A CASE STUDY:
THE IMPACT OF THE 1962 NORTHEASTER ON DELAWARE'S ATLANTIC COASTLINE

by

Elizabeth Ann McCarty

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geological Sciences.

Fall 2009

A CASE STUDY:
THE IMPACT OF THE 1962 NORTHEASTER
ON DELAWARE'S ATLANTIC COASTLINE

by

Elizabeth Ann McCarty

Approved: ____
John Madsen, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
Susan McGeary, Ph.D.
Chair of the Department of Geological Sciences

Approved: ____
Nancy Targett, Ph.D.
Dean of the College of Earth, Ocean, and Environment

Approved: ____
Debra Hess Norris, M.S.
Vice Provost for Graduate and Professional Education

“We learn geology the morning after the earthquake.”

-Ralph Waldo Emerson

ACKNOWLEDGMENTS

John Madsen, Ph.D, Department of Geosciences, University of Delaware, for his advisement throughout my program at the University of Delaware.

Kelvin Ramsey, Ph.D., Delaware Geological Survey, and Susan McGeary, Ph.D., Chair, Department of Geosciences, University of Delaware, for their participation on my committee and assistance throughout my program.

Tony Pratt and Jennifer Wheatley, Department of Natural Resources and Environmental Control, for providing aerial photographs of the storm.

Dr. Andrew Morang, U.S. Army Corps of Engineers Engineering Research & Development Center, for providing aerial photographs and other pertinent information.

Bart Wilson, United States Geological Survey (USGS), and DNREC's Delaware Coastal Program, for Light Detection and Ranging (LiDAR) and Digital Elevation Model (DEM) data.

Miriam Pomillio and Lillian Wang, Delaware Geological Survey, for assistance with ESRI's GIS software and its many applications and quirks.

Eric Wright, Ph.D., Department of Marine Studies, Coastal Carolina University, and M. Scott Harris, Ph.D., Department of Geology, College of Charleston, for support and advisement with GIS software, coastal processes, and other technical aspects.

Prashant Sansgiry,Ph.D., Chair, Mathematics & Statistics Department of Coastal Carolina University for his guidance in statistical analyses.

Fellow Graduate Students & Office Mates, University of Delaware, for their help, support, and friendship throughout this process

Mark Eisner & Staff, Advanced Land and Water, Inc. for advisement, patience, and friendship throughout the completion of my thesis.

This manuscript is dedicated to:

My family and friends, especially my parents, for their love, support, and encouragement throughout my educational career.

My husband, Rhett, for his constant love, patience, and understanding, especially throughout the course of my graduate program. I could not have achieved this goal without him.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The 1962 Northeaster, called by many "The Storm of the Century," was one of Delaware's most devastating coastal storms. It lasted over more than five consecutive, semi-diurnal, perigean spring tidal cycles (Zhang et al., 2002). Maximum winds reached 112.7 km/hr (70 miles/hr), waves were an average of 6-9 m (20-30 ft), and the storm surge reached 2.9 m (10 ft) (Carey & Dalrymple, 2003). Overwash from beaches brought greater than 1.2 m (4 ft) of sand onto the streets, homes, and buildings of communities along the Delaware coastline (Podufaly, 1962).

This thesis presents a case study of the impact of the 1962 Northeaster on Delaware's Atlantic Coast shoreline. The destructive nature of the storm is quantified using historical aerial photographs, shoreline change data, and Light Detection and Ranging (LiDAR) digital elevation maps. The potential impact of a future storm of this magnitude occurring along Delaware's modern shoreline is briefly discussed.

Within a Geographic Information System (GIS) framework, georeferenced historic aerial photographs were analyzed for changes in shoreline position, aerial extent of overwash, and number and areas of extensive building damage caused by the storm. For these analyses, the Delaware Atlantic Coast

shoreline between Cape Henlopen to the Delaware-Maryland was divided into twelve zones, each approximately 3.7 km (2.3 mi) in length.

To quantify erosion due to the storm, the landward displacement of the Delaware shoreline between 1960 (pre-storm) and 1962 (post-storm) was measured at 500 m (1,640 ft) intervals along its length and the maximum amount of landward displacement within each of the zones was determined. The maximum amount of erosion as a result of the storm was 150 m (490 ft) in the zone located within the Delaware Seashore State Park, just north of the Indian River Inlet. Significant amounts (100-130 m (330-430 ft)) of shoreline erosion occurred in the northern portion of Delaware Seashore State Park and near South Bethany and Fenwick Island. The zones with the greatest amounts of maximum erosion as a result of the 1962 Northeaster coincide with the areas of significant longer-term erosion identified by Honeycutt (2003).

Areas of overwash due to the storm were digitized on the 1962 post-storm aerial photographs. The total extent of overwash in the study area was 8.34 km^2 (3.2 mi^2) with the most visibly pronounced areas along the bay barrier portion of the shoreline south of Dewey Beach, Delaware. Maximum and minimum lateral (landward) displacement of overwash sand was measured for each zone. The maximum amount of lateral displacement, ~650 m (2150 ft), was found to be located just south of Bush Island in Delaware Seashore State Park. The least amount of lateral overwash, ~45 m (150 ft), occurred near Rehoboth Beach.

Buildings present in the 1960, 1962, and 2002 aerial photographs were digitized as GIS point shapefiles. The 1962 post-storm aerial photographs indicated that the destruction of buildings was highly correlative to the areas of overwash from the storm. As shown by the 2002 aerial photographs, a great deal of residential development took place along the Delaware Atlantic shoreline. For example, in the area of Bethany Beach the increase in structures was as high as 812%.

In order to assess the potential effects of another storm of this magnitude on the modern coastline, elevation maps based on LiDAR were used to show areas most at risk due to a 2.9 m (10 ft) storm surge, equivalent to that determined for the 1962 storm. As with the 1962 Northeaster, these high risk areas include the vast majority of the coastline. The effect of 6-9 m (20-30 ft) wave heights, similar to that observed during the 1962 storm, on top of the storm surge was also considered. For example in the areas of greatest development near Bethany Beach, where major overwash and flooding occurred during the 1962 storm, it would be predicted that large-scale erosion of the dune barrier systems with subsequent overwash could occur followed by flooding with levels of inundation approaching 12 m (36 ft). Although modern building codes are much improved from 1962, one could still expect that a future coastal storm of the magnitude of the 1962 Northeaster would have significant impact on Delaware's coastal communities.

Chapter 1

INTRODUCTION & BACKGROUND

Intense coastal storms, such as northeasters and hurricanes are the greatest threats to the East Coast of the United States. These storms threaten the coastline's geologic features and valuable real-estate. Hurricanes and northeasters produce high winds and waves that do a great deal of damage, storm surge, and heavy rain, causing flooding, overwash, and inlet cuts, fills, or migrations (NOAA, 1998). It is of key importance that these storms and their effects are researched and understood.

This study focuses on the most devastating northeaster in Delaware's recorded history and its effect on the Atlantic Ocean coastline of Delaware, from Cape Henlopen at the northern-most point, to the Delaware-Maryland border at its southern-most point. The 1962 Ash Wednesday Storm has been called the storm of the century by coastal scientists and residents alike (Carey & Dalrymple, 2003). The uniqueness and magnitude of the storm, as well as the lack of digital data regarding the storm, provide a prime opportunity to digitize and analyze the profound effects of this storm on Delaware's shoreline.

In this study, historic aerial photographs were digitized and analyzed pre- and post-storm for changes in shoreline, overwash, inlet cuts and fills, and movement of buildings from their foundations. The analysis of the aerial photographs helped to further quantify the effects of this storm event on Delaware's coast. Light Detection and Ranging (LiDAR) data and Digital Elevation Models (DEM) were used to analyze how the modern dunes and topography of Delaware's modern shoreline might respond to an event with a storm surge of 2.9 m (9.5 ft), and wave heights as high as 9 m (29.5 ft) on average, similar to that experienced during the 1962 Northeaster. Given the extensive development of coastal property along the Delaware shoreline since the 1962 event, this analysis provides insight into the potential damage that could be caused if a storm of this magnitude were to occur again in the area.

1.1 COASTAL STORMS: NORTHEASTERS

Although northeasters are generally less frequent than hurricanes, of shorter duration, and impact a smaller area, they are usually stronger, more damaging storms and have more of an effect on Delaware's shoreline than hurricanes do (Carey & Dalrymple, 2003). In recorded history, there have been no storms to directly hit the state of Delaware at hurricane strength (Blake et al., 2005).

Named for the direction from which the winds come, these storms differ from hurricanes. Northeasters generally originate in the middle latitude, westerly wind belt, and are classified as extratropical storms. These intense low pressure storms form outside of the tropics and receive their power not from the warm ocean water, but from the temperature differences between a cold air mass and warm air mass (Carey & Dalrymple, 2003). Figure 1.1 shows how these storms are characterized. Northeasters move parallel to the coast, and therefore can cause a great deal more damage than hurricanes, which generally move perpendicular to the coast. This is because as a storm runs parallel to the coast, it has a greater effect on a larger area for longer periods of time (Carey & Dalrymple, 2003).

Northeasters differ from hurricanes because, they are a year round phenomena. The most active time of the year starts in autumn and continues through spring. In fact, 63% of all storms occur within this period (Dolan et al., 1988). A maximum number of northeasters generally occur between December and April, with the most destructive occurring between January and March. The fewest number of storms occur from June to August (Dolan & Davis, 1992). Approximately 30-35 northeasters each year will generate enough energy to cause wave action to be highly detrimental to the barrier beaches and frontal dunes of coasts in the United States (Bosserman & Dolan, 1968).

During a northeaster, waves can exceed 6 meters in height and winds can exceed 64.37 km/hr (40 mph), with gusts to 112.65 km/hr (70 mph) (Carey & Dalrymple, 2003). Although they have a lower intensity, northeasters are so devastating because they have higher frequencies, longer durations, and larger impact areas than hurricanes. These excessive wave heights, high winds, and long durations play a large role in the breakdown of dune systems, the amount of overwash caused by the storm, and subsequent breaching of the shoreline.

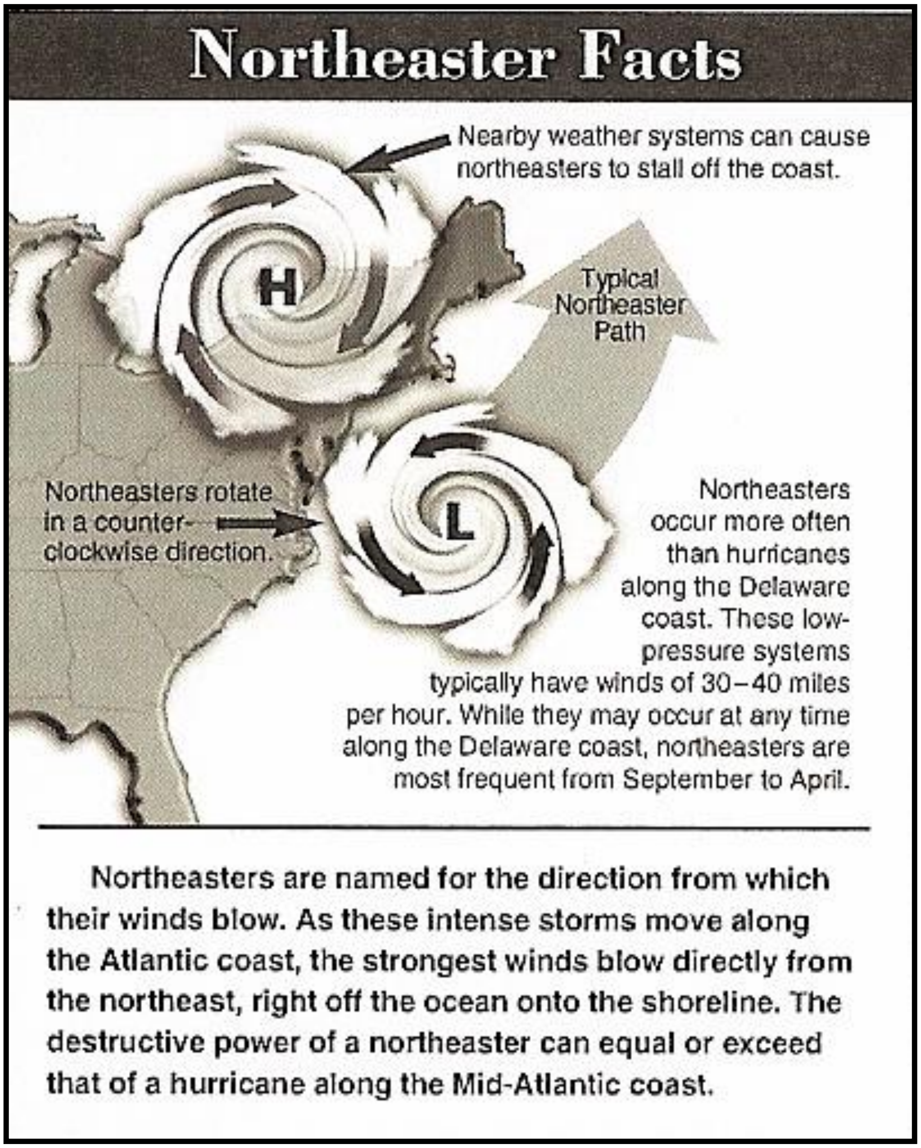

Figure 1.1 **Diagram of a Northeaster.** Northeasters are named for the direction from which their winds blow, and mostly affect the Northeast United States (Carey & Dalrymple, 2003).

The morphological change to a beach system as a result of a storm starts with the process of overwash. Overwash is described by Donnelly et al. (2006) as “the flow of water and sediment over the crest of the beach that does not directly return to the water body where it originated,”. Many factors play into the size and shape of an overwash event, as well as whether it occurs in the first place. These factors include the size and shape of the dunes, the water level, wave height, and the duration of the storm, not to mention the stability of the beach and what vegetation it may or may not have.

In developed areas, like much of the shoreline of Delaware, these overwash events may be extremely devastating; in extreme cases such as the 1962 Northeaster, they can be a precursor to breaching (Donnelly et al., 2006) as dune systems are damaged in the process. Dune systems are important to a coastline because they absorb wave energy, hold back storm surge, and protect the areas behind them, such as marsh systems, buildings, and towns (Pries et al., 2008). Donnelly et al. describe the six morphologic changes a beach goes through in the overwash process, increasing in their severity. Many places along Delaware’s coastline went through all of these steps, others stopping just before breaching. These steps as described by Donnelly et al. are as follows:

1. **Crest Accumulation** –whether on a dune crest, beach crest, or in an overwash throat.

2. **Dune Rollback** – resulting from the erosion of the seaward side of a dune and deposition on the landward side.

3. **Dune Lowering** – with deposition of sediment landward of the dune.

4. **Dune Destruction** – with deposition of sediment landward of the dune.

5. **Barrier Rollback -** sediment eroded from the beach and seaward side of the barrier, transported as sheets, and deposited over old marsh vegetation or in the bay.

6. **Barrier Breaching & Inlet Formation**

In addition to overwash, a double-bar feature can form just off the shoreline due to storm events. When beaches experience higher wave conditions and energy due to storm events, the berm is destroyed (Komar, 1998). Sediment from the berm is then moved offshore, forming a bar or several bars parallel to the shoreline (Komar, 1998). These bars serve to dissipate incoming wave energy further, greatly decreasing the amplitude of incoming storm waves, creating a protective barrier for the shoreline (Komar, 1998).

Several different scales have been developed for classifying northeaster storms. Halsey's 1986 storm scale focuses on the tidal duration and damage. Under this classification, the 1962 Northeaster would be a Class 5 storm: lasts 4-5 tidal cycles, washover completely chokes low-lying islands and roads, and the dunes are heavily eroded. Dolan & Davis' 1992 scale is based on wave height, duration, and several aspects of storm damage. Under this classification, the 1962 storm would be classified as a Class 4 or Class 5 storm, depending on where you are on the coastline. Under these classifications, wave heights reach as much as 7 m (23 ft), and the duration ranges from 63 to 96 hours. Damages include severe to extreme beach and dune breaching and erosion, massive overwash, and severe structural damage. Whatever storm scale one uses to classify the 1962 Northeaster, all of them describe an extremely destructive storm in every aspect.

1.2 STUDY AREA: DELAWARE'S ATLANTIC COASTLINE

This study focuses on Delaware's Atlantic coastline from Cape Henlopen to the southern border of Delaware (Figure 1.2). The approximately 40 km (25 mi) shoreline is composed of transgressive barrier-lagoon systems and headland beaches (Kraft et al., 1987). The tidal range along this portion of the Mid-Atlantic coastline is mesotidal (Davis & Fitzgerald, 2004). Figures 1.3 and 1.4 show normal (i.e., fair weather) and storm conditions with respect to tidal levels in the region. Of specific concern in this study is the build-up of wave heights and storm surge during storm conditions that could lead to extensive erosion and potential overwash of the dunes along the barrier beaches along this coastline.

Delaware's coastline includes the communities of Rehoboth Beach, Dewey Beach, Indian Beach, Bethany Beach, and Fenwick Island. Almost directly in the middle of this stretch of Atlantic shoreline is Indian River Inlet, a heavily stabilized inlet allowing access to Rehoboth Bay to the north and Indian River Bay to the south. The inlet separates the barrier beaches, which consist of Dewey Beach and Indian Beach toward the north, and the Delaware State Seashore Park to the south. The next barrier system, Fenwick Island, is south of Bethany Beach, and just north of the Delaware-Maryland border. This barrier system protects Little Bay to the north, and Little Assawoman Bay to the south.

Figure 1.2 **Study Area for this Project.** This study focuses on the Atlantic Coast portion of Delaware, from Cape Henlopen at the northernmost point to the southern border between Delaware and Maryland.

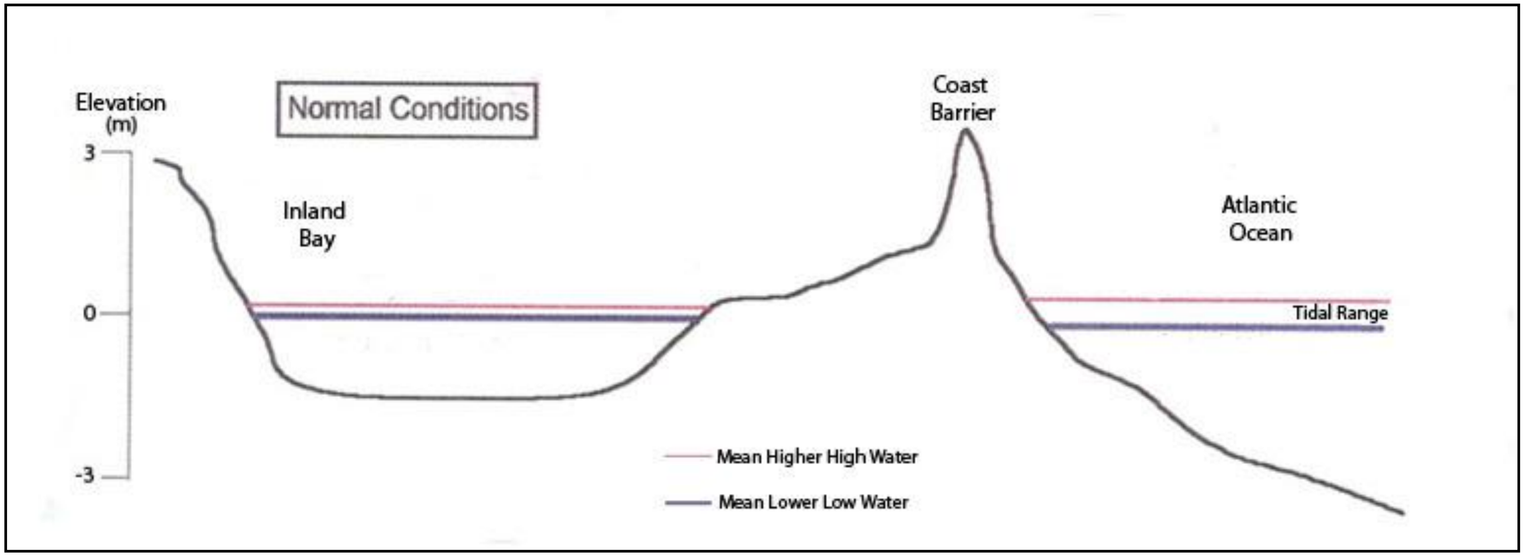

Figure 1.3 **Normal Conditions of Delaware's Barriers.** Shows the normal tidal and water level conditions on Delaware's Atlantic Coast (Ramsey et al., 1998). Note: The scale has been modified from the original to be shown in meters instead of in feet.

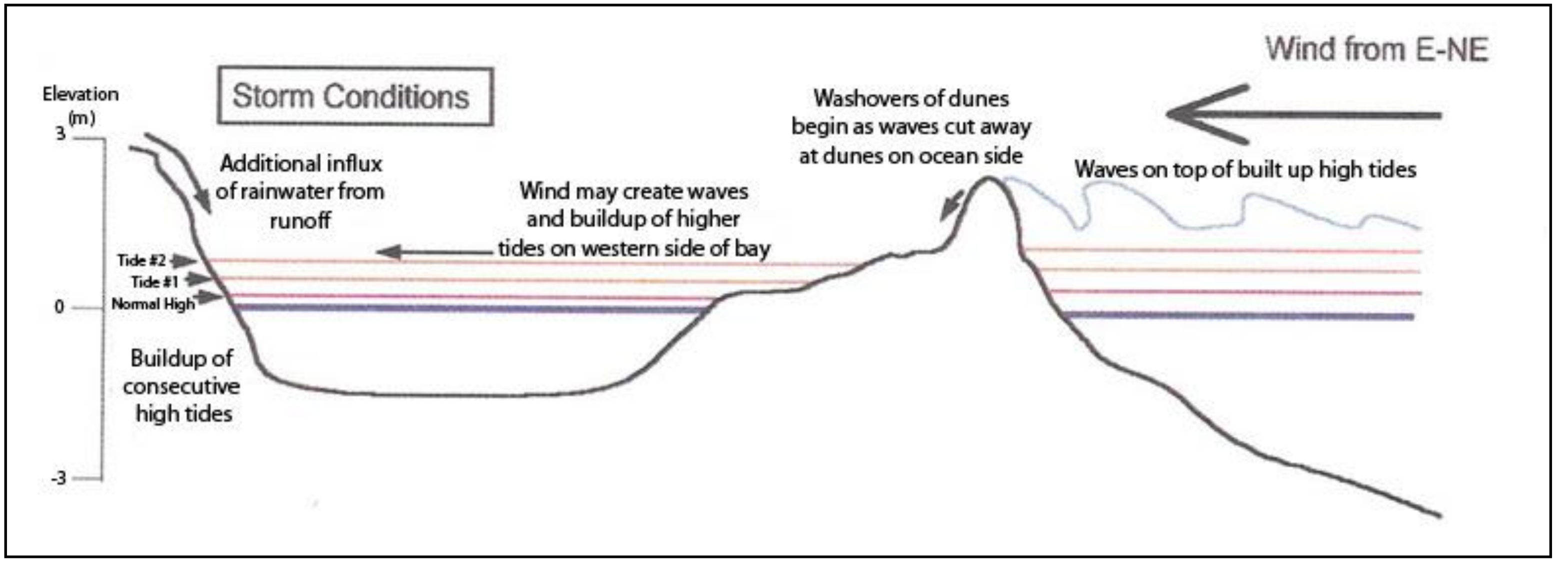

Figure 1.4 **Storm Conditions of Delaware's Barriers.** Shows the storm tidal and water level conditions on Delaware's Atlantic Coast (Ramsey et al., 1998). Note: The scale has been modified from the original to be shown in meters instead of feet.

