D_{90}:	4894.8	-0.026	COARSE GRAVEL: 0.0%	COARSE SILT: 0.0%
(D_{90} / D_{10}):	4.808	0.011	MEDIUM GRAVEL: 5.4%	MEDIUM SILT: 0.0%
(D_{90} - D_{10}):	3876.9	2.266	FINE GRAVEL: 11.6%	FINE SILT: 0.0%
(D_{75} / D_{25}):	2.056	0.264	V FINE GRAVEL: 53.1%	V FINE SILT: 0.0%
(D_{75} - D_{25}):	1366.8	1.040	V COARSE SAND: 21.0%	CLAY: 0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	μm	μm	φ	μm	φ	
MEAN ($\bar{x}$):	2614.2	1875.2	-0.907	2187.8	-1.129	Very Fine Gravel
SORTING (σ):	2035.3	2.552	1.352	2.520	1.333	Poorly Sorted
SKEWNESS (Sk):	2.084	-1.422	1.422	-0.219	0.219	Fine Skewed
KURTOSIS (K):	7.819	5.713	5.713	2.248	2.248	Very Leptokurtic

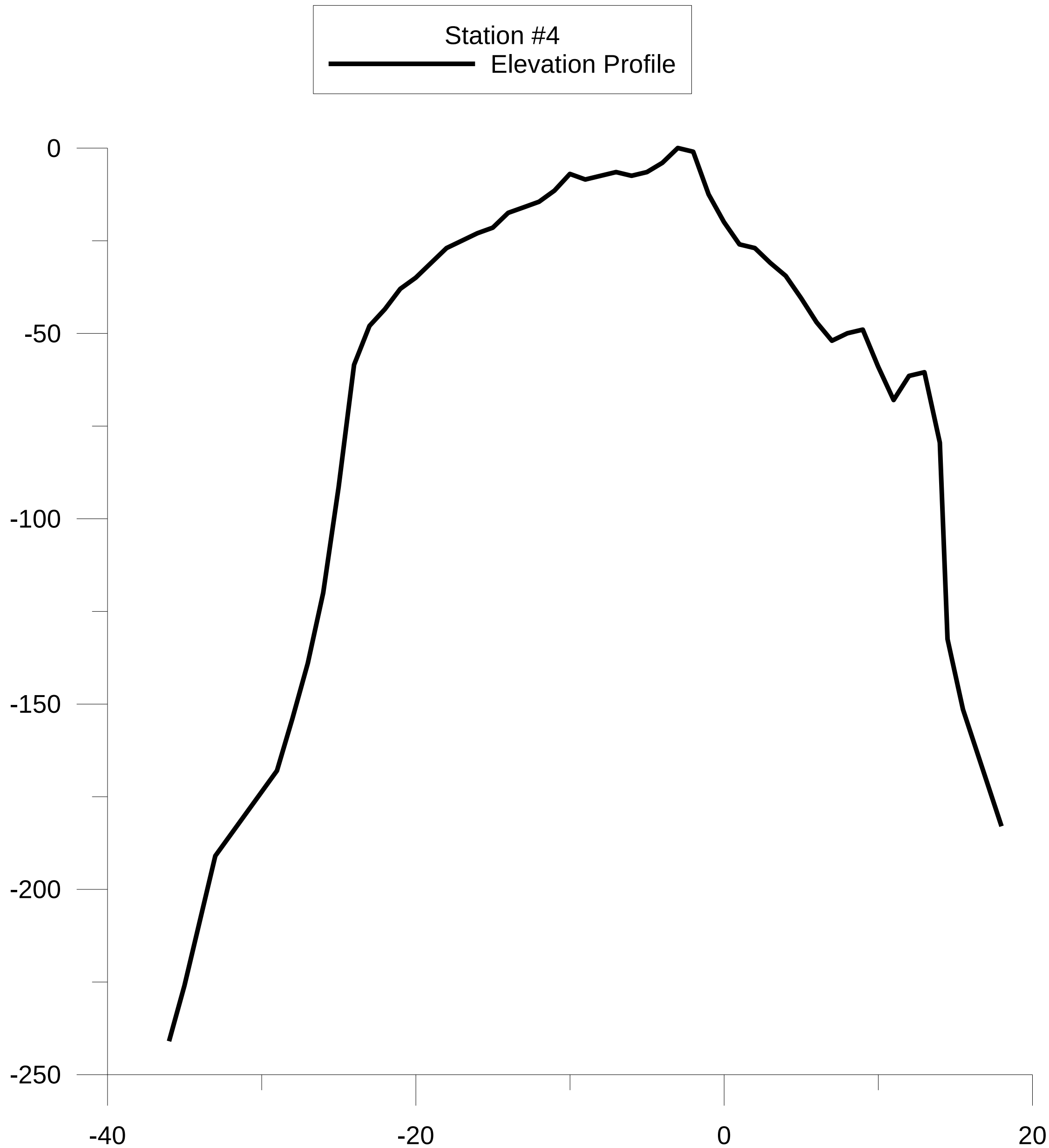
APPENDIX B
PROFILES

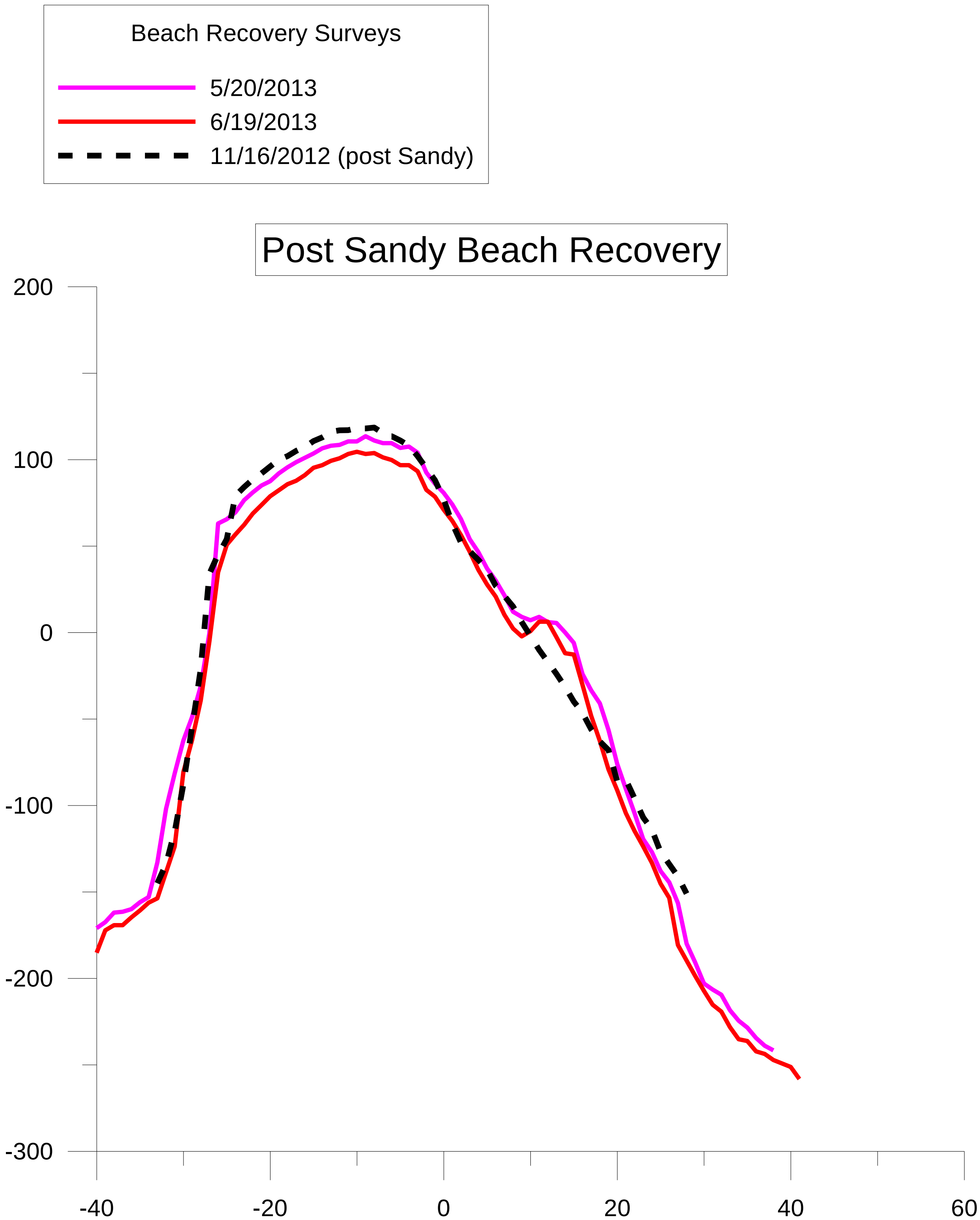



Station #2
Elevation Profile
0
-100
-200
-300
-40
-20
0
20
40



Station #3
Elevation Profile
0
-50
-100
-150
-200
-250
-40
-20
0
20
40


Station #4
Elevation Profile
0
-50
-100
-150
-200
-250
-40
-20
0
20



Beach Recovery Surveys
5/20/2013
6/19/2013
11/16/2012 (post Sandy)
Post Sandy Beach Recovery
200
100
0
-100
-200
-300
-40
-20
0
20
40
60

APPENDIX C
DIGITIZED BEACH OUTLINES VS. 2014 WORLD IMAGE PHOTOGRAPH

1934

1951

1968

1986

1991

2010

2012

2014