1.3 1962 Northeaster: Climatology

The 1962 Northeaster has become a benchmark for coastal research (Oates, 2007). This storm impacted not only Delaware's coastline, but also several other coastlines in the northeast United States, from New York to North Carolina (Dolan et al., 1988). Its slow movement up the coastline contributed in large part to the extensive damage across the Atlantic Coast (Cooperman and Rosendale, 1962).

During the storm in the Delaware area, maximum winds reached 112.65 km/hr (70 mph), waves were an average of 6-9 m (20-30 ft), and the storm surge reached 2.9 m (9.5 ft) (Carey & Dalrymple, 2003). Overwash from beaches brought over 1.2 m (4 ft) of sand into the streets, homes, and buildings of communities along the Delaware coastline (Podufaly, 1962). Based on data from the Lewes tide gauge (Figure 1.5), the 1962 Northeaster lasted over more than five consecutive, semi-diurnal, perigean spring tidal cycles (Zhang et al., 2002). A typical northeaster generally occurs over several tidal cycles (Carey & Dalrymple, 2003).

Because of the specific meteorological conditions set up over the course of two days before the storm (Table 1.1) and because it stalled over the coast during spring tidal conditions, the 1962 Northeaster was much more devastating than anyone had predicted (Dolan & Davis, 1992; Oates: Uccellini, 2007). The perigean spring, long duration tidal conditions, the large pressure gradient between the high and low pressure systems associated with the storm, and the relatively large fetch of approximately 1600 km (1000 miles) from the coastline to the storm's center of low pressure, created a dangerous sea state, allowing wave and water damage due to flooding to be greatly increased (Oates:

Pratt, 2007; Dolan & Davis, 1992). There was insufficient time for the beach to regenerate itself between each tidal cycle, and therefore, as each successive tide built upon another, there was less beach area to protect the coastline from the storm wave action (Podufaly, 1962).

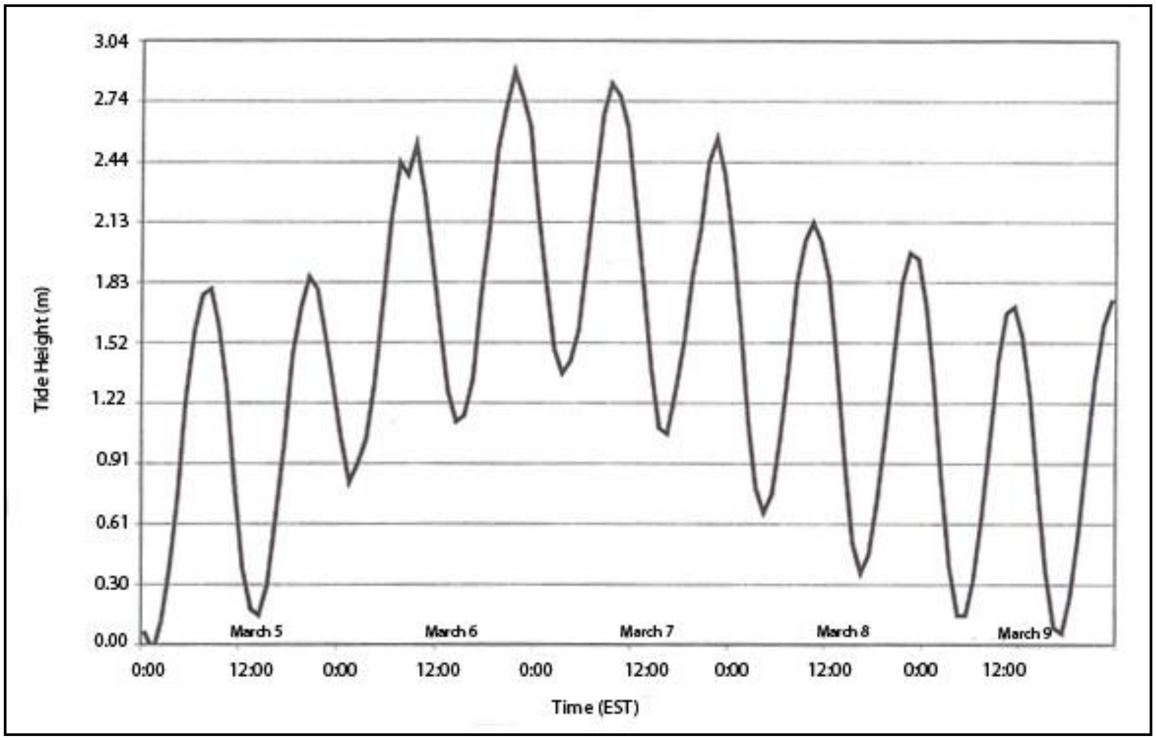

Figure 1.5 **Storm Tides for the 1962 Northeaster.** Tides based on the MLLW datum from the tidal gauge at Lewes, DE (Ramsey et al., 1998). Note: The scale has been modified from the original to be shown in meters instead of feet.

Date	Conditions
March 4	- Started off the Atlantic coast of Florida. - A strong high is centered over the Canadian Arctic Archipelago. - A ridge is extended south-southeastward over the Middle Atlantic States. - A moderate low is located over the upper Mississippi Valley
March 5	- Interior low - deep circulation and moved across the southern portion of the Canadian high toward the Ohio Valley. - Surface low – began to dissipate, while a wide area of low pressure and several separated centers developed between the Carolina coast and the wave forming off the Florida coast. - Deep low – associated with the dissipating interior low and continued its eastward movement.
March 6	- The deep low became situated over the Carolina coastline, triggering an intensification of the coastal low, starting to better define the several different centers. - Its northeastward moving direction was blocked by the high over the Canadian Arctic Archipelago, now centered over Labrador.
March 7 to March 8	- The same high moved southward toward New England. - The coastal low storms began to intensify and move east-northeast. - The low elongated in an east-west direction and developed a steep pressure gradient. - Strong northeasterly winds developed from these conditions.

Table 1.1 **Climatology of the Storm.** This table describes the climatology of the 1962 Northeaster. It has been modified from the description of the storm given by Cooperman and Rosendale in 1962.

1.4 The Storm in Delaware

The first indication of the 1962 Northeaster in Delaware occurred the morning of March 6, 1962. The northeaster moved slowly into the area and as the day progressed, waves began lapping over the boardwalk in Rehoboth Beach and into the streets (Oates:

Stevenson, 2007). In the back-bay barrier areas, homes were flooded by 1-1.2 m (3-4 ft) waves (Oates: Carey, 2007).

The next day, the low pressure system associated with the storm stalled off the Mid-Atlantic Coast (Oates: Carey, 2007). This brought stalling conditions to the Delaware beach area. As each consecutive tidal cycle passed, the storm surge level amplified, reaching a maximum of 2.9 m (9.5 ft) above mean sea level (Carey & Dalrymple, 2003). As the water continued to rise and waves reached further across the barriers and beaches, dune systems began to fail and ocean waters began to meet waters of the Inland Bays along almost every stretch of Delaware's barrier islands (Oates: Carey, 2007). Even towns off the coast, such as Milton and Millsboro experienced extreme flooding due to the rising of tidally influenced tributaries (Figure 1.6).

Figure 1.6 **Flooding in Milton, DE.** Even in towns as far as 11 km from the coastline flooding occurred during the 1962 Northeaster. Areas close to tidally influenced streams and inlets were greatly affected by the storm (Photograph courtesy of the Delaware State Archives).

By March 8th, buildings along the coast were experiencing foundation failure with the structural damage occurring as tidal cycle after tidal cycle eroded sand from underneath the foundations, causing buildings to be tipped forward into the ocean from their front pillars and concrete supports (Oates: Pratt, 2007).

1.5 Storm Damage

In Delaware, seven lives were lost in the 1962 Northeaster and property damage amounted to about $70 million in 1962 (an equivalent of $400 million in 2001 dollars) (Carey & Dalrymple, 2003). Damage from the storm was caused in three main ways:

1. The first and most devastating was the complete breakthrough of ocean waters across the barrier islands. This caused significant damage to

homes, businesses, parks, and other structures located on the barrier islands (Podufaly, 1962).

2. The second means of damage was through dune and beach erosion. As these features eroded, homes and other structures located in the vicinity of the beach became susceptible to foundation failure due to liquefaction of sand beneath them (Podufaly, 1962).

3. Lastly, extensive flooding was the third method of damage.

As an example, Figure 1.7 shows an area in the southern portion of Sussex County, Delaware before and immediately after the storm. The two buildings of interest are marked with red and yellow stars in both images. The bottom image shows the same area after the storm. Note the extensive overwash and flooding. The same buildings are marked with the same stars. The red building is completely inundated with bay water, and the yellow one not only received a great deal of overwash, but also inundation of bay water. The Rehoboth area in particular experienced 1-2 m (3-6.5 ft) of water above street level (Podufaly, 1962). In addition to the storm surge, the constant build up of water, tide upon tide created an environment where flooding was constant, rather than episodic. It was this phenomenon over the approximate 75 hour duration of the storm that not only flooded oceanfront homes and buildings, but also many back-barrier and tidally influenced communities.

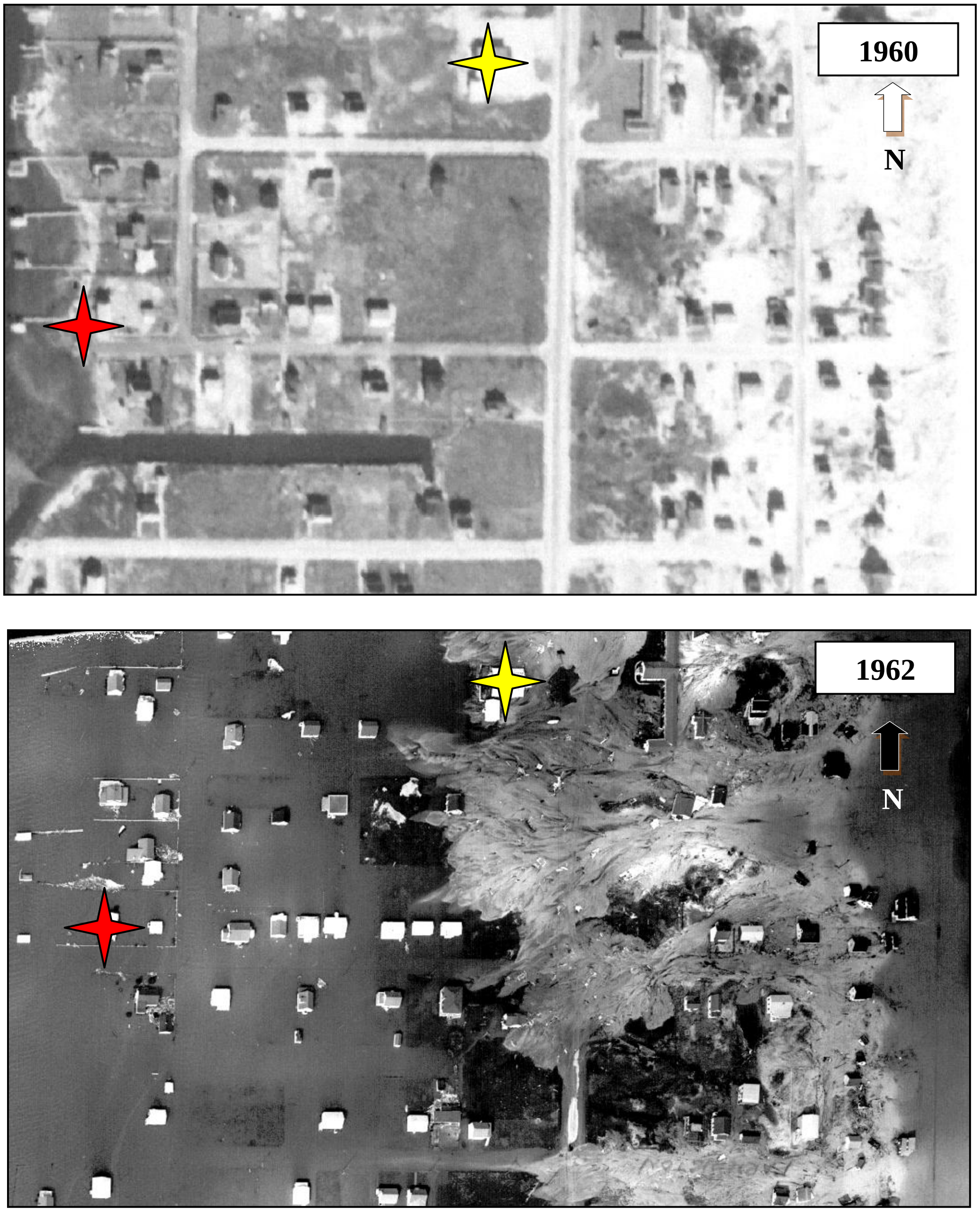

Figure 1.7 Extensive Building Damage. Shows a comparison of aerial photographs in the southern portion of Sussex County, DE. The 1962 series of aerials shown in this figure were not used for other parts of this study because the collection was incomplete. These particular 1962 aerial photographs were taken the day after the storm, therefore, they show the extensive flooding. Buildings with the matching stars are the same.

1.6 Damage Response

President Kennedy declared the states of Delaware, Maryland, New Jersey, and Virginia to be disaster areas on March 9th, 1962. The United States Army Corps of Engineers (USACE) began "Operation Five-High" as a response effort along Delaware's shorelines immediately after the storm (Podufaly, 1962). Overwash sand was trucked back onto the beaches to renourish the storm damage (Figures 1.8 and 1.9). Sand fences were erected along the newly constructed dunes in order to 'naturally' build up and sustain the dunes through aeolian transport (Podufaly, 1962).

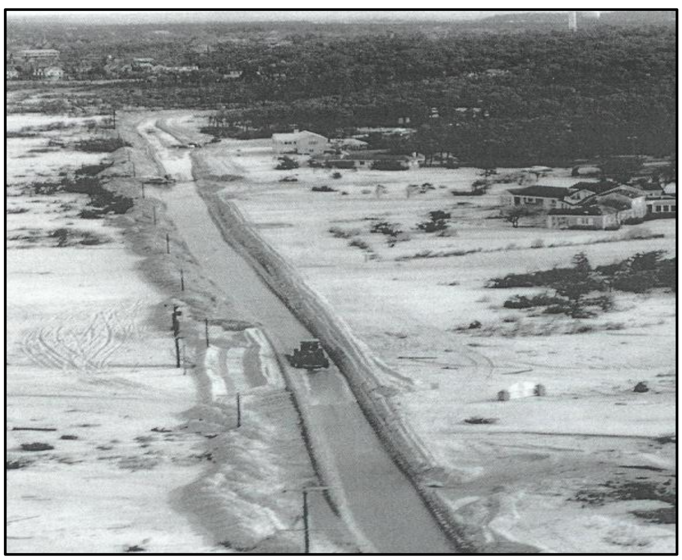

Figure 1.8 **Recovery Operations.** When waters receded, sand was removed from the streets, yards, and homes and placed back onto the beach for renourishment. No outside sources of sediment were necessary (Photograph courtesy of the Delaware State Archives).

Communities were encouraged to plant vegetation to protect the dunes from further erosion (Podufaly, 1962). According to Zhang et al. (2002), based upon repeated sets of beach profiles, it was estimated that it took approximately 15 years for the Delaware beaches impacted by the 1962 Northeaster to recover to their long-term trend positions. This cannot be well seen on aerial photographs, however, because the USACE renourished the coastline and rebuilt dunes as part of Operation Five-High just after the 1962 storm. As they could not be expected to fully renourish the beaches to their original state, it took up to 15 years after the storm for the beaches to equilibrate.

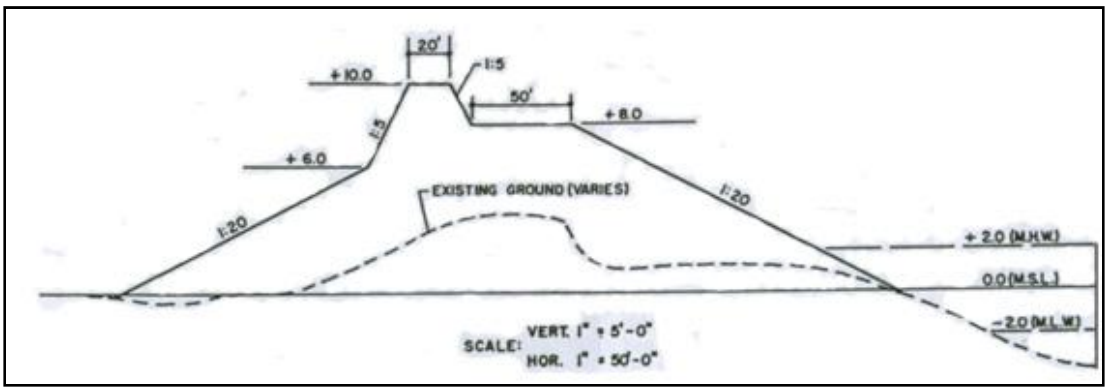

Figure 1.9 **USACE Plan for Renourishment.** Plan for renourishing the beach and the dune system of damaged beach systems after the 1962 Northeaster (Podufaly, 1962). Note: 1 foot = 0.3048 meters.

1.7 Post 1962 Northeaster Storms

Since the 1962 Northeaster, several storms have impacted the Delaware coastline, although none have matched the degree of damage caused by the 1962 storm. The major post 1962 Northeaster storms are the 1991 All Hallows' Eve Northeaster and the coastal storms that occurred in January and February of 1998.

The All Hallows' Eve coastal storm was a northeaster that caused major erosion along the East Coast of the United States (Davis & Dolan, 1992). This storm was rather unique because Hurricane Grace was west of Bermuda at the time, and was contributing to the energy of the northeaster (Davis & Dolan, 1992). Deep water wave heights surpassed 10.5 m, which were higher than the 9.1 m wave heights estimated for the 1962 Northeaster (Davis & Dolan, 1992). North Carolina sustained the most damage from this storm, as the storm stalled off its coast due to Hurricane Grace near Bermuda. As Hurricane Grace moved north and toward the United States coast, and the northeaster moved further northeast, they converged and New York and Massachusetts sustained severe damage to their coastlines (Davis & Dolan, 1992).

Another set of large storm events that affected Delaware was a set of coastal storms occurring through January 27-29 and February 4-6, 1998. As shown in Figure 1.10, the highest observed storm tide levels measured in Lewes, DE occurred on January 26th at approximately 2.7 m, and February 5th at just under 2.6 m (Ramsey et al., 1998). These levels are not as high as the tidal levels recorded during the 1962 Northeaster, where the height exceeded 2.9 m (9.5 ft) (Figure 1.10). The coastal damage from these storms was due mostly to flooding and high winds, but there was also some dune and overwash damage in areas of unnatural dunes and in areas that had been previously breached by other storms (Ramsey et al., 1998). The 1998 coastal storms exceeded that of the All Hallows' Eve storm but didn't surpass the 1962 Northeaster. The 1998 storms were about an order of magnitude less than that of the 1962 Northeaster in terms of overall severity and coastal change (Ramsey et al., 1998).

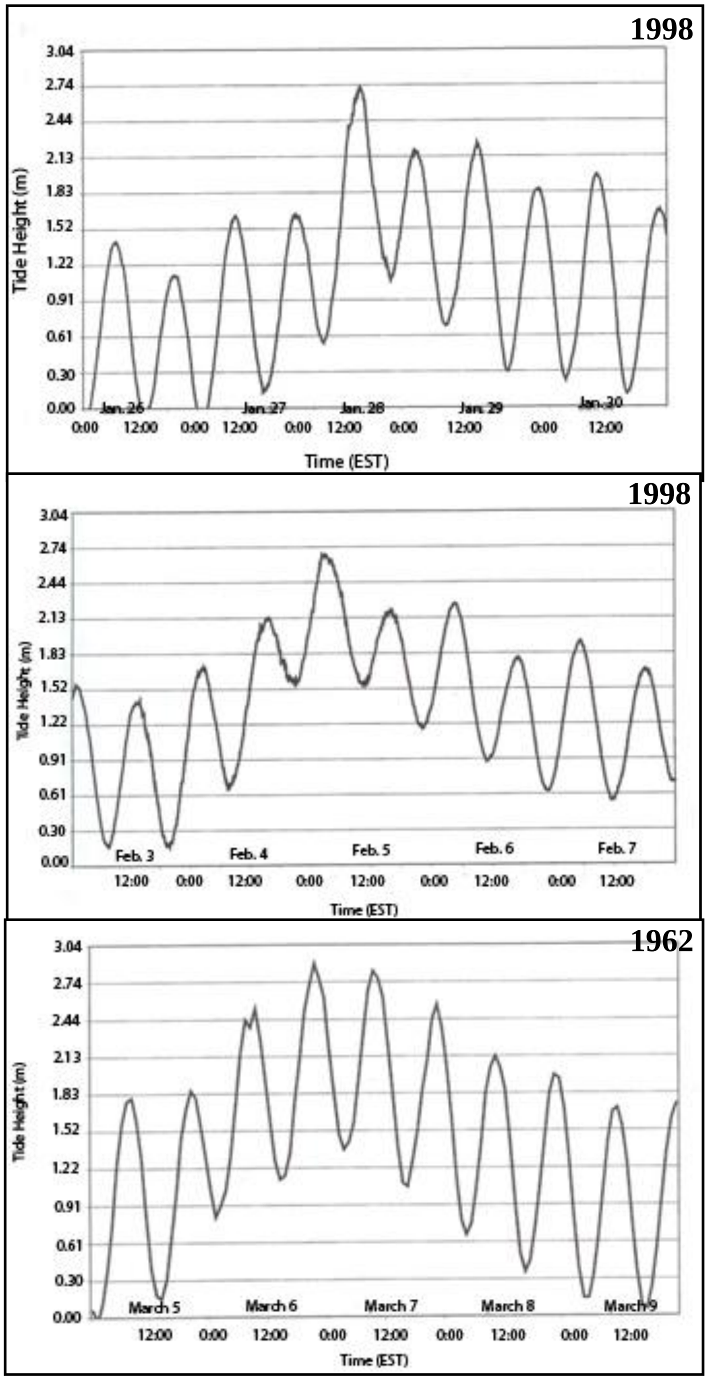

Figure 1.10 Storm Tidal Levels for the 1998 Coastal Storms and the 1962 Northeaster. Jan. 26-30, 1998; Feb. 3-7, 1998; Mar. 5-9, 1962. Levels based on MLLW datum at Lewes, DE tidal gauge (Ramsey et al., 1998). Note: Scale was modified to be shown in meters.

Chapter 2

METHODS

Four aspects of the storm were observed in this particular study. These include an analysis of shoreline change, overwash, building damage, and potential future damage using LiDAR data. Shoreline, overwash, and LiDAR digitizations are divided up into 12 different zones. See Figure 2.2 or Appendix A to view the locations of each zone. Examples of the digitized 1960, 1962, 1968, and 2002 shorelines superimposed on the 1962 aerial photographs are shown in Figures 3.1-3.5. Examples of significant features from each zone are described in the figure captions. A detailed table of the shoreline measurement lines and their features, as well as all of the digitized shorelines superimposed on the 1962 aerial photographs for the zones are included in Appendix A.

2.1 Aerial Photographs

Historic aerial photographs from the years 1960 and 1962 were obtained from the Delaware Department of Natural Resources and Environmental Control (DNREC) and the USACE. These photographs were digitally scanned into ESRI's Arc Map, version 9.1 (a geographic information systems) and georeferenced with aerial photographs from the years 1954, 1968 and 2002 that had already been digitized by the Delaware Data

Mapping & Integration Laboratory (DataMIL), a part of the Delaware Geological Survey. The DataMIL aerial photographs were projected in NAD 83 Harn Delaware State Plane, so all other aerial photographs and shapefiles were digitized using the same projection. The 1960 and 1962 aerial photographs were georeferenced to DataMIL photographs of 1968 (Figure 2.1). The 1962 aerial photographs were taken on March 15, seven days after the storm, and they have approximately 60% overlap. The 1960 aerial photographs had a few missing from the collection, just south of Cape Henlopen. Because of their age and method of storage, it is likely that the aerial photographs could have been lost or damaged over the years.

The referencing error was calculated for both 1960 and 1962 using the Root Mean Square (RMS) of the residuals for each individual photograph. The RMS value is unitless and for the 1960 aerial photographs was 2.6, while 1962 was 3.6. A possible explanation for the worse RMS value for the 1962 photographs is due to the poor resolution of the photographs and the lack of usable points because of damage from the northeaster.

Although there are several methods that one can use to calculate the error in georeferencing, such as those laid out by Hapke et al. (2006) another method chosen. The GIS software provides an automatic calculation of the RMS value of the residual values for each individual photograph. It is a means to measure magnitudes of varying quantities and assigns a weighted average of the error residuals for the photographs. The methods laid out by Hapke et al., which calculate the georeferencing errors to a more precise degree were not used for this study because that degree of precision is not appropriate in this case due to the nature of the project and quality of the data.

Each of these factors can affect the shoreline many feet one way or the other, depending on their magnitude. The water does not simply rise uniformly. Wave height , wave action, and wind could not be digitized easily. Wave height was attempted to be digitized by adding the average wave height during the 1962 Northeaster to the storm surge reported of 2.9 m (9.5 ft). Wind energy, however, cannot be digitized the way waves and storm surge can. Wind does play a large role in these types of storms and how they behave. The 1962 Northeaster had such high waves, large surge, and long duration because of the wind. The wind had a fetch of 1600 km (1000 mi) (Oates: Pratt, 2007). Should these factors come to be used in a future study, then a more precise method of error calculations could be more appropriate.

Because there were significant changes in Delaware's coastline due to the 1962 Northeaster, the photographs were very difficult to georeference. Difficulties arose with the type of points available and shadows cast from structures and trees at the time the photographs were taken. Shadows make it extremely difficult to precisely determine the corner of a building or tree. The quality of the aerial photographs also made them difficult to georeference. Although extreme care was taken to ensure that the photographs were accurately georeferenced, they are very slightly misaligned in some places. Once the aerial photographs were georeferenced, the shorelines, overwash fans, and buildings were digitized using GIS.

In order to be able to show changes in the shorelines and the amount of overwash, the shoreline has been divided into 12 zones. (Figure 2.2). Each zone is approximately the same size of approximately 3.7 km (2 mi) in length, and has between 400 (1312 ft) and 450 m (1476 ft) of overlap with one another, as not to leave out any portion of the shoreline. Portions of the shoreline will be addressed from north to south as Zone 1, Zone 2, and so on.

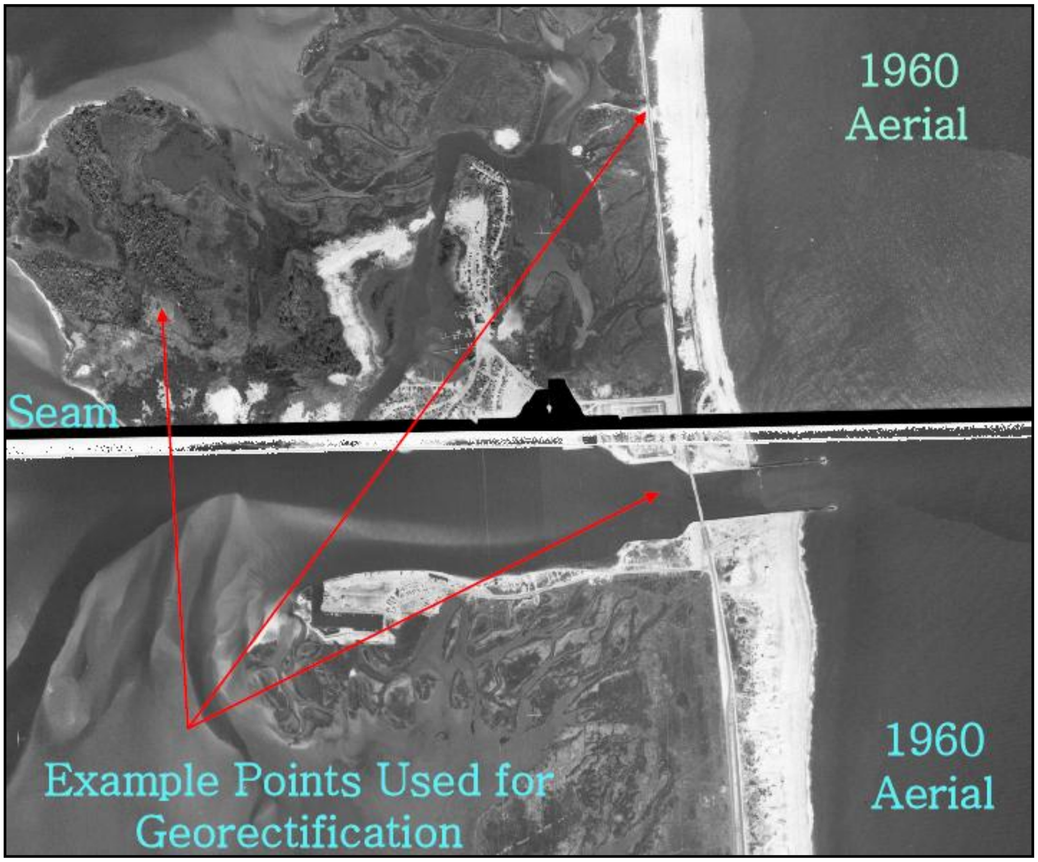

Figure 2.1 **Georeferencing of Aerial Photographs.** Two photos line up at the seam. This image also shows good referencing points (i.e. trees, corners of buildings, and stabilized inlets).

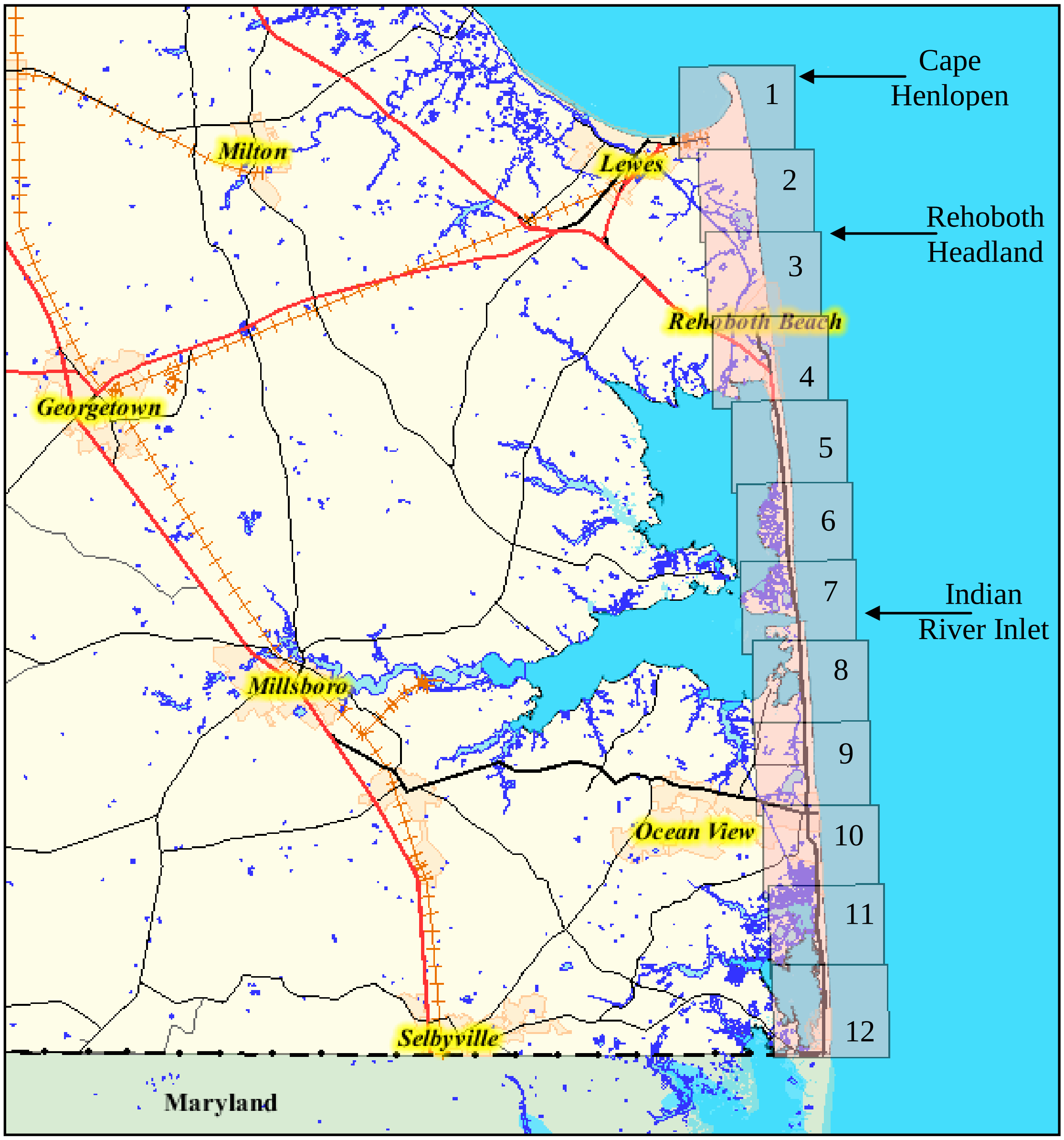

Figure 2.2 **Zones of Study Area.** The study area divided into 12 zones so that changes in shoreline, overwash, and building destruction can be seen and compared.

2.2 Shorelines

The initial step in the analysis of the shoreline data was the digitization of the position of the shoreline from the 1960, 1962, 1968, and 2002 aerial photography. The 1954 shoreline was somewhat incomplete, so for showing the shorelines in the figures, this shoreline was left out. To determine the procedure best suited for digitization, shoreline indicators as compiled by Boak and Turner (2005) were studied for their applicability to the Delaware shoreline and the methodologies employed by the United States Geological Survey (USGS) and the Delaware Geological Survey (DGS) in the generation of GIS shapefiles of the Delaware state coastline were examined (DGS, 2002).

The wet/dry line as a shoreline indicator was chosen for the digitization of the Delaware shorelines in this study. As described by Hoek et al. (2001) this line is characterized by the distinct difference in brightness on aerial photographs between wet and dry sand. It represents the maximum runup limit of a rising tide as shown by the portion of the beach that is still wet versus that which has remained dry (Overton et al., 1999). The wet/dry line was used instead of a high tide line or a low tide line because it is unknown at what time the aerial photographs were taken; therefore, the tidal cycle over which they were taken could not be determined. In the interest of consistency in reference to the comparison of the shorelines to one another, it was determined that all shorelines should be digitized using the wet/dry line.

The 1962 aerial photographs show a double-bar coastline along most of the Delaware coast. The appearance of the double-bar feature makes it difficult to identify a shoreline position for these photographs. Digitizing the double-bar feature in the 1962 aerial photographs, though difficult, was also done using the wet/dry line. In most cases, where the bar was detached from the visible beach, the wet/dry line on the beach was used. Using any other methodology, like the high tide or the low tide line, would have made it nearly impossible to determine a shoreline for 1962. The double-bar feature on the 1962 coastline is further discussed in Chapter 3 of this study.

Man-made structures, such as jetties and piers were digitized as well, but were included only if they were present before the 1962 Northeaster. Looking at features that existed before the storm allowed for the best comparison to post-storm features, therefore isolating the event and its effects. The 1960, 1962, and 1968 shorelines were digitized at a resolution of 1:5,509 m for purpose of consistency. The 2002 shoreline was digitized at a resolution of 1:2,351 m since the photos were a higher quality; since these are in color, it was easier to see the wet/dry line at this resolution.

Following the digitization of the shorelines, a method of quantifying the changes in the shorelines was explored. The first method explored to compute long-term shoreline change was the Digital Shoreline Analysis System (DSAS), created as an add-on to the ESRI ArcMap software. This add-on was designed to calculate shoreline rate-of-change over time by creating orthogonal transects at a specified spatial interval. It then calculates the rate-of-change for defined shorelines over a specified time frame (Thieler et al., 2005). The 1962 Northeaster is a single storm event at a fixed point in time. This study focuses on the specific effects of that storm; thus it is not practical nor accurate to try to quantify the effects of such events as a long term rate. Therefore, two different approaches were considered and taken.

The shoreline was also analyzed from Cape Henlopen to the southern border of Delaware, zone by zone, to determine the areas of maximum erosion and maximum deposition. The measurements for each of these parameters were recorded for each zone. This was done because while the method of making measurements at fixed distances along the coastline yields overall idea of the changes that occurred, it still does not tell us the maximum displacement shoreward. The shorelines were compared to one another. The 1960 shoreline to the 1952 shoreline, 1962 to 1960, 1968 to 1962, and 2002 to 1968.

In order to quantify the amount of shoreline erosion and/or deposition, the lateral (landward) displacement of the shoreline from its 1960 position was measured at a set distance of 500 m from one another along the shoreline, beginning at Cape Henlopen, and ending at the Delaware-Maryland border. The goal was to have enough representative evenly-spaced measurement lines across multiple shorelines. Basically, this is the same process that the DSAS program uses, the difference being that DSAS uses far more intersects at a specified baseline and distance. This process merely measures the change in distance from one shoreline to another. The displacements and the location information for the measurement lines are presented in Table AA.1 of Appendix A. The results of the shoreline analysis are presented and discussed in section 3.1.

2.3 Overwash

On the 1962 aerial photographs, overwash due to the 1962 Northeaster was very distinct and easy to digitize. These areas of overwash were digitized from the 1962 aerial photographs into a polygon shapefile. The shoreline portion of the polygon was defined by the 1960 shoreline. The area of total overwash due to the storm was then calculated for the coastline using the ESRI GIS software (Figure 2.3). The area of overwash was then overlain on the 2002 aerial photographs to show the areas that would be overwashed in the future.

In addition to calculating the actual area of overwash, the maximum and minimum displacement due to overwash was measured for each zone. This was done by examining each zone, measuring several locations until the maximum and minimum values were determined in the same manner as was done for the shorelines. The results of the overwash analysis are presented and discussed in section 3.2.

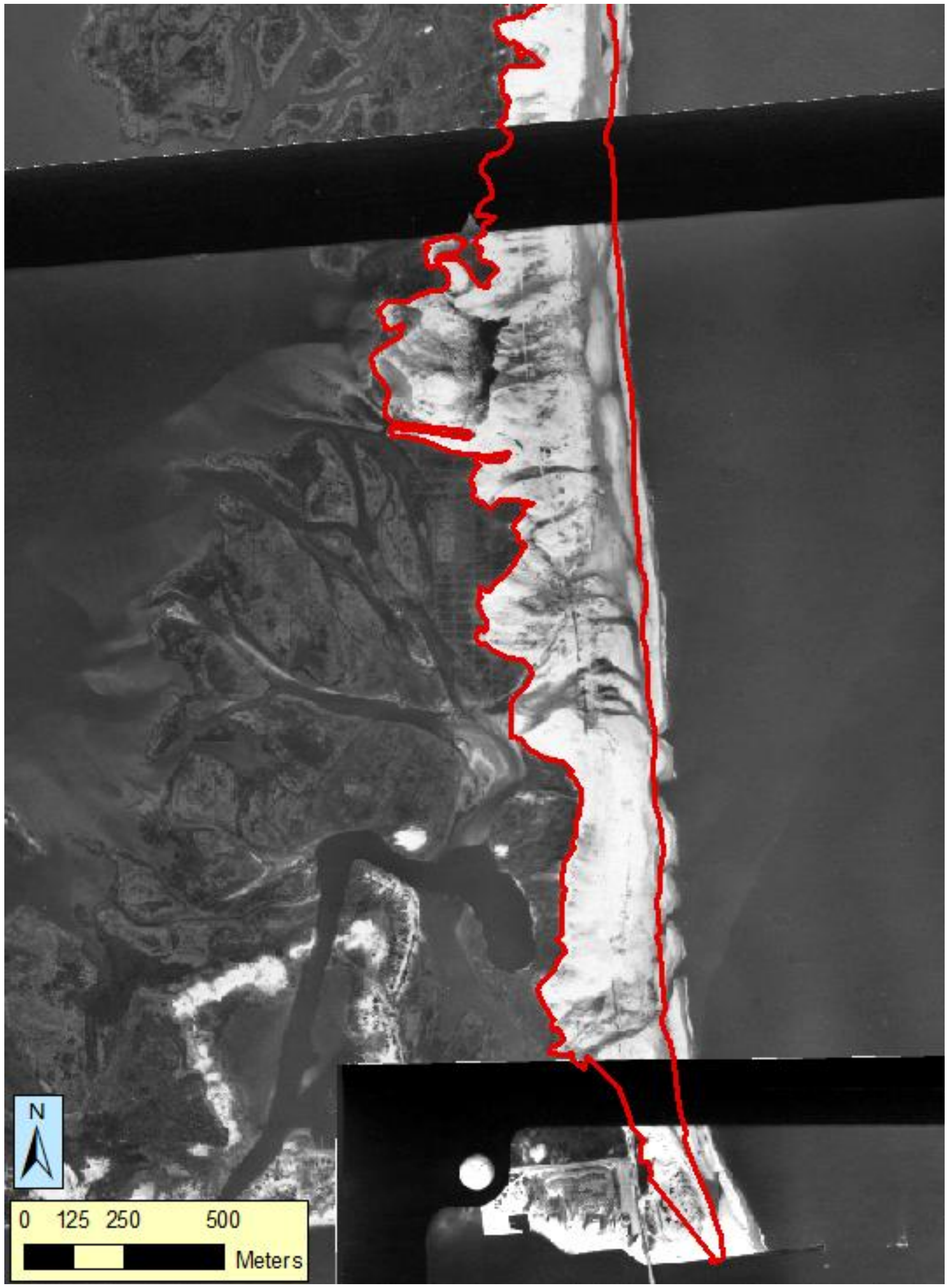

Figure 2.3 **Area of Overwash.** The area of overwash was calculated through an application within the GIS framework. A polygon shapefile was first created, outlining the overwash, using the 1960 shoreline as the seaward baseline. Using a simple GIS application, the area was then calculated.

2.4 Buildings

Buildings present in the 1960, 1962, and 2002 aerial photographs were digitized initially as point shapefiles. To decrease the effects of georeferencing errors between the photographs from different years (1960 RMS Error = 2.6; 1962 RMS Error = 3.6), the buildings in 1962 not significantly impacted by the storm (i.e., movement off foundation) were defined by their 1960 locations. Quality of the images, differences in the times that they were taken, and errors in georeferencing contributed to the discrepancies in the images lining up perfectly. North of Rehoboth Avenue (the principle east-west street) in Rehoboth Beach, there are 1960 aerial photographs missing from the collection. Due to the age of the aerial photographs, they were very difficult to find. Images are missing from the collection from which they were acquired, for an unknown reason. One can only speculate that the photographs became lost in the several ownerships and movements since they were taken in the 1960s. Unfortunately, even after several attempts to locate them, these aerial photographs could not be obtained. Therefore, buildings could only be analyzed up to Rehoboth Beach and not further north to Cape Henlopen.

Following the digitization of the buildings, a manual density calculation was conducted on three zones of the shoreline. Zones 4, 9, and 10 are some of the most densely built up along Delaware's coastline, and will also be examined under the screen of the LiDAR imagery. To calculate the density of the buildings within each zone, the area of the digitized buildings within these zones was calculated in the same fashion as the overall area of overwash. Within each area, all of the buildings were counted, and a density was calculated. The number of buildings in these three zones were also counted to determine the percent increase in buildings over time. The results of the building damage analysis are presented in section 3.4 of this study.

2.5 LiDAR/DEM Data

Light Detection and Ranging (LiDAR) and Digital Elevation Model (DEM) data were used to assess how the modern shoreline could be impacted by storm surges of the magnitude measured during the 1962 Northeaster. The data were obtained from the Delaware Geological Survey and the Delaware Department of Natural Resources and Environmental Control In order to predict the areas of the shoreline that would be inundated by a storm of the same magnitude, a plane was set at the level of the 1962 Northeaster storm surge. The storm surge above Mean Lower Low Water (MLLW) that occurred during the 1962 Northeaster was estimated at 2.9 meters, based on the National Tidal Datum Epoch (NTDE) of 1960-1978 (Oates: Carey, 2007, and NOAA, 2009). LiDAR data are based upon the National Tidal Datum Epoch of 1983-2001 and are NAVD88 (North American Vertical Datum of 1988) . There is a difference in sea level of 0.8 m between the MLLW 1960-1978 Epoch and the modern MLLW Epoch. Because of the differences in the two datums and the increase in sea level since 1962, the storm surge level had to be converted to NAVD88 to match the LiDAR data. After converting this level, the areas of the coastline above modern mean sea level up to elevations of 2.01 m (NAVD88 storm surge) were defined as the inundation surfaces and were overlain upon 2002 aerial imagery with the 2002 building shapefile to determine the areas of greatest impact if another storm of this magnitude were to occur. These images were analyzed zone by zone to determine the effects of such a storm. The three areas that appeared to be the most heavily populated were looked at more closely to estimate the number of buildings that would be damaged by a 2.01 m storm surge above modern mean sea level.

The estimate of the areas of inundation, based on the storm surge only, is actually a minimum inundation level. The actual inundation in a storm of similar magnitude with the same levels of storm surge would vary greatly on the wave height during the storm. Wave action along the dunes would destroy the dunes much faster and cause much more damage. This process would cause more areas to be impacted by the amount of storm surge in comparison to water simply rising without any wave action. The results of this analysis of potential damage from a future equivalent storm are presented in section 3.5 of this study.

Chapter 3

RESULTS & DISCUSSION

Shorelines were analyzed after digitization and erosional rates were compared with those stated by Honeycutt in (2003) to determine if the areas of weakness that are seen in the aerial photographs match those areas of weakness that Honeycutt found. Honeycutt's erosional rates and areas of vulnerability were compared with the amount of shoreline erosion and displacement caused by the 1962 Northeaster.

A vast majority of Delaware's shoreline that was overwashed was the dune system. The effect of the overwash on surrounding neighborhoods and buildings was also assessed. Areas of overwash can become overwashed again in the future. The 1962 overwash area from the 1962 storm was overlain on top of the 2002 aerial photographs of Delaware to show what areas could potentially become overwashed again in the future.

A great deal of real estate was damaged as a result of this particular northeaster. A combination of poor building practices and the sheer size, strength, and duration of the storm are to blame. The density of buildings pre-storm and post-storm illustrates the sheer size of the storm and allows us to look more closely at the damage to the modern shoreline, while the building density of the modern 2002 shoreline serves to illustrate the damage that would be caused by another storm of this magnitude. This is important in that it allows for the prediction of what areas may be affected most should a comparable storm occur again in the future.

Lastly, LiDAR data were used to apply the 1962 Northeaster storm surge, and the average storm wave height in Delaware to the modern shoreline of Delaware to determine what kind of impact a comparable storm might have today.

3.1 Shorelines

Zone 1 shows Cape Henlopen and the changes that have occurred there (Figure 3.1). The maximum erosion in this zone was 54 m (due to the 1962 Northeaster), the least affected of those on the coastline (Table 3.1). The spit has grown significantly since the 1960s. There are three areas highlighted on Figure 3.1 where the water has breached the beach and reached fairly far back into the mainland. Zones 5 and 7 experienced significant breaching of the barrier system between the Atlantic Ocean and Rehoboth Bay (Figures 3.2 and 3.3). Maximum erosion amounts in these zones were 106 m (350 ft) and 77 m (250 ft), respectively (Table 3.1). Although in many places the breaching doesn't cut across the entire barrier, toward the lower region of Zone 5, the water from the Atlantic Ocean likely met the water of the bay during the storm (Figure 3.2). Zone 7 has one of the largest breaches in this zone (Figure 3.3), where the maximum erosion is as much as 150 m (492 ft) (Table 3.1). This breach meets the tidal inlet on the back side of the barrier. This zone also has an area of deposition of 102 m (335 ft) next to Indian River Inlet (Table 3.1) that occurred as a result of the 1962 Northeaster. This area experienced deposition due to a jetty that stabilized the inlet; sand during the storm accumulated at this locale (Figure 3.3). Normally, this would not be the case, as direction of the longshore transport is northward (Ramsey et al., 1993). The turbulent waters from the storm created this atypical accretion in this locale.

South of Indian River Inlet, erosion and breaching due to the storm were just as significant. For example, Zone 9 not only shows over 90 m (295 ft) of erosion, but also breaching (Figure 3.4). This area corresponds with an area of large overwash that crosses U.S. Route. 1. Zone 12 also shows areas of significant erosion and breaching (Figure 3.5). More than 130 m (427 ft) of maximum erosion occurred along the southern portion of Delaware's coastline. Breaching in the northern portion of this zone extends across the entire barrier.

One of the most pronounced effects of the 1962 Northeaster on Delaware's shoreline was the formation of a double-bar feature. These double bars with small cuts in-between, can be seen in the majority of the aerial photographs taken in 1962 after the storm. An example of the double-bar feature can be observed in Zone 12 (Figure 3.5, 3.6). These features can no longer be observed in the 1968 or later aerial photographs.

Zone	Erosion Maximum	Deposition Maximum	Physiographic Region (Ramsey et al., 1993)
1	-54	0	spit complex
2	no data	no data	no data
3	no data	no data	no data
4	-70	0	bay barrier
5	-106	0	bay barrier
6	-150	0	bay barrier
7	-77	102	headland
8	-92	0	bay barrier
9	-98	0	headland
10	-82	0	headland
11	-121	0	bay barrier
12	-131	0	bay barrier

Table 3.1 **Maximum Shoreline Erosion or Deposition.** This table shows the maximum erosion and/or deposition for a given zone between 1960 and 1962 shorelines and the physiographic regions in which they occur. Negative numbers indicate erosion, while positive indicate deposition. Measurements are given in meters.

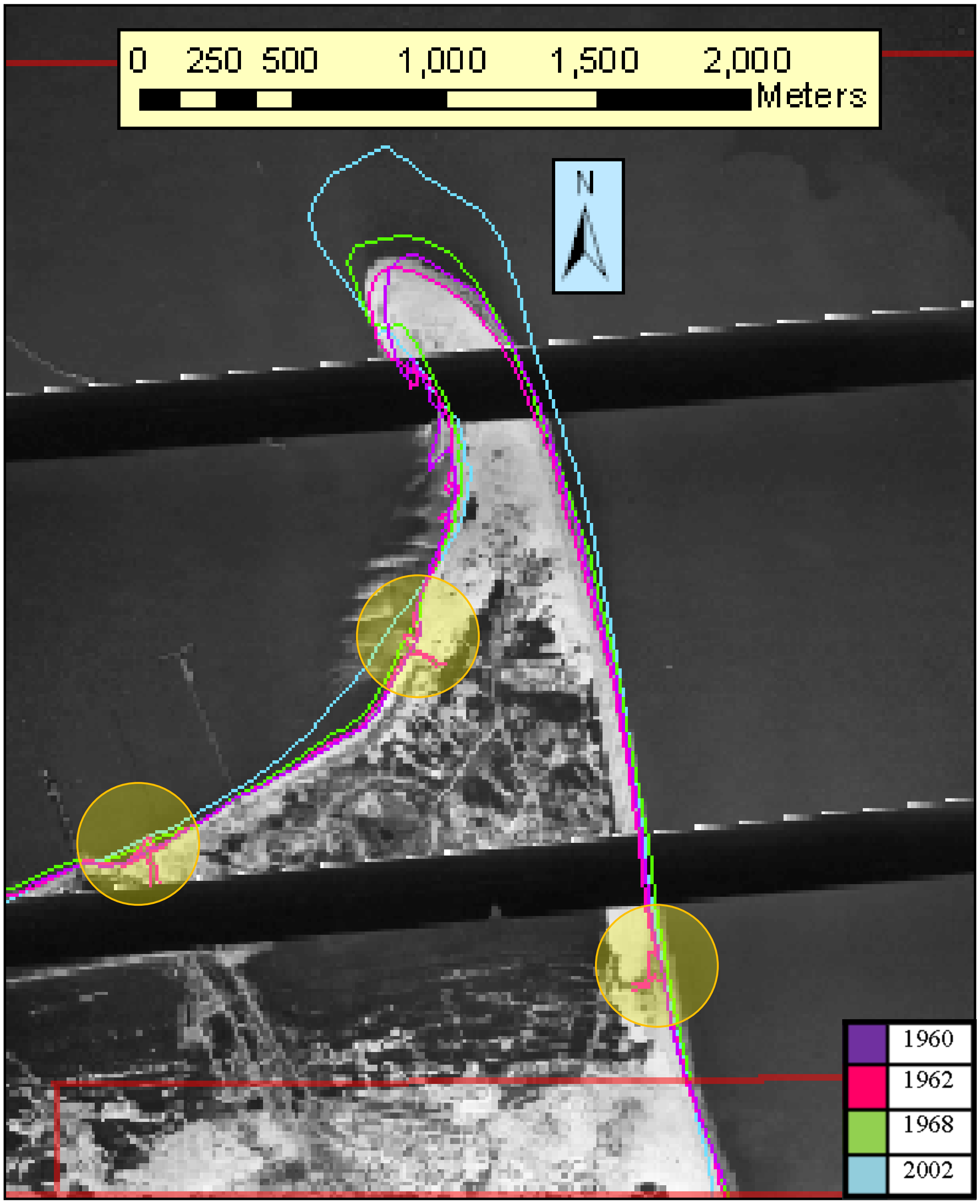

Figure 3.1 **Zone 1 Digitized Shorelines.** This aerial photograph shows the shorelines of Zone 1. As shown by this image, Cape Henlopen has migrated further west and north into Delaware Bay since 1960. As highlighted by the circles, there are 3 areas, where the 1962 Northeaster had a significant impact on the shoreline.

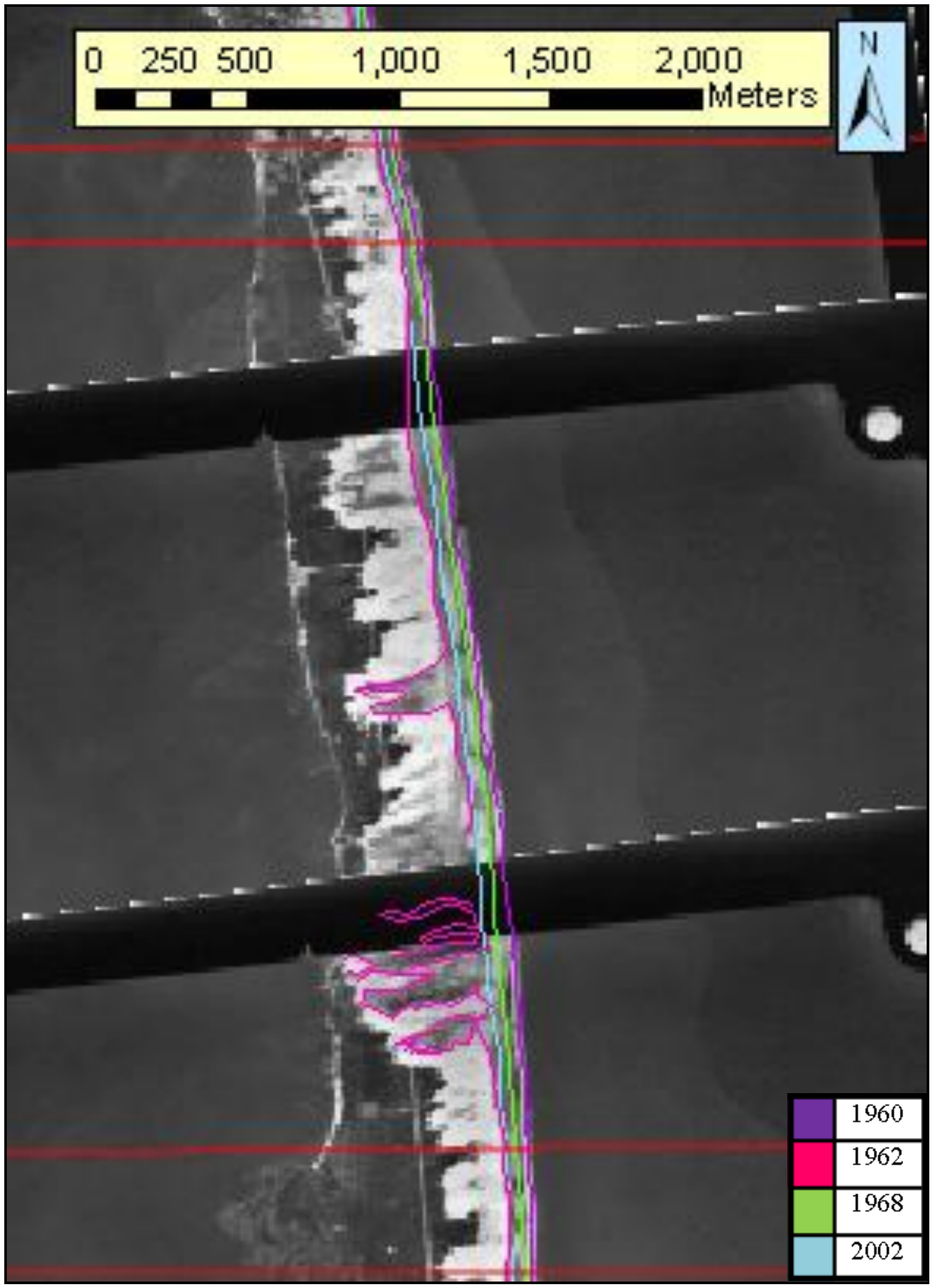

Figure 3.2 **Zone 5 Digitized Shorelines.** As shown by this image, there are areas of significant inlet fingering due to the breaching of water through the barrier.

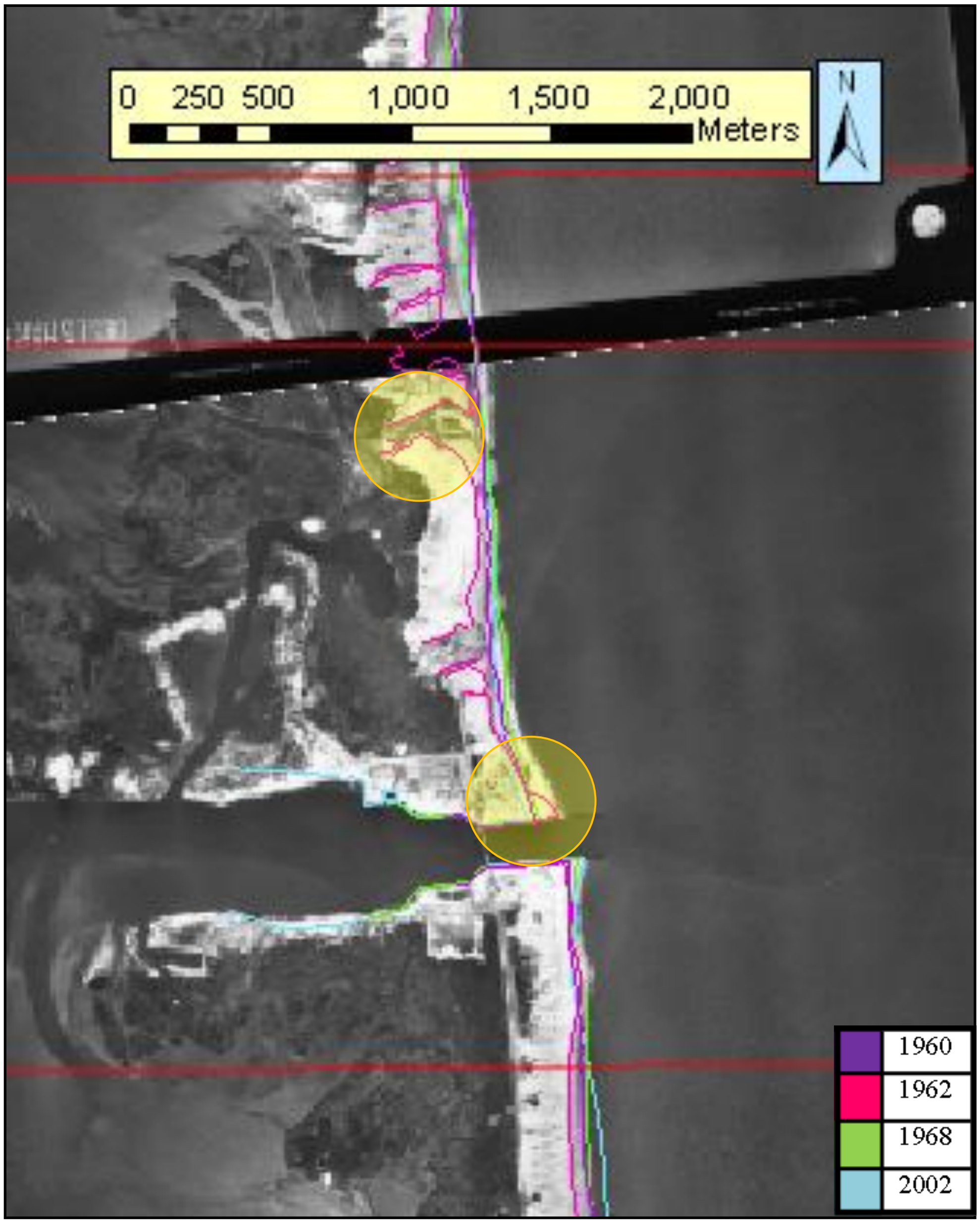

Figure 3.3 **Zone 7 Digitized Shorelines.** As shown by this image, there are areas of significant inlet fingering due to the breaching of water through the barrier. In the uppermost highlighted area, the water from the ocean breached through to the tidal channel. The second area highlighted shows the deposition of sediment on the northern side of the jetty, while to the southern side, there is a great deal of erosion.

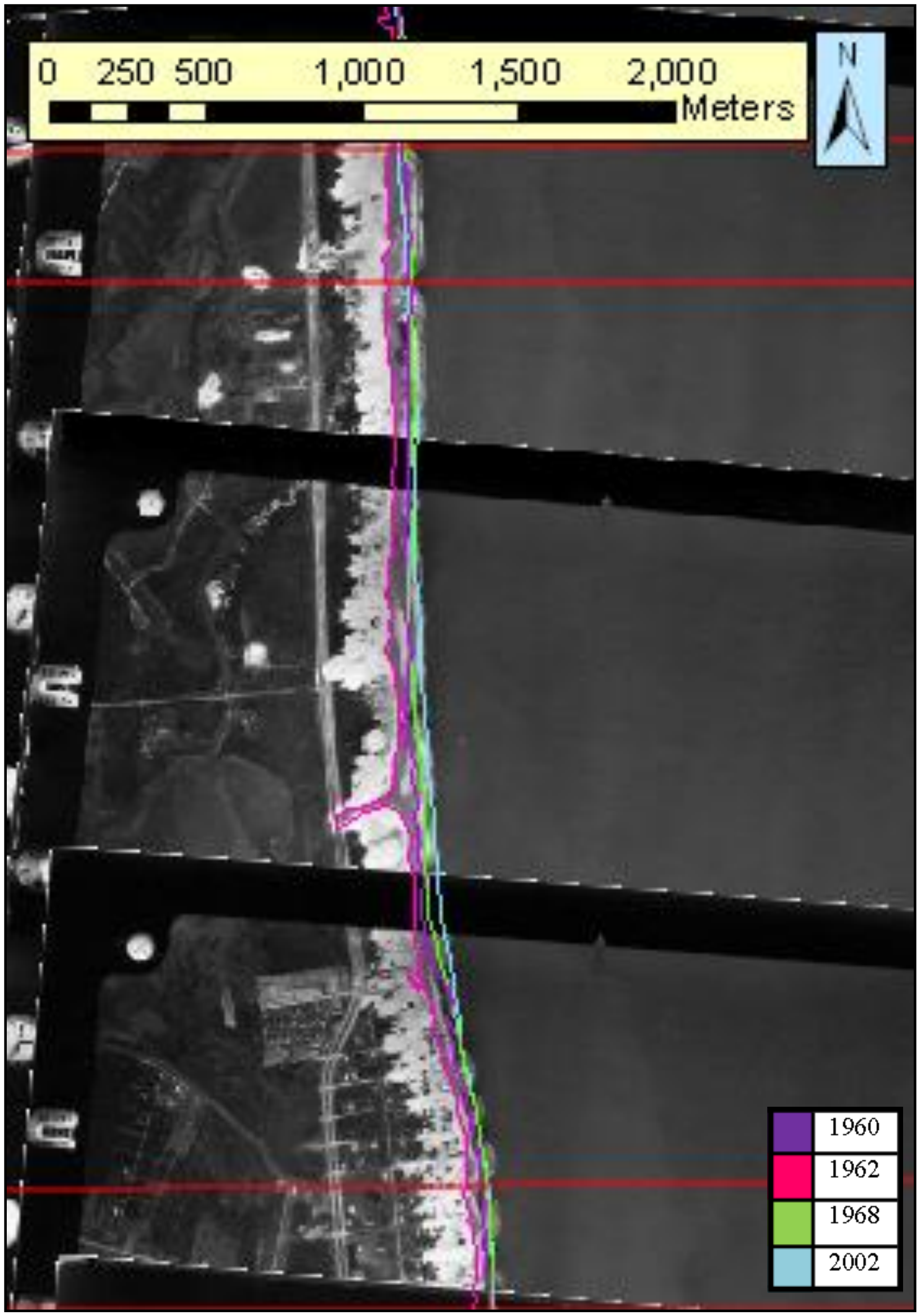

Figure 3.4 **Zone 9 Digitized Shorelines.** As shown by this image, there is an area, mid-photo, of significant breaching, with a great deal of erosion throughout the rest of this portion of the shoreline.

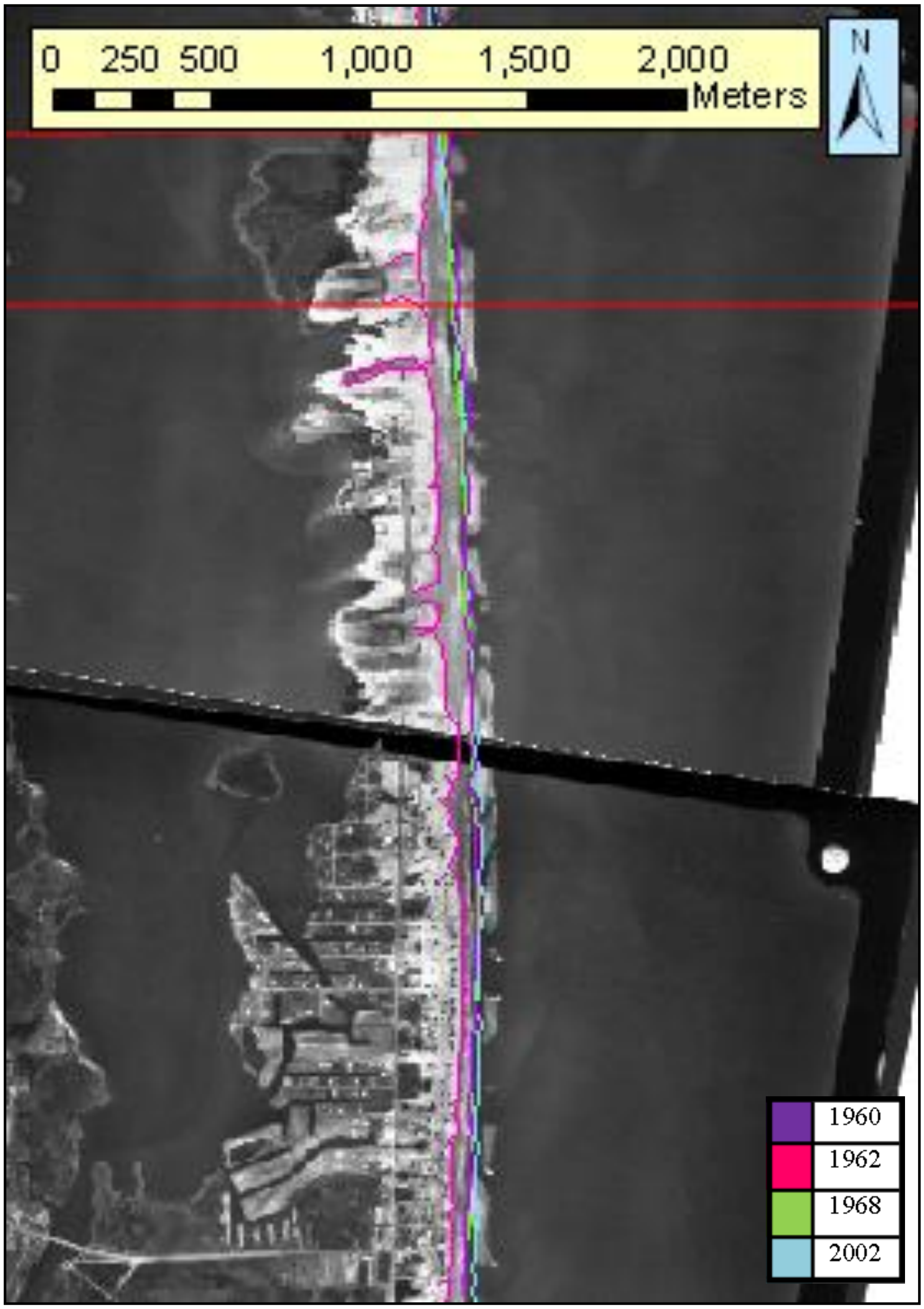

Figure 3.5 **Zone 12 Shoreline.** Shows the shorelines of Zone 12. As with the other images south of Indian River Inlet, this image shows a significant loss of shoreline. There are also two major breaches at the top of this image, where the ocean meets the bay.

Figure 3.6 **Double Bar Feature (Zone 12).** This photograph shows more closely the apparent double-bar feature that occurred due to the northeaster in the area of Fenwick Island. Notice the “islands” of sand that will eventually become re-attached to the coastline.

The shoreline analysis involved a quantitative analysis as well as the qualitative analysis. Based on an analysis of shoreline data from 1845-1997, Honeycutt (2003) determined that the average shoreline erosion rate from Cape Henlopen to Indian River Inlet is approximately 1.4 m/y (4.6 ft/y). Figure 3.7 shows Honeycutt's shoreline change rates for the shoreline between Cape Henlopen and Indian River Inlet. According to this figure, the areas of greatest erosion occur to the south of Cape Henlopen toward the Rehoboth Headland and south of the Rehoboth Headland close to the Indian River Inlet. Shoreline accretion, rather than erosion, is occurring in the vicinity of Cape Henlopen due to the general northward longshore transport of sand toward the Cape Henlopen Spit (Figure 3.1). The graph from Honeycutt (2003) showing the areas of highest average erosion were compared to the shoreline digitization results of this study to determine if the greatest erosion to the shoreline resulting from the 1962 Northeaster occurred within the regions that could be defined, on a long-term basis, as the most vulnerable to erosion.

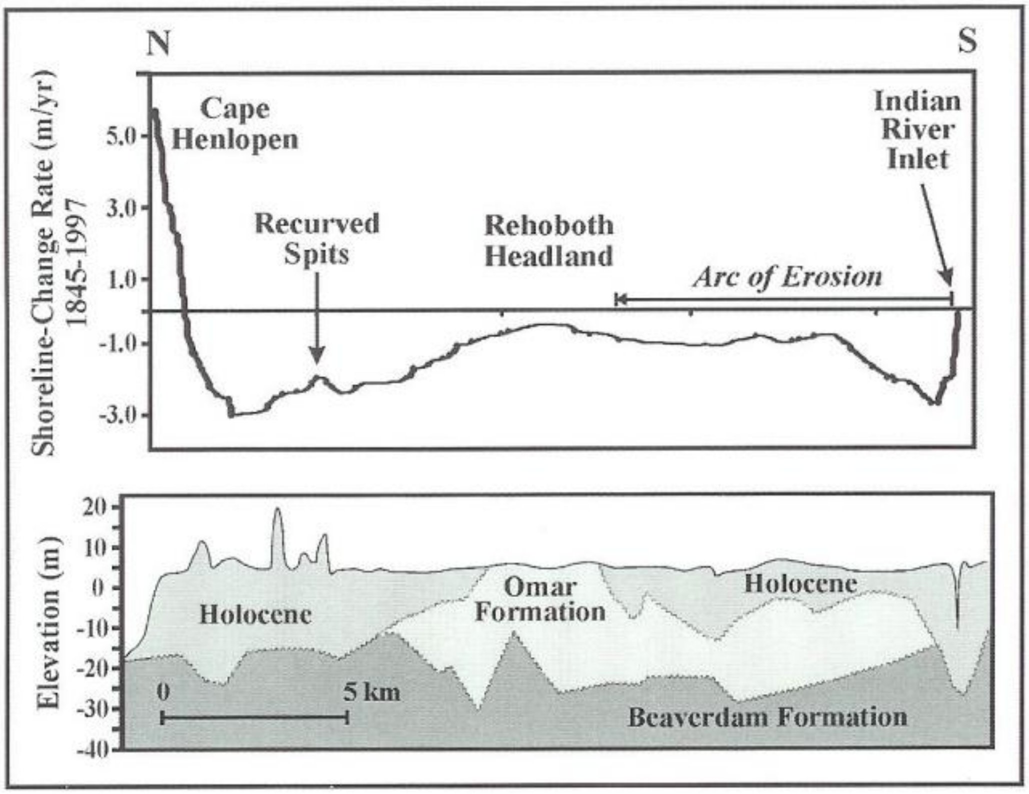

Figure 3.7 **Amount of Erosion and Geologic Formations.** Shows the areas of significant rates of shoreline erosion and their corresponding geology (Honeycutt, 2003).

The following series of figures are based on the 500 m (1640 ft) transects set along Delaware's coastline. As shown in Figures 3.8 and 3.9, the shoreline changed significantly due to the 1962 Northeaster. The areas of greatest erosion occur on the bay barrier system just north of Indian River Inlet (19,000 m distance), as well as the bay barrier system in the area of Fenwick Island. The data support Honeycutt's Arc of Erosion, and also support the fact that generally, the bay barrier portion of a coastline tends to be the most vulnerable to shoreline changes. In Figure 3.10, the data support the rebound of the coastline due to the renourishment efforts of the Army Corps of Engineers immediately following the storm. The majority of erosional damage caused by the 1962 Northeaster was repaired during this renourishment effort, rather than naturally. Figure 3.11 illustrates a more balanced distribution of erosion and deposition, as this graph compares the changes between the 1968 and 2002 shoreline, a span of more than 30 years, over which no storm comparable to the 1962 Northeaster occurred again.

As described in Chapter 2 of this study, not only were the shorelines measured at fixed distances from one another, but the shoreline was also analyzed for the maximum amounts of displacement per each zone. This was done because although measuring the shorelines at fixed distances gives a relatively representative look at the shoreline, it may not show the actual maximum displacement experienced.

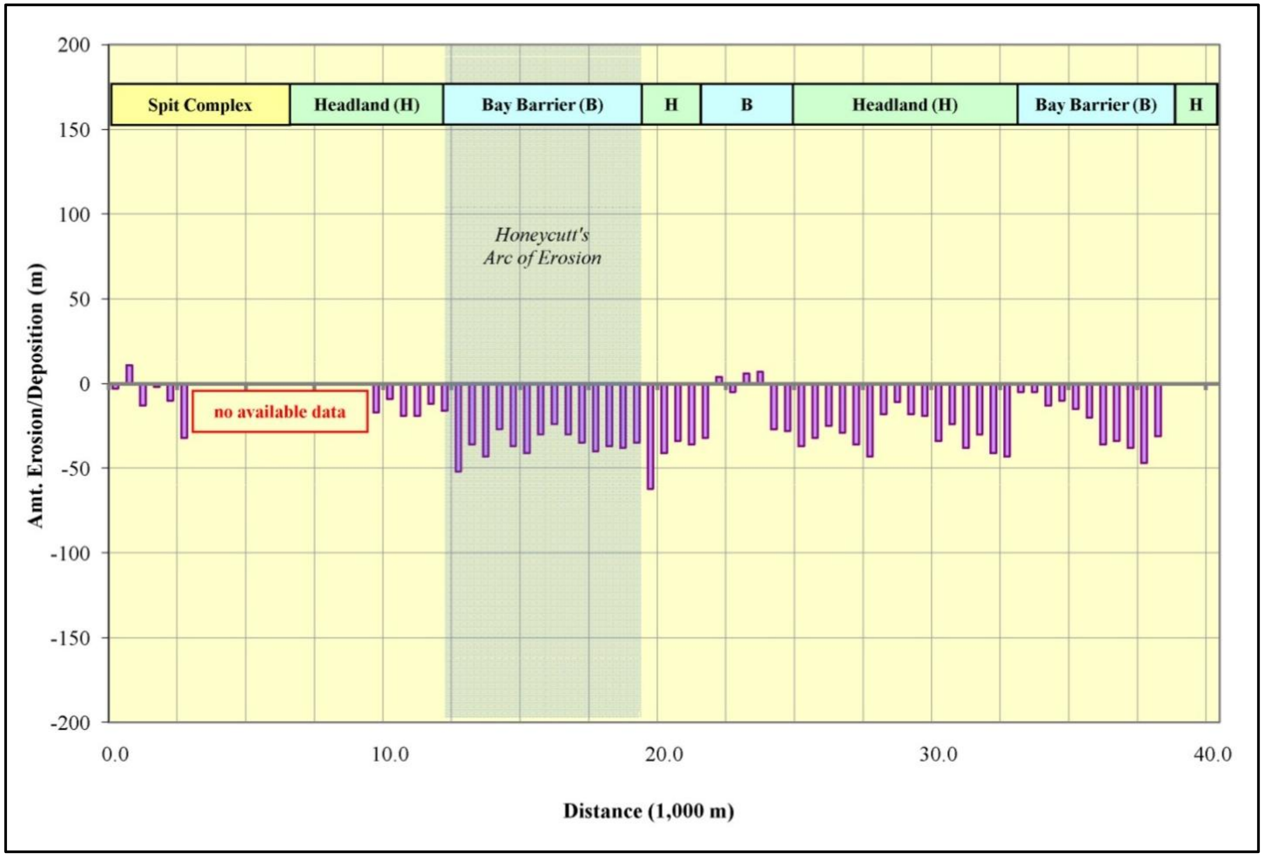

Figure 3.8 **1954-1960 Erosion/Deposition along the Shoreline.** Shows the amount of erosion and/or deposition along Delaware's shoreline between the years 1954 and 1960. This graph also shows the Physiographic Regions based on the map created by the Delaware Geological Survey for Special Publication No. 25, as well as Honeycutt's Arc of Erosion (Honeycutt, 2003).

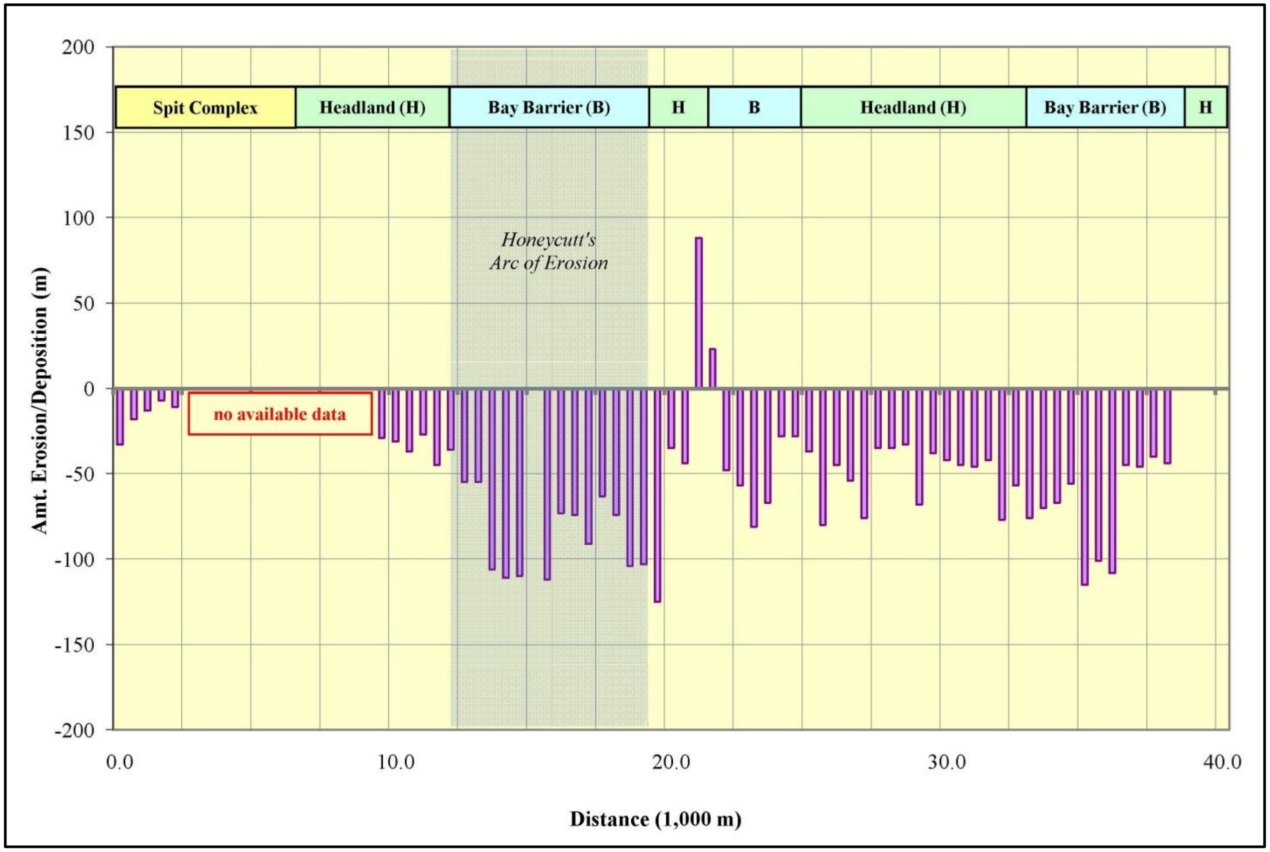

Figure 3.9 **1960-1962 Erosion/Deposition along the Shoreline.** Shows the amount of erosion and/or deposition along Delaware's shoreline between the years 1960 and 1962. This graph also shows the Physiographic Regions based on the map created by the Delaware Geological Survey for Special Publication No. 25, as well as Honeycutt's Arc of Erosion (Honeycutt, 2003).

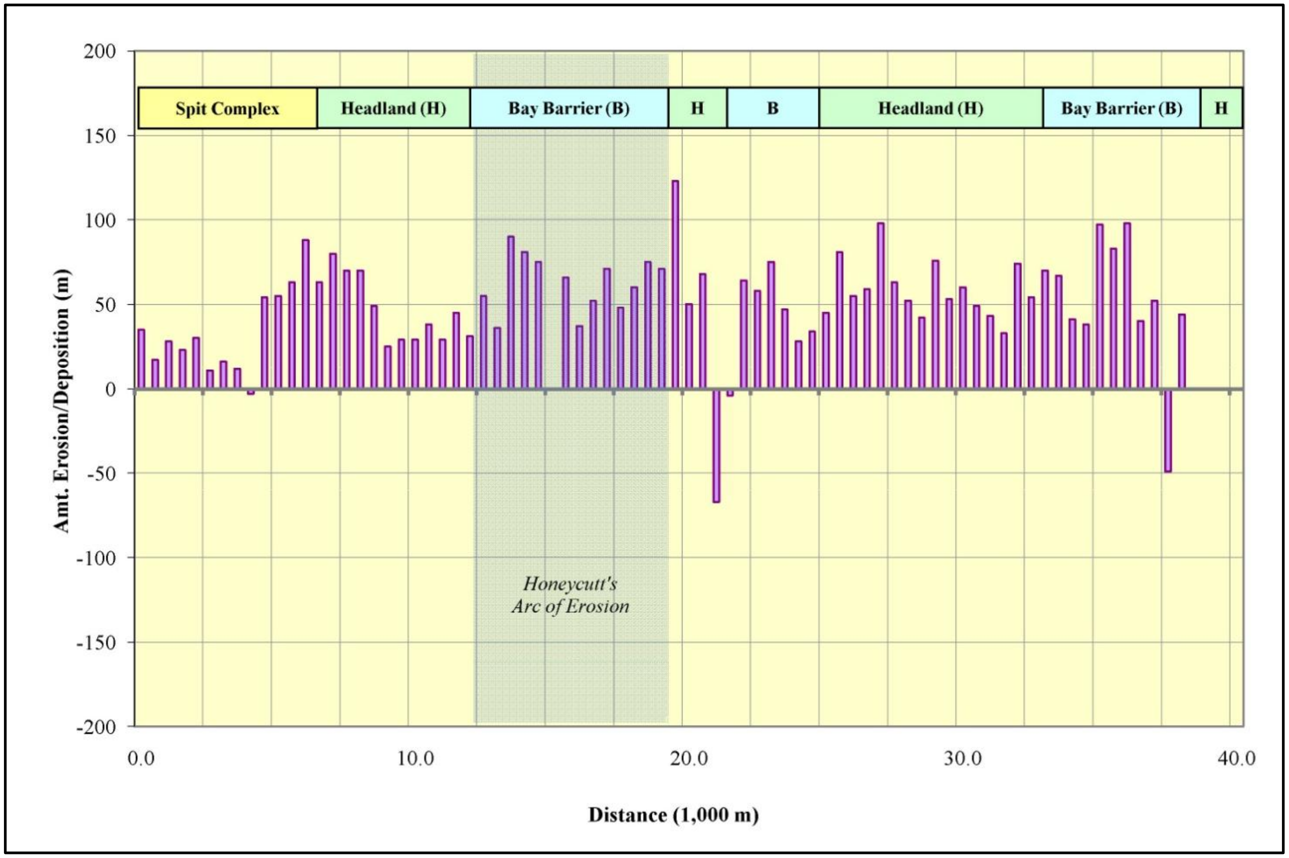

Figure 3.10 **1962-1968 Erosion/Deposition along the Shoreline.** Shows the amount of erosion and/or deposition along Delaware's shoreline between the years 1962 and 1968. This graph also shows the Physiographic Regions based on the map created by the Delaware Geological Survey for Special Publication No. 25, as well as Honeycutt's Arc of Erosion (Honeycutt, 2003).

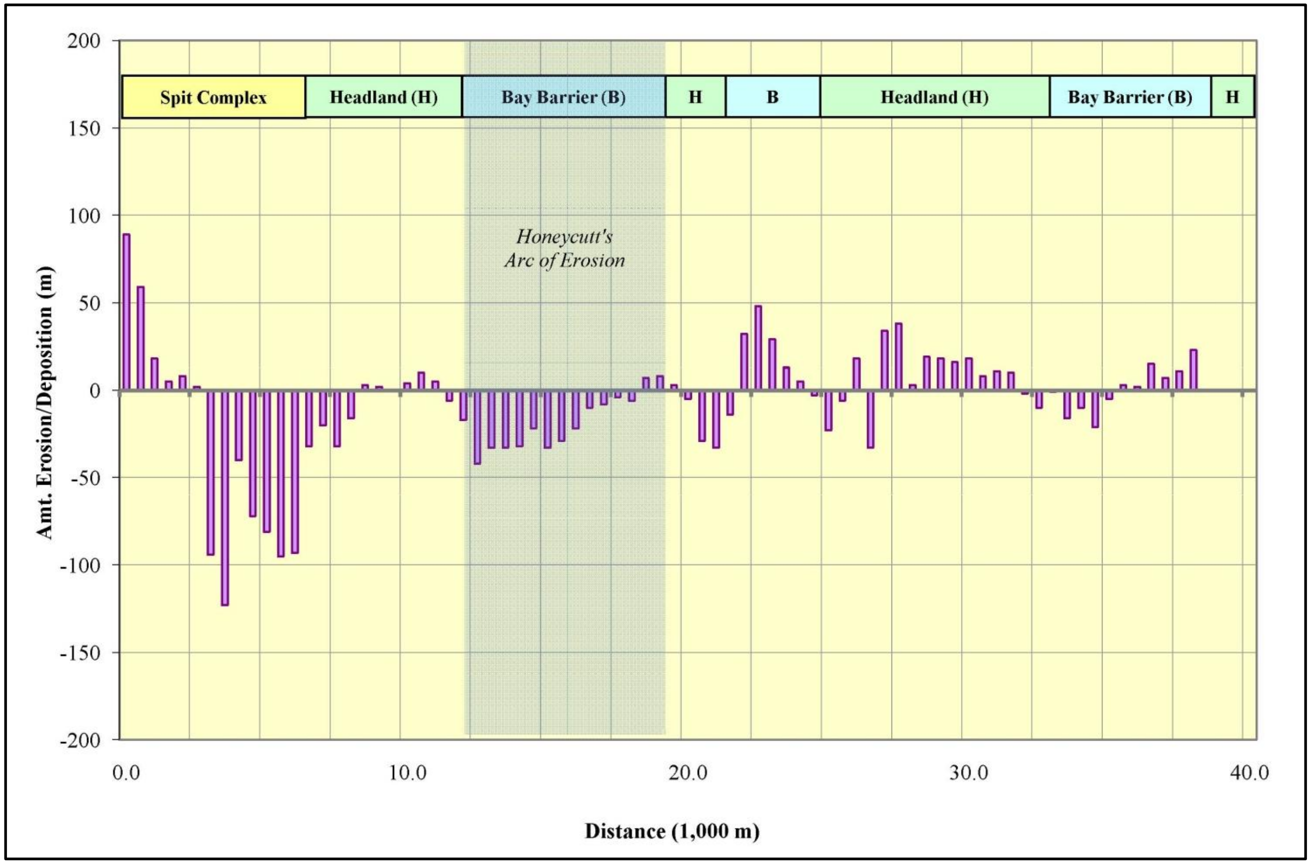

Figure 3.11 **1968-2002 Erosion/Deposition along the Shoreline.** Shows the amount of erosion and/or deposition along Delaware's shoreline between the years 1968 and 2002. This graph also shows the Physiographic Regions based on the map created by the Delaware Geological Survey for Special Publication No. 25, as well as Honeycutt's Arc of Erosion (Honeycutt, 2003).

Table 3.1 shows the maximum amount of erosion or deposition that was measured in each of the twelve zones as a result of the storm. The maximum amount of erosion measured was approximately 150 m (492 ft) in Zone 6 which is located at Delaware Seashore State Park, just north of Indian River Inlet, with significant maximum erosion amounts of 106 m (348 ft), 121 m (397 ft), and 131 m (430 ft) in Zones 5 (northern portion of Delaware Seashore State Park), 11 (South Bethany and northern Fenwick Island) , and 12 (Fenwick Island), respectively.

The zones with the greatest amounts of maximum erosion as a result of the 1962 Northeaster coincide with the areas of significant longer-term erosion identified by Honeycutt (2003). Zones 4-7 occur in the area that Honeycutt (2003) defines as the "arc of erosion" (Figure 3.7). These zones have maximum erosion amounts between 70 m (230 ft) and 150 m (492 ft) (Table 3.1). Zones 5, 6, 11, and 12 all have displacements of shoreline greater than 100 m, the maximum as much as 150 m (492 m) in Zone 6. All of the measurements within these zones occur on bay barriers. Both methods of measuring the amount of erosion/deposition along Delaware's shoreline due to the 1962 Northeaster (set distance measurement lines, and the max erosion/deposition measurements) support that bay barriers are likely to show the most erosion. Between 1962 and 1968, there was significant deposition as the shoreline recovered from the erosional effects of the 1962 Northeaster. The average amount of deposition during this interval was 47 m (154 ft). In large part, although it cannot be completely quantitatively determined, this recovery was due to the immediate renourishment efforts of the U.S. Army Corps of Engineers following the storm. Between 1960 and 1962 from Cape Henlopen to Indian River Inlet, an average of 0.54 m of erosion was observed. When the whole shoreline was averaged over this time interval, the difference was roughly the same. Average change from Cape Henlopen to Indian River Inlet between the years 1968 and 2002 was approximately 19.9 m (65 ft) of erosion, suggesting that on the whole, the shoreline is retreating as supported by Honeycutt's study.

From 1968 to 2002, the shoreline over most of its length returned to conditions characterized by fair-weather erosional conditions. A notable exception is in Zone 1, where dramatic deposition continues as the Cape Henlopen Spit continues to accrete (Figure 3.7). The average rate of erosion for the coastline north of Indian River Inlet between these years (1968 and 2002) is 0.56 m/year. This number was found by using the measured changes in shoreline over the years (1954 to 2002) and calculating a rate, then averaging the rates across the stretch of shoreline to get an overall rate-of-change. This value is much less than that determined by Honeycutt (2003).

Shorelines are very dynamic features and are controlled by dynamic processes. They undergo cycles of change throughout different seasons; a good example being storm-weather conditions versus fair-weather conditions. One can find that a shoreline is prograding over a specific decade, while another could look at shorelines over a century and find that it is actually retreating. Therefore, it is not surprising that the rate found in this study was quite different from that of Maria Honeycutt. This study used four shorelines over a span of 49 years, centered around the largest northeaster this coastline has ever seen. Honeycutt on the other hand used many shorelines in a span from 1845 to

1997. Therefore, a long-term shoreline erosion rate is not appropriate for this study, as it is not representative of what the shoreline is actually doing.

3.2 Overwash

Overwash along Delaware's Atlantic coastline was significant due to the 1962 Northeaster. The area of the most visibly pronounced overwash was found within Zone 5, south of Dewey Beach, Delaware (Figure 3.2). Although the actual lateral displacement was less than other areas, it was visually pronounced. As shown by the 1960 aerial photographs, this area was not developed to a great degree (Figure 3.12). The major features were U.S. Route 1 and a small building. Figure 3.13 shows the same area seven days after the 1962 Northeaster. Overwash extends to the bay behind the barrier, with water breaching almost completely through. Rt. 1 has been completely covered by overwash, and the building visible pre-storm has been destroyed (Figure 3.13). By 1968, as shown by aerial photography, the beach in this area has almost completely recovered from the damage caused by the 1962 Northeaster (Figures 3.14). The channeling apparent on the back side of the barrier on the 1968 and 2002 aerial photographs are not due to the storm (Figure 3.15). These man-made channels were constructed sometime between 1962 and 1968 to decrease the amount of mosquito breeding by draining the marsh; this method is called mosquito ditching and was popular in Delaware up until the late 1960s (Lesser, 2007). Although the 1962 Northeaster breached most of the barrier along Delaware's shoreline, the coastline appears to have fully recovered without any permanent scars of this massive northeaster. The three other major areas of overwash are discussed further in the following section, as they correspond with significant damage to buildings.

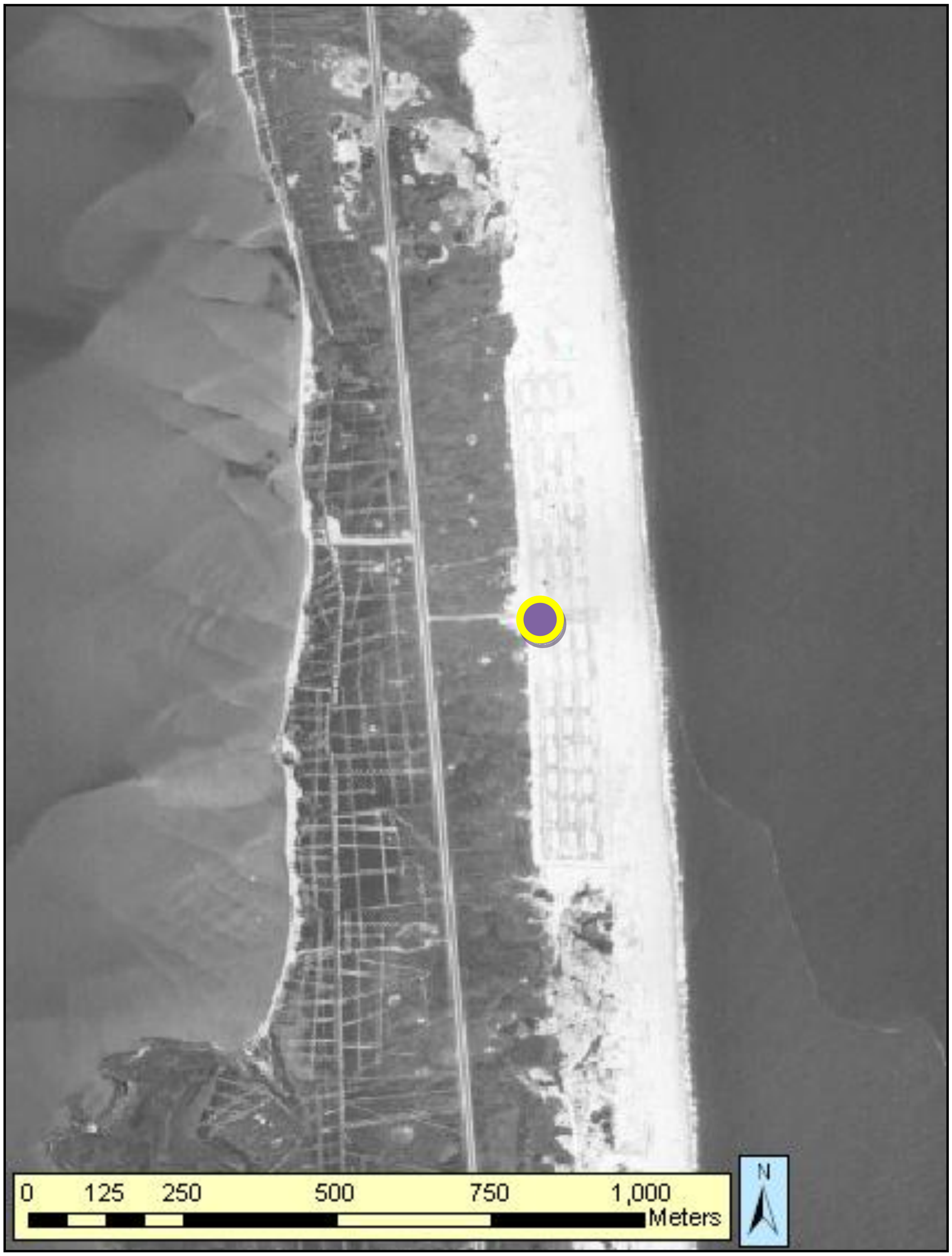

Figure 3.12 **1960 Aerial Photograph of the Overwash Area.** Shows part of the coastline, south of Bethany Beach, before it was overwashed by the 1962 Northeaster. The purple dot shows where a structure is.

Figure 3.13 **1962 Aerial Photograph of the Overwash Area.** Shows the area south of Bethany Beach, 7 days after the 1962 Northeaster went through the area. The purple dot shows where the structure was. Not only does the overwash breach the island, but the ocean almost meets the bay, and probably did during the storm.

Figure 3.14 1968 Aerial Photograph of the Overwash Area. Shows the same portion of the shoreline in 1968. There doesn't appear to be any permanent scarring from the 1962 northeaster. Mosquito channels can be seen on the back side of the barrier.

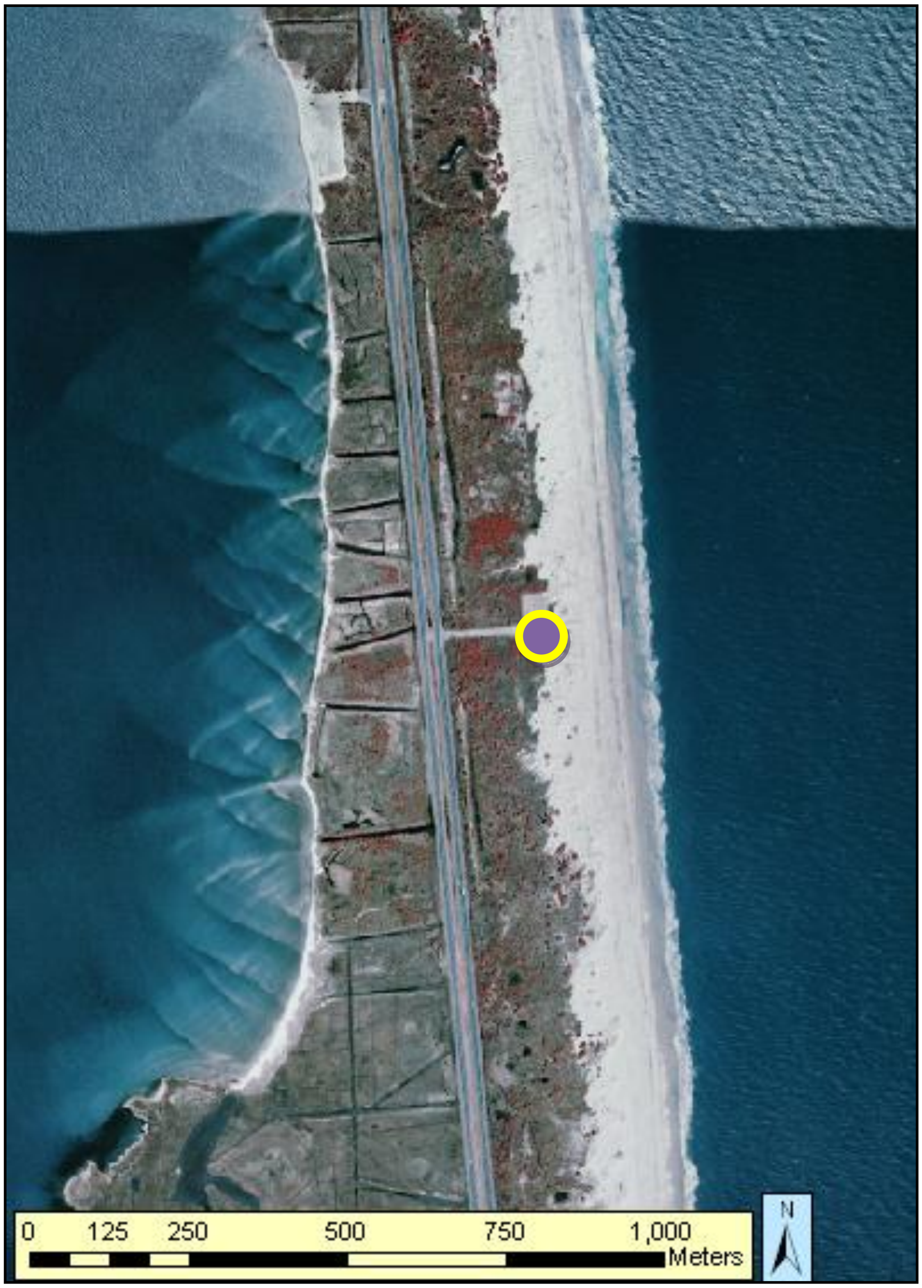

Figure 3.15 2002 Aerial Photograph of the Overwash Area. Shows the same portion of the shoreline. The beach has rebounded for the most part, but is narrower than it was in the 1960s.

A very large portion of Rt. 1, the main highway running from the northern part of Delaware through its southern border, was covered by overwash from the storm. Using the GIS Spatial Analyst Tool from ESRI on the digitized areas of overwash, the total area of overwash along Delaware's shoreline was calculated to be 8.34 km^2 (3.22 mi^2). This area does not include the Cape Henlopen State Park region because it was difficult to discern overwash versus the overall presence of sand in the park. The area is insignificant when compared to the lateral displacement and actual volume of sand displaced to non-beach portions of the shoreline.

Following an approach similar to that used in the shoreline analysis, maximum and minimum lateral (landward) displacement of sand was measured for each zone (Table 3.2). The maximum amount of lateral displacement, ~650 m (2133 ft), was found to be located at the lower end of Zone 6 and upper end of Zone 7, which is just south of Bush Island in Delaware Seashore State Park. Here, the overwash extended into Rehoboth Bay, and more than likely during the storm Atlantic Ocean waters flooded into Rehoboth Bay. The least amount of lateral displacement of overwash, ~45 m (148m), occurred in Zone 2 in Rehoboth Beach. Similarly to the areas where the shorelines had the most lateral displacement, the maximum areas of overwash also occurred on barrier beach systems.

The U.S. Army Corps of Engineers report published in 1963 outlined all details of the storm, its effects on the shorelines it affected across the East Coast, and the methods by which the beaches and areas affected were cleaned up and restored. One of the first orders of business was to restore the dune systems destroyed during the storm. Table 3.3 shows the length of shoreline restored in linear meters, as well as the volume of sand that was put back on the beach as dunes. According to the report, for these areas, no additional sand had to be dredged or brought in from other areas; they used sand from the streets and the miles of overwash created by the storm. The USACE does not report specific measurements of the volumes of sand displaced by the storm; however, we can gain a good understanding of what those volumes were by knowing the amount of sand that was brought in from the overwash fans along these specific stretches of the Delaware coastline. The largest volume of sand that was in the area from the Coast Guard Station to Indian River Inlet. Along a stretch of 2,560 m, a total volume of 221,721 cubic meters was trucked back onto the beach system as dunes. Note that this area is within Honeycutt's Arc of Erosion. These volumes further support that bay barrier systems are most susceptible to loss of beach and to large amounts of overwash. They are more susceptible to overwash because they are lower lying than other areas of the shoreline, such as headlands, and because they have water on both sides of the island, they can flood from both sides (CETS, 1987).

Zone	Maximum Displacement (m)	Minimum Displacement (m)
1	---	---
2	513	**44**
3	320	46
4	368	51
5	596	148
6	**647**	148
7	**647**	97
8	356	51
9	356	83
10	338	74
11	444	185
12	546	125

Table 3.2 **Maximum and Minimum Lateral Displacement.** The maximum and minimum lateral (landward) displacement of overwash is shown for each zone. Zone 1 was excluded in the measurements because of the predominance of sands in the Cape Henlopen State Park area.

Region of the Coastline	Length of Beach Renourished (lm)	Volume of Sand put on Beach (cubic m)
Rehoboth Beach	1,524	165,288
Dewey Beach	1,433	62,734
Indian Beach to Coast Guard Station	4,694	113,722
Coast Guard Station to Indian River Inlet	2,560	221,721
Beach Cove to Bethany Beach	1,402	28,389
Bethany Beach	1,463	53,250
South Bethany to York Beaches	1,128	49,747

Table 3.3 **Volumes of Sand Displaced.** Volumes of sand displaced for each of the coastal areas of the DE shoreline are taken from the 1963 U.S. Army Corps of Engineers report for the 1962 Northeaster. The volumes represent the amount of sand put back on the beach during post-storm renourishment efforts. All of the sand brought back to rebuild the beaches came from the beach and dune system, and was storm-displaced sediment.

3.3 Buildings

As described and shown earlier in this study, building damage was yet another component to storm damage from this large-scale extratropical storm. Many homes and other buildings were destroyed not only by inundation and wave action, but also by overwash created through the destruction of the dune systems. It is important to have a look at the way overwash affected the buildings along the shoreline because if this type of storm were to occur again, such an analysis could help identify areas of above average risk and which buildings in such areas are more vulnerable to damage. Therefore, this study walks through a few key areas where overwash greatly affected the buildings along the coastline, and identifies how they were affected.

While the building density analyses do not show a great deal of increase in the development of Delaware's Atlantic Coastline, aerial photography does show this difference. The first attempt to quantify building damage as a result of the 1962 Northeaster, a density analysis was attempted through the GIS interface. The attempt, however, was unsuccessful; this GIS function is better suited toward population density studies. Very dense areas of development in an area also set on vulnerable portions of the coastline mean a great deal more people affected by the storm.

As shown by the 1962 aerial photographs (Appendix A), the destruction of buildings appears to be highly correlative to overwash fans. It should be kept in mind that the buildings present in 1962 were not built under modern building standards; in fact, many of the building specifications that are in place today came about as a consequence of the 1962 Northeaster. The 1962 buildings were generally built on top of cinderblocks; when the water came up onto the beach, sand liquefied beneath the house, and it tipped forward into the water. Foundation failure was the main cause of damages (Oates: Pratt, 2007). Not only did buildings collapse under these conditions, but they were also moved and relocated by the flow of sand and water. Four locations were chosen to illustrate the impact of the overwash fans on the buildings and structures in the area (Figure 3.16). Each location was chosen based on the size of the overwash fan and the level of impact it had on the buildings in the area (Figure 3.16). The aerial photographs show which buildings remained after the storm and which had disappeared. Unfortunately, the condition of the remaining structures cannot be determined from the photos.

Location 1 is north of Indian River Inlet, and only had three buildings in the area in 1960, before the storm (Figure 3.17). After the 1962 Northeaster only two of those three buildings remain (Figure 3.18). Location 2 is south of Location 1, and just north of Indian River Inlet (see Figure 3.16). Seven buildings existed in this area before the storm (Figure 3.19). The 1962 Northeaster pushed a significant amount of sand and water over the beach and Rt. 1, which can be seen down through the center of the aerial photograph (Figure 3.20). Only four of the original seven buildings remained after the storm. Location 3 is just below the Indian River Inlet (Figure 3.16). Figure 3.21 shows the 1960 aerial photograph with the 1960 buildings superimposed on them. In this area, there were twenty buildings, and after the 1962 Northeaster had ravaged this area, only eleven of those buildings remained (Figure 3.22). Three of the homes that were right along the beach were completely destroyed and washed away. The rows of buildings seen in the center of the photograph were either completely destroyed by water and sand, or they were moved from their foundations. Lastly, Location 4 is located near Fenwick Island. There was significant impact due to the overwash on the buildings in this area. In 1960, there were sixteen buildings present (Figure 3.23). After the 1962 Northeaster, however, only seven were still there, again, most moving from their original foundations (Figure 3.24).

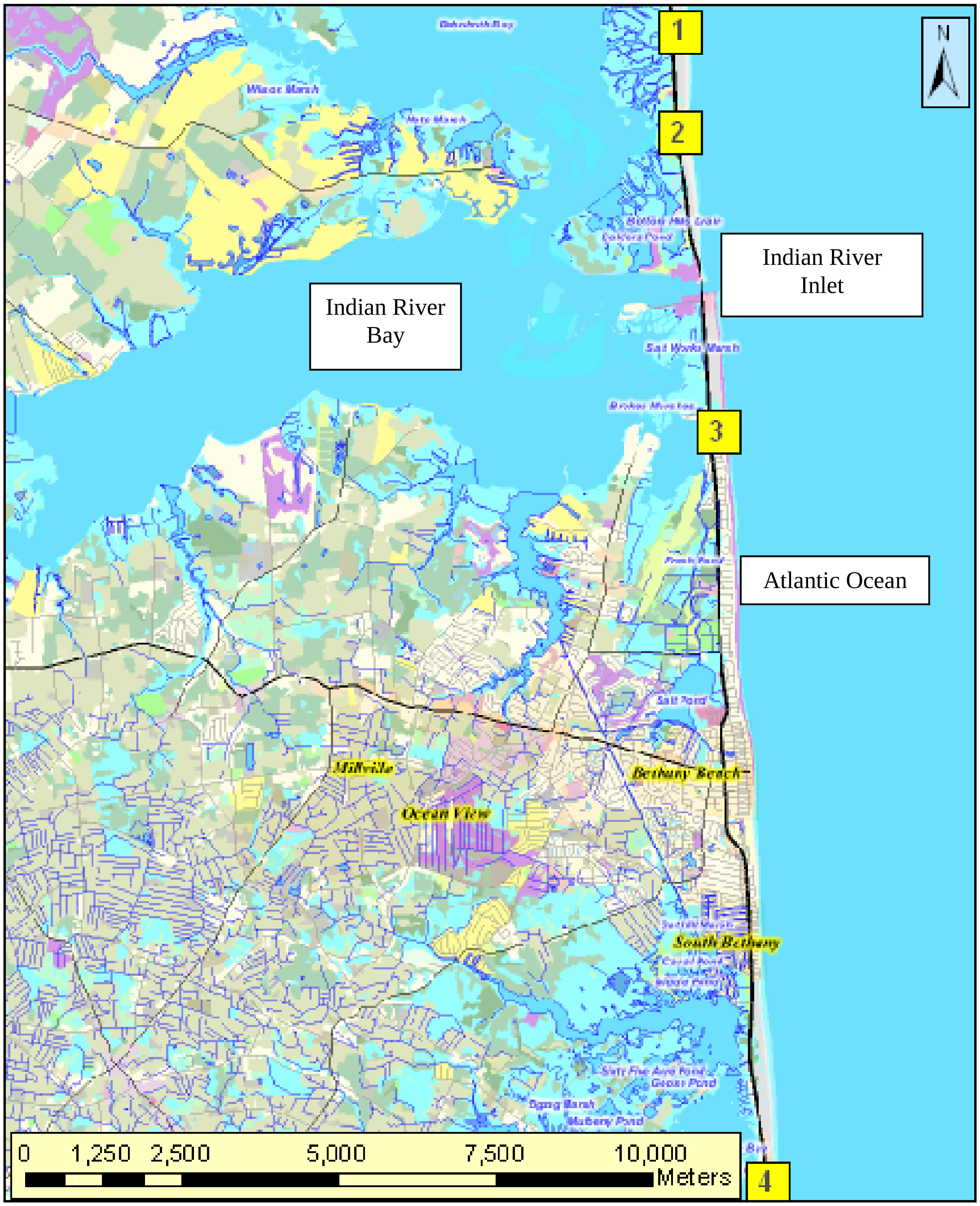

Figure 3.16 Location of Overwash Influenced Building Damage. Map showing the for areas discussed in the text, where overwash significantly influenced building damage.

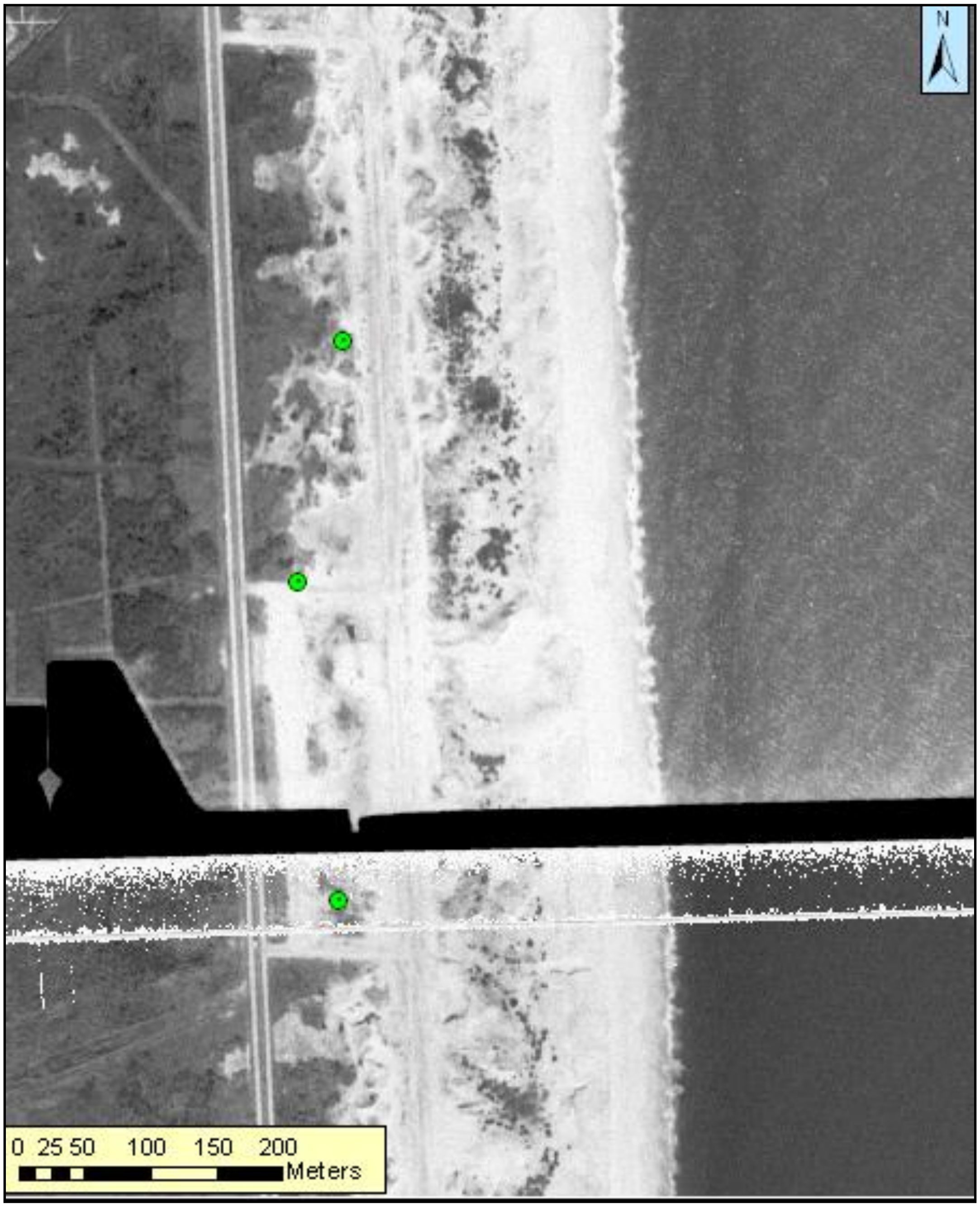

Figure 3.17 Location 1; 1960 Aerial Photograph of 1960 Buildings. The 1960 aerial photograph shows an area where overwash from the 1962 Northeaster has damaged or destroyed buildings that were there before the storm (green dots).

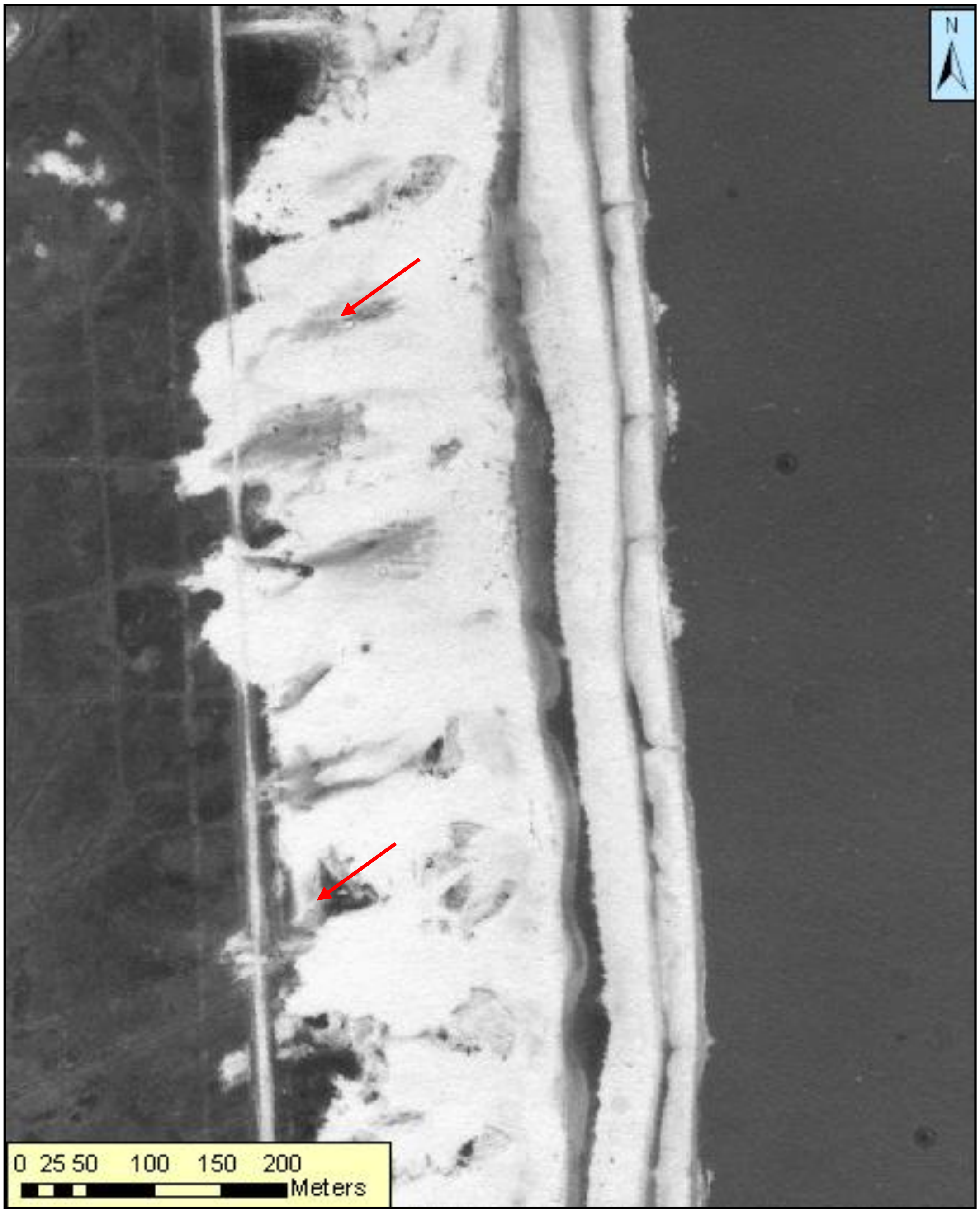

Figure 3.18 Location 1; 1962 Aerial Photograph of Surviving Buildings. Only two of the buildings survived the 1962 Northeaster in this area. Whether these buildings survived well enough to be livable after the storm cannot be determined by these aerial photographs.

Figure 3.19 Location 2; 1960 Aerial Photograph of 1960 Buildings. The green dots show the preexisting buildings in this 1960 photograph. This locale is south of Location 1, and just north of Indian River Inlet.

Figure 3.20 Location 2; 1962 Aerial Photograph of Surviving Buildings. Only four of the seven buildings survived the 1962 Northeaster in this area. Again, the type of damage sustained by the remaining buildings cannot be determined by the aerial photographs. The overwash washed out several of the buildings in this area.

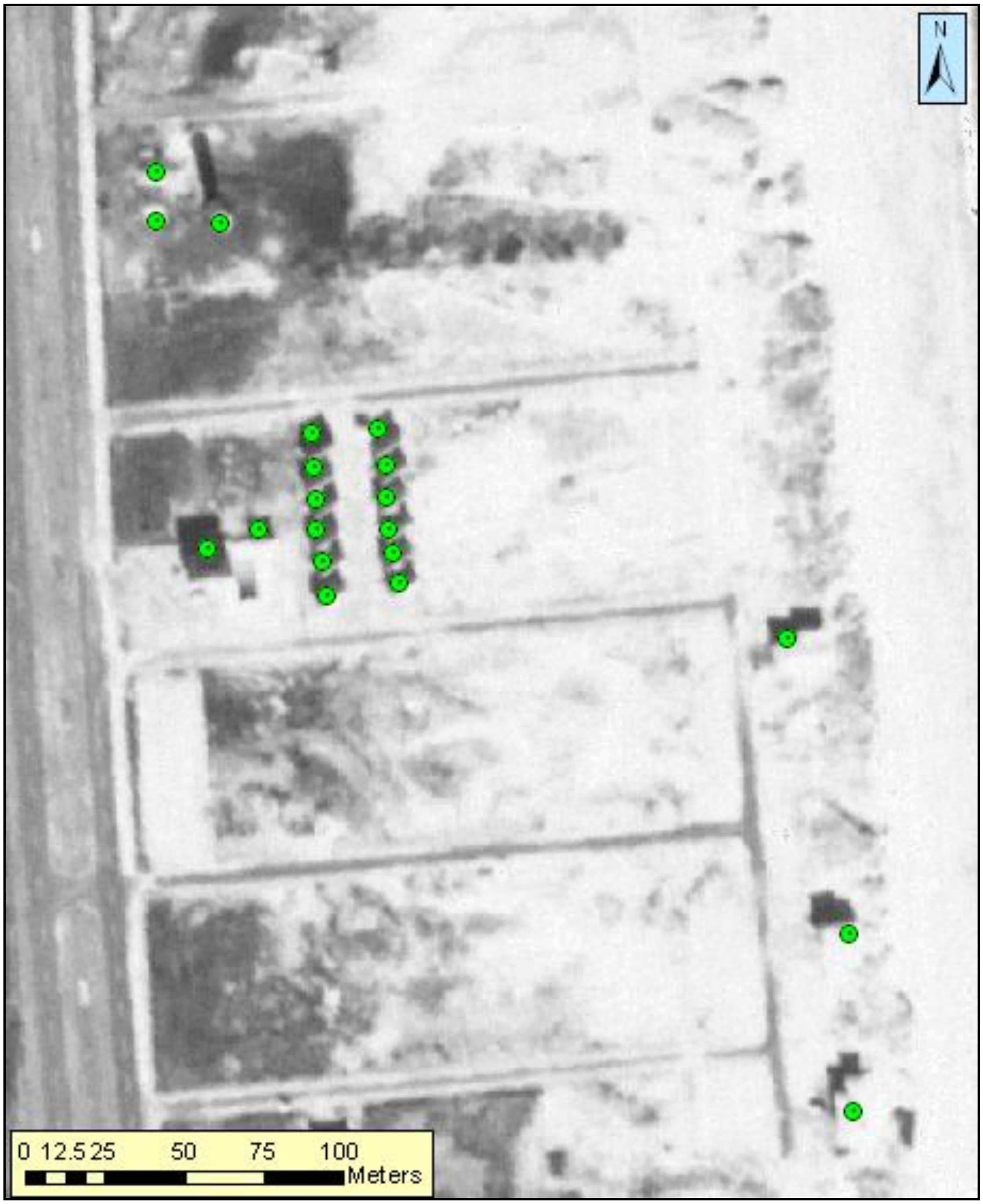

Figure 3.21 Location 3; 1960 Aerial Photograph of 1960 Buildings. The green dots show the buildings in this 1960 photograph. This locale is just south of Indian River Inlet.

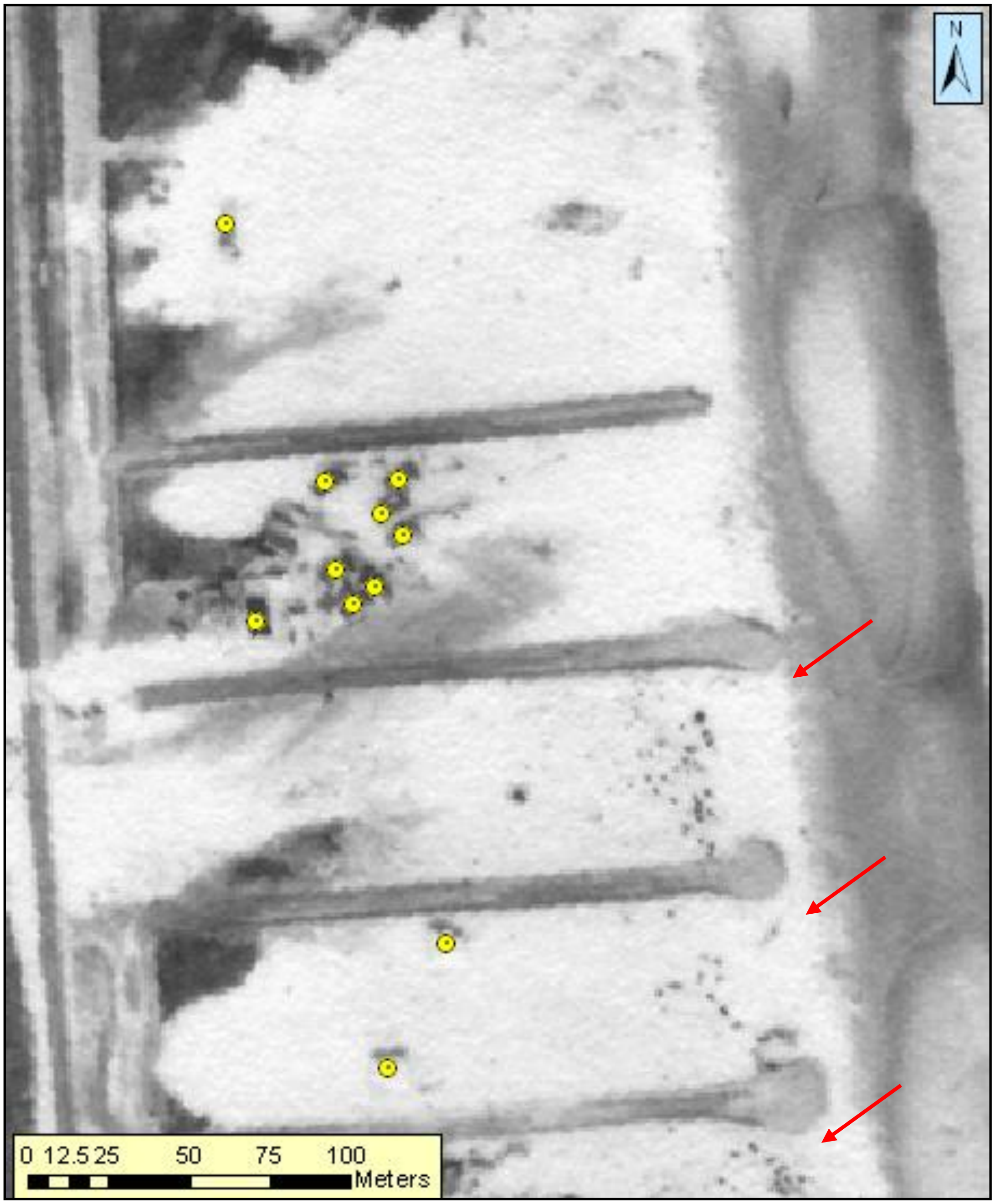

Figure 3.22 Location 3; 1962 Aerial Photograph of Surviving Buildings. Out of the 20 buildings that were present before the northeaster, only 11 survived, however, they were moved from their original foundations. The three buildings closest to the shore in the previous photograph were completely demolished. The red arrows here shows where they once were.

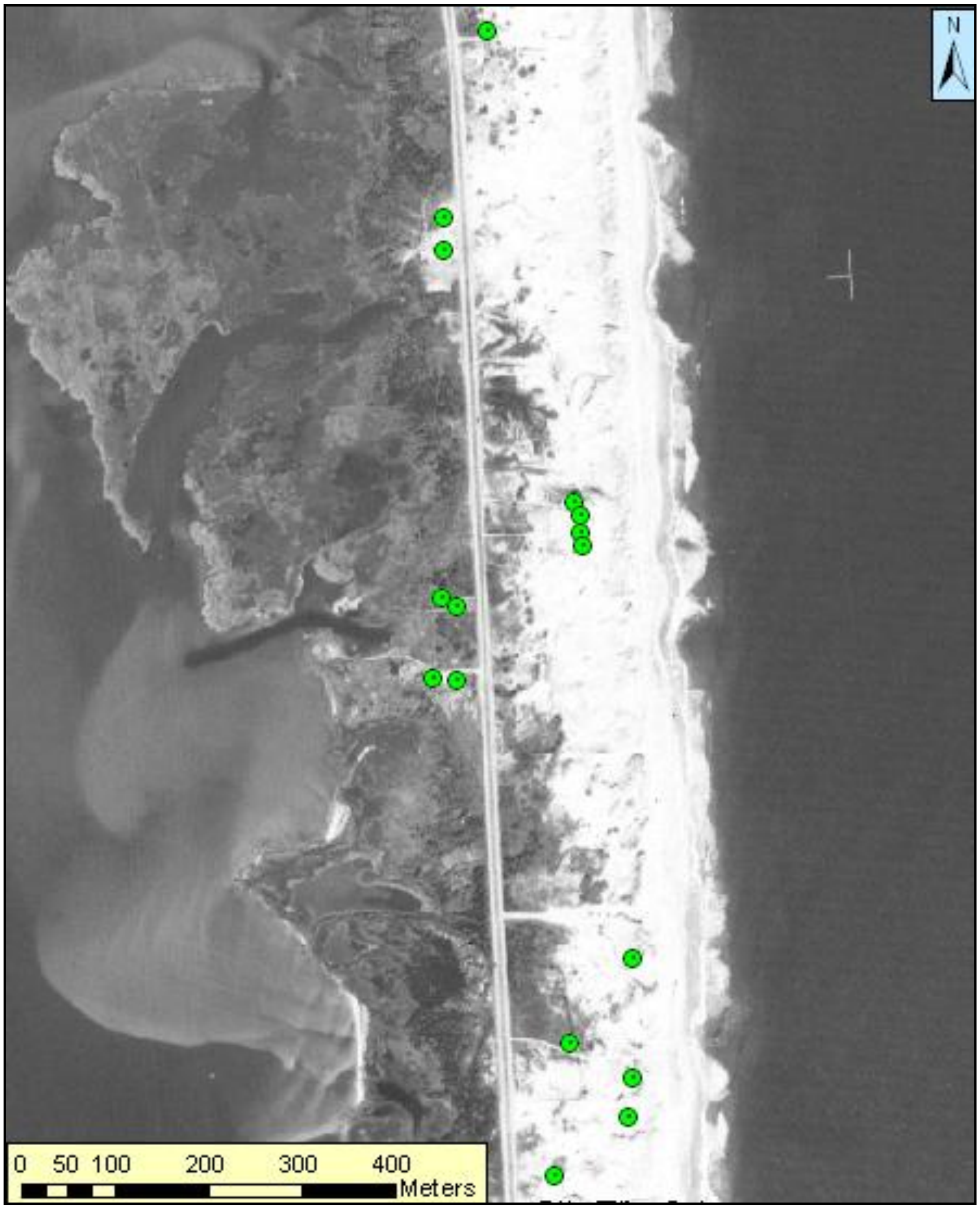

Figure 3.23 Location 4; 1960 Aerial Photograph of 1960 Buildings. The green dots show the buildings in this 1960 photograph. This locale is Fenwick Island.

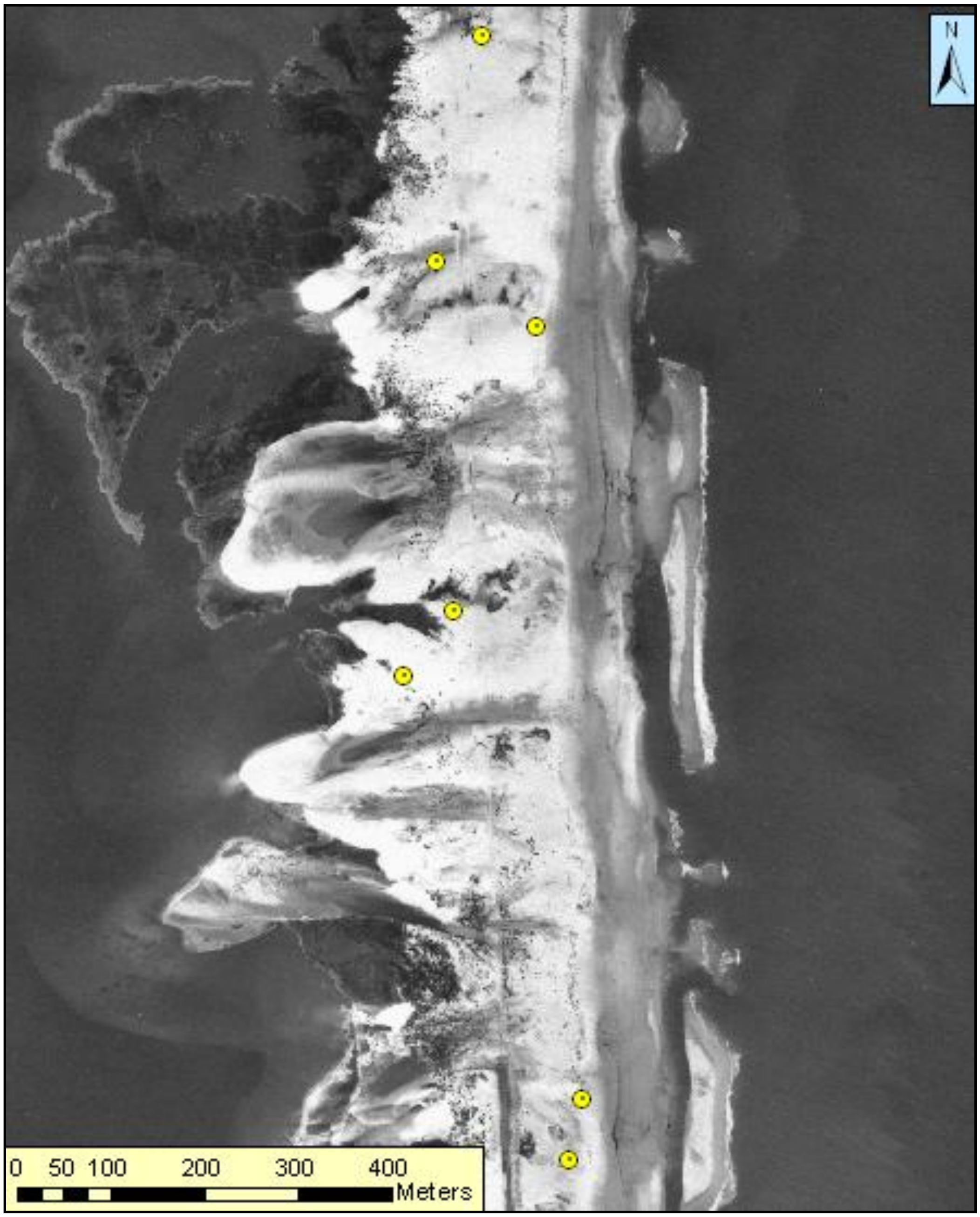

Figure 3.24 Location 4; 1962 Aerial Photograph of Surviving Buildings. Before the northeaster hit, of the sixteen buildings that were present in 1960, only seven remained after the extreme overwash in this area. This is the area of most extreme building devastation. As with the other overwash areas, it is difficult to determine the extent of damage of these surviving buildings.

It is also important to make an attempt to quantify the number of buildings per area that would be affected by a storm of this magnitude, should it occur again. In order to do so, a density must be calculated for the number of buildings in a particular area. In this study, this was done manually from GIS data. For example, the 1960 density of buildings in Zone 4, in the northern Rehoboth area, was approximately 0.043 buildings per square meter, while in 2002, this number increases 125% to 0.097 buildings per square meter (Table 3.4). However, the most impressive increase was seen in South Bethany Beach in Zone 10. The density went from 0.010 buildings per square meter in 1960 to 0.095 buildings per square meter in 2002; an increase of over 800%.

Clearly development is an important factor to think of when considering the effects of storm events along a coastline. As years progress, and development increases, the threat to property and human life similarly increases. From a coastal management perspective, these numbers must play a large role in emergency preparation for such storm events. The ramifications of these numbers will be further discussed in Section 3.4 of this study.

Parameters	Zone 4	Zone 9	Zone 10
No. 1960 buildings	1318	395	491
No. 2002 buildings	2970	1493	4476
Difference between no. of buildings	**1652**	**1908**	**3985**
Area of digitized buildings (sq. meters)	3,075,218	3,502,379	4,715,373
1960 manual building density (per 100 sq. meters)	0.043	0.011	0.010
2002 manual building density (per 100 sq. meters)	0.097	0.043	0.095
Percent increase from 1960 to 2002	**125**	**278**	**812**

Table 3.4 **Manual Density Analysis.** This table shows tabulations for the manual density analysis performed on Zones 4, 9, and 10.

3.4 LiDAR/DEM Data

LiDAR data and DEM data were obtained from the U.S. Geological Survey and are based on NAVD88. They were obtained for the purpose of estimating what kind of damage might occur along Delaware's modern beaches if this magnitude of storm were to occur again. LiDAR was taken for the entire Atlantic Coast of Delaware, illustrating the elevation of the coastline in meters. These data were viewed using Fledermaus software, then transferred to GIS for manipulation.

Since the highest recorded storm surge in Delaware during the 1962 Northeaster was recorded at 2.9 m based on MLLW for the Epoch 1960-1978. To correct for the differences in tidal datums, the 2.9m (9.5 ft) storm surge level was corrected to NAVD88. Therefore, a 2.01 m (6.5 ft) storm surge plane was set for the LiDAR at this elevation to show the areas of Delaware's coastline that would be inundated under a storm surge of that magnitude. When applied, most of coastal Delaware is under water due to the storm surge, with the exception of the Great Dune in Cape Henlopen State Park, and a small crest of the dune along the coastline.

Note that this flooding level includes only the height of the storm surge as a static rise in sea level and does not take into account the wave height or wave action associated with the storm. When wave heights are taken into account, the picture becomes even more grim. For example, wave heights during the 1962 Northeaster averaged between 6 and 9 meters (20-30 ft) (Carey & Dalrymple, 2003). Granted, these wave heights were derived from perfect storm conditions, such as a 1600 km fetch and a duration of 5 tidal cycles. These factors, including several others, must be taken into account when estimating the effects of a storm on a particular coastline, but are beyond the scope of this particular study. Regardless, it can be conservatively estimated that with wave heights on the order of 6-9 m (20-30 ft), that the coastal dunes could be (and were during the 1962 Northeaster) topped by ocean waves, while also being subjected to erosion due to constant wave action. Further, with these wave heights, inundation would be as much as 8.9 to 11.9 m (30-40 ft), which is very significant. To put this in a more visual perspective, given the wave heights added to the storm surge, in reference to the elevation LiDAR, even the gray areas would be covered in water, enough to overcome the dunes. This level is not just a static rise in water level but a high energy pounding of the shoreline by waves and would, and did, break down and break through dune systems.

To examine in greater detail the potential impacts of a storm of this magnitude, the areas of the coastline with greater population densities that have experienced the largest degree of overwash due to the storm (Section 3.3) examined using a further manipulation of the LiDAR data within a GIS framework.

Figures 3.25 to 3.28 show the current elevation of the coastline across the entire coastline, and then over the chosen zones, 4, 9, and 10. The LiDAR is superimposed over the 2002 aerial imagery for comparison. The highest elevations are shown in dark brown and gray, and include the Great Dune at Cape Henlopen, the Rehoboth Headlands, and the dunes along the shorelines. Unfortunately, some of the lowest elevations along the shorelines are where most of the development occurs (excluding Rehoboth), as well as marshy areas. In fact, several of the marshy areas can be as much as 1 m below sea level. This can be seen in portions of each of the studied zones.

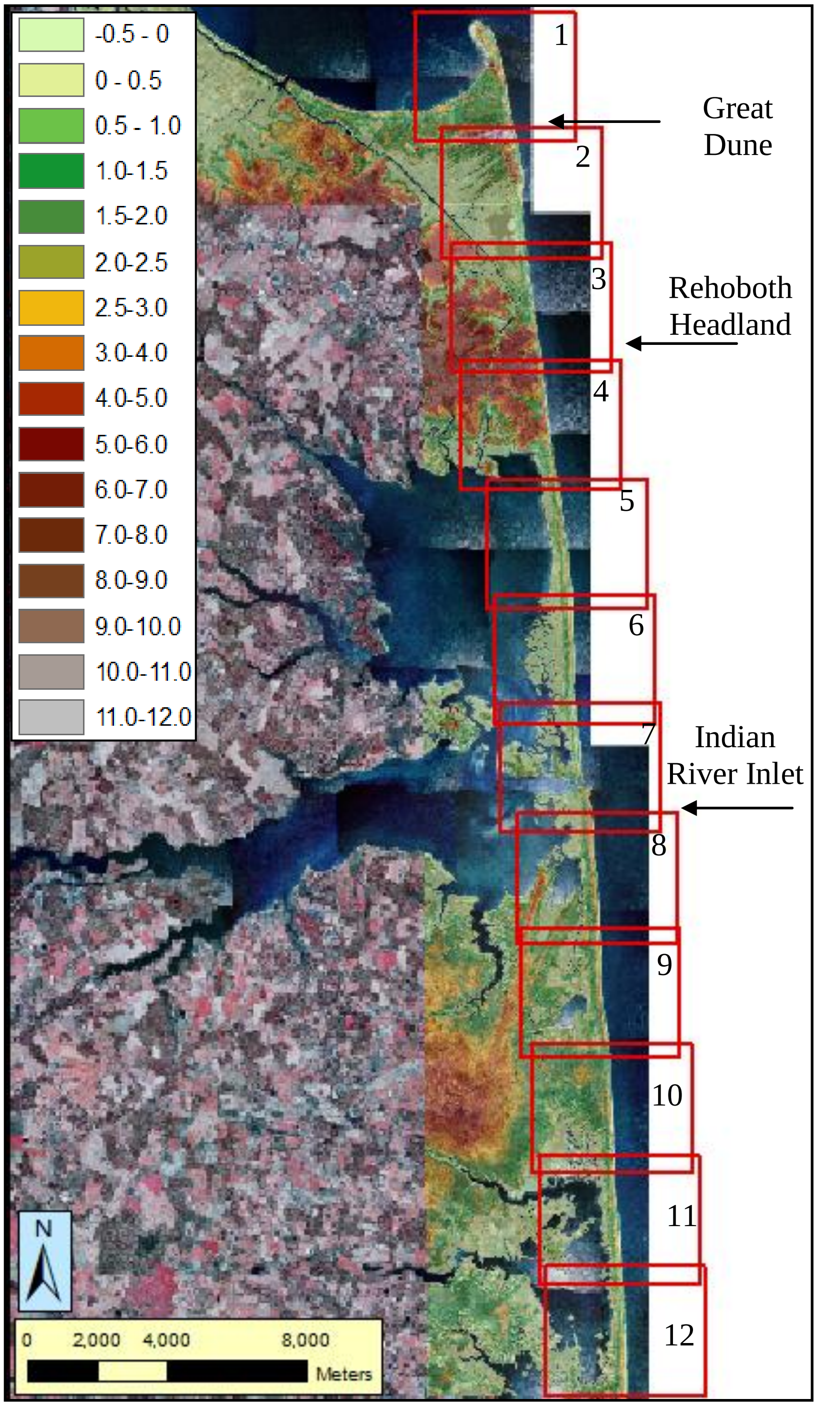

Figure 3.25 LiDAR Elevations along the Coastline. Shows LiDAR elevations taken along Delaware's coastline. The scale is shown in meters.

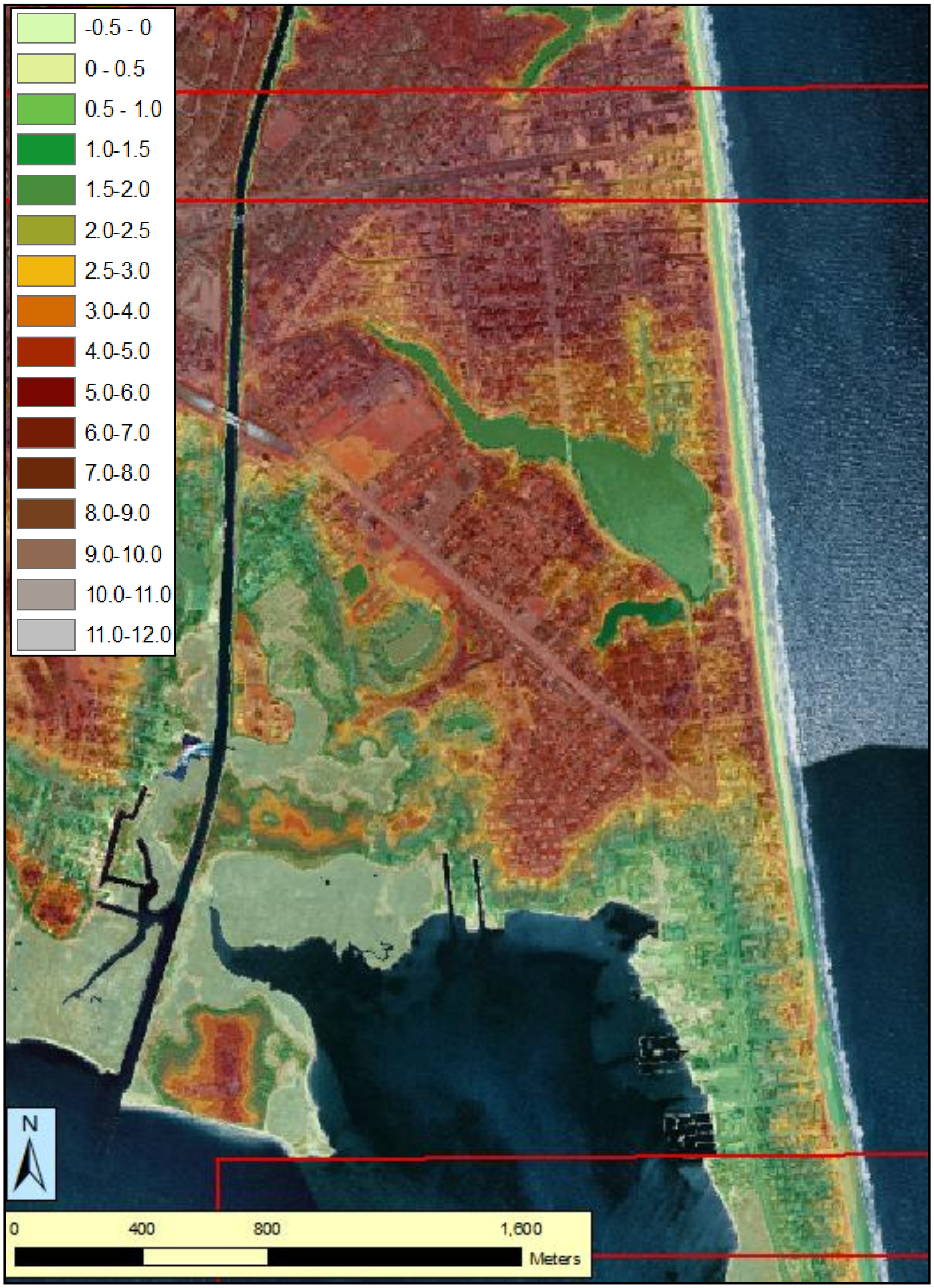

Figure 3.26 Zone 4 LiDAR Elevations. Shows the LiDAR elevation imagery for Zone 4, at Rehoboth Beach. The scale is shown in meters.

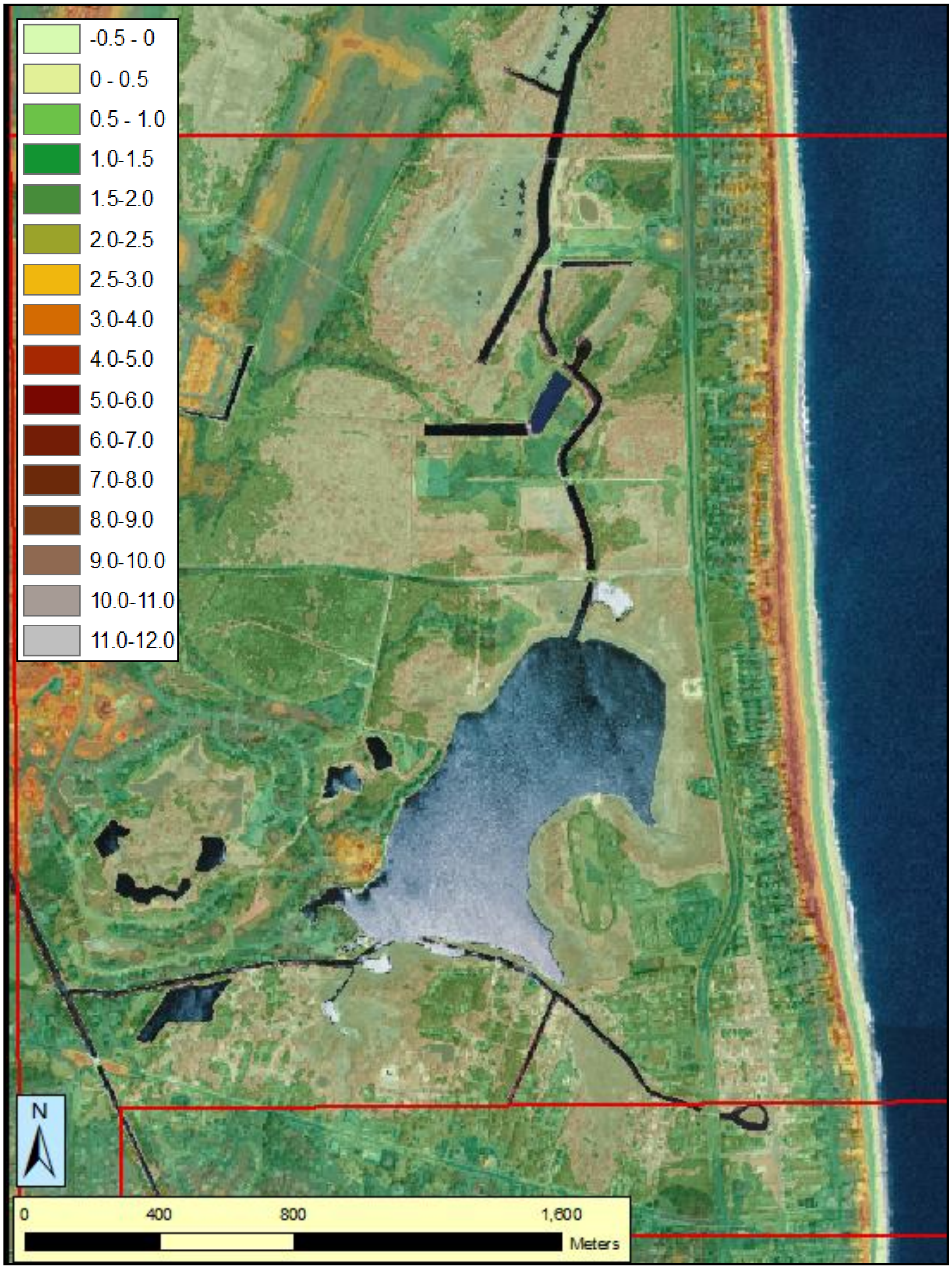

Figure 3.27 Zone 9 LiDAR Elevations. Shows the LiDAR elevation imagery for Zone 9, at Bethany Beach. The scale is shown in meters.

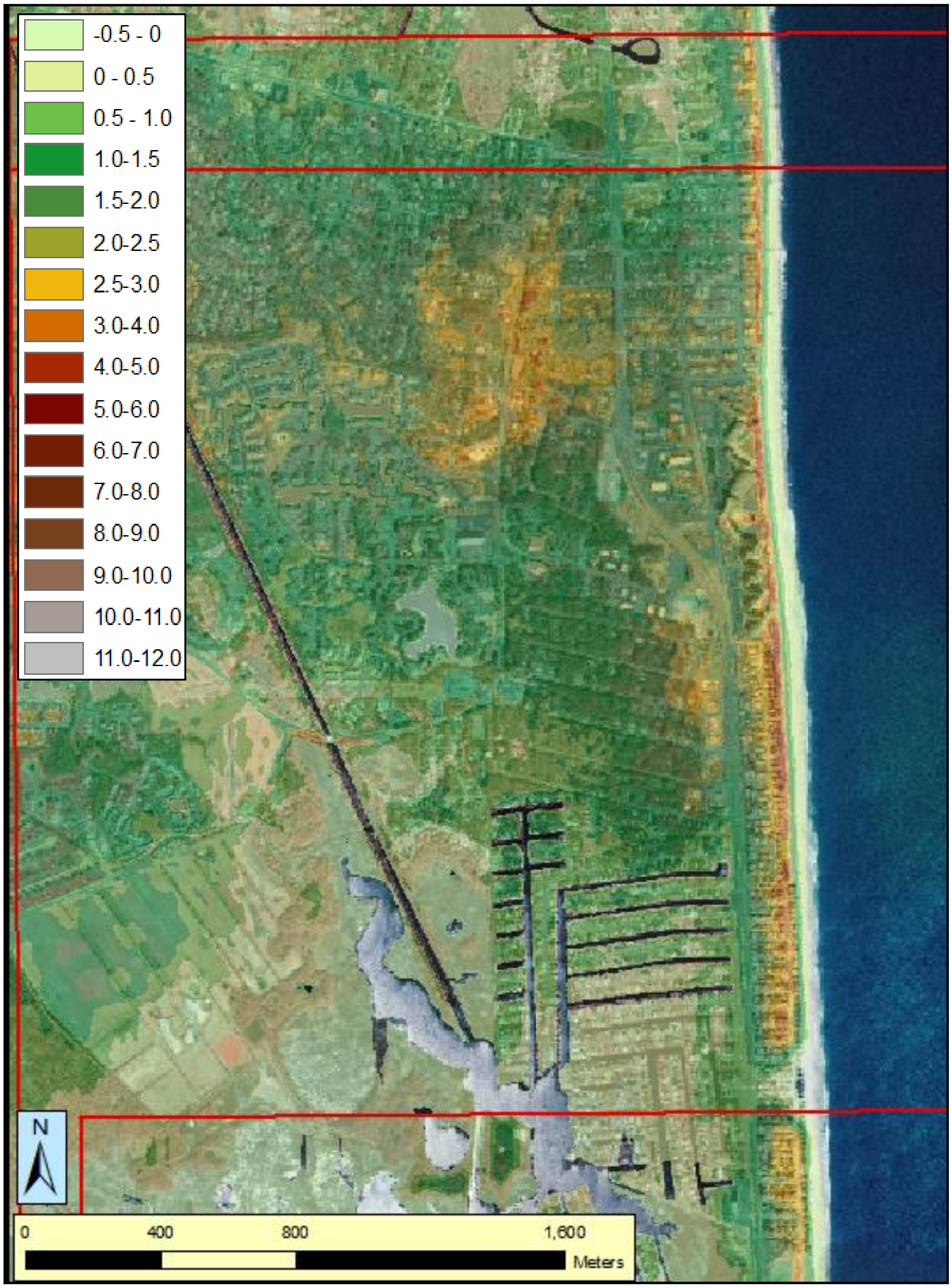

Figure 3.28 Zone 10 LiDAR Elevations. Shows the LiDAR elevation imagery for Zone 10, at South Bethany Beach. The scale is shown in meters.

Figure 3.29 shows the depth of inundation due to a 2.01 m (6.5 ft) storm surge (NAVD88) over the entire coastline within the zones defined in this study. Again, for all LiDAR images, this is not inclusive of the wave heights. If wave heights were included, many of the areas colored in yellow, orange, and some of the red areas would be inundated with water. Figure 3.30 shows the depth of inundation in the Zone 4 region of the coastline, in the Rehoboth Beach area. This is one of the more populated areas along Delaware's coastline, and as the image shows, a great deal of the mainland is safe from inundation, while the majority of the barrier has been completely inundated with water. This parallels what actually happened during the 1962 Northeaster, as the headland and higher elevated areas sustained the least amount of damage due to the storm surge and wave action, sustaining mainly wind and rain damage, while the barriers and other low-lying, tidally influenced inland areas and barriers were inundated with water and sand. Areas of dark red may remain untouched by storm waves; however, other areas, the lighter reds, oranges, and yellows, would be inundated to a greater degree than shown.

If the average wave height of 6-9 m (20-30 ft) was added on top of the surge, inundation could be as much as 11 m (30 ft). Figures 3.31 and 3.32 show Zones 9 and 10, where a great deal of damage occurred due to the 1962 Northeaster. These zones also show, under similar storm conditions, these would be areas of great damage again. The maximum depth of inundation in this image is almost 3 m (10 ft) on the bay shorelines and marshy areas, not including wave height. This is because these areas are below sea level, and therefore accommodate more water from the storm. Wave height included, the area of maximum inundation could reach 12 m (40 ft).

When LiDAR is used to image the buildings and structures that are along the coastline, one can compare and see how many buildings will be affected by the storm, and how deeply they would be inundated. Zone 4 (Figure 3.30) shows very little area that is inundated by water. In fact, the most inundation is back off the beach, in a low-lying area. Here residents would see between 1 and 1.5 m (5 m) of inundation due to storm surge, and another 6-9 m (20-30 ft) on top of that due to waves. The level of inundation rises and the area influenced expands when you move further down the barrier portion of the southern end of Rehoboth Beach.

Zone 9 (Figure 3.31), at Bethany Beach, shows much more area that is inundated by water. Excluding the dunes, and the western portion of this zone, there is no area that is inundated by less than 1 m (3 ft) of water. When wave action and wave height are added, even the dunes succumb to the sea. This is a huge impact on this portion of the coastline, as it is heavily populated with residents and visitors alike. As previously described in Section 3.3 of this study, this area has approximately 1493 buildings and structures established as of 2002. Seven years later, in 2009, it can be assumed that this number has only increased, therefore increasing the number of people potentially affected by such a storm event.

Lastly, Zone 10 (Figure 3.32), at South Bethany Beach was greatly affected during the 1962 Northeaster, and will be again, should another storm of such great magnitude occur in the future. Similar to Zone 9, there is very little area within this zone not under at least 1 m (3 ft) of water. This portion of the shoreline holds 4476 buildings and structures, three times as many as Zone 9.

It is important to note that these assumptions based on the LiDAR images focus on the observed 2.01 (NAVD88) m (6.5 ft) maximum storm surge set by the 1962 Northeaster. It does not take into account the 6-9 m (20-30 ft) wave heights that were observed as well. When you include the maximum wave heights observed, these inundation levels increase by 6-9 m (20-30 ft) as well. It can then be conservatively assumed that under constant wave action of such large waves, the dunes, which according to the LiDAR imagery, are well above the level of the storm surge, would likely not survive the constant battering from waves. As seen in the 1962 Northeaster, the dune systems were destroyed between the second and third day of the storm. When factored in, the waves raise the level of inundation a great deal, as mentioned previously in this section.

If a storm like this were to occur again in the future, the LiDAR and data from the storm show that much of the modern shoreline would be affected and inundated with a great deal of water. In looking at the elevation images of LiDAR data, the average height of the dunes along Delaware's shoreline fall between 6 and 9 m (20-30 ft).

Wind, waves, and storm surge must all be factored into what might happen along the shoreline should a storm occur again of this magnitude. Although buildings and homes are under new, more stringent building codes that will prevent them from falling into the ocean as homes did in 1962, they will still succumb to flooding and overwash.

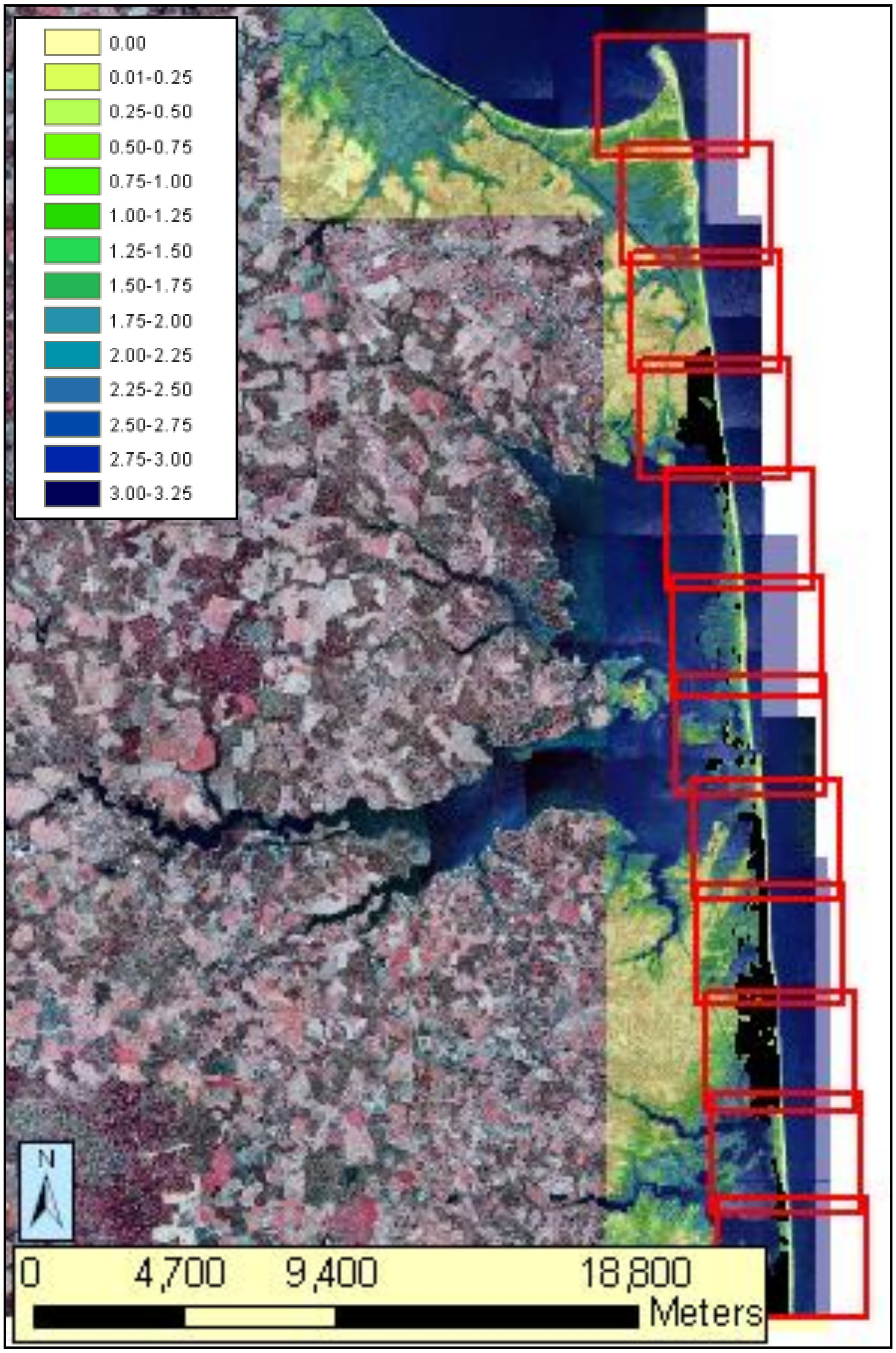

Figure 3.29 LiDAR Inundations along the Coastline. Shows the LiDAR inundation imagery along Delaware's coastline from a 2.01 m storm surge. The scale is shown in meters.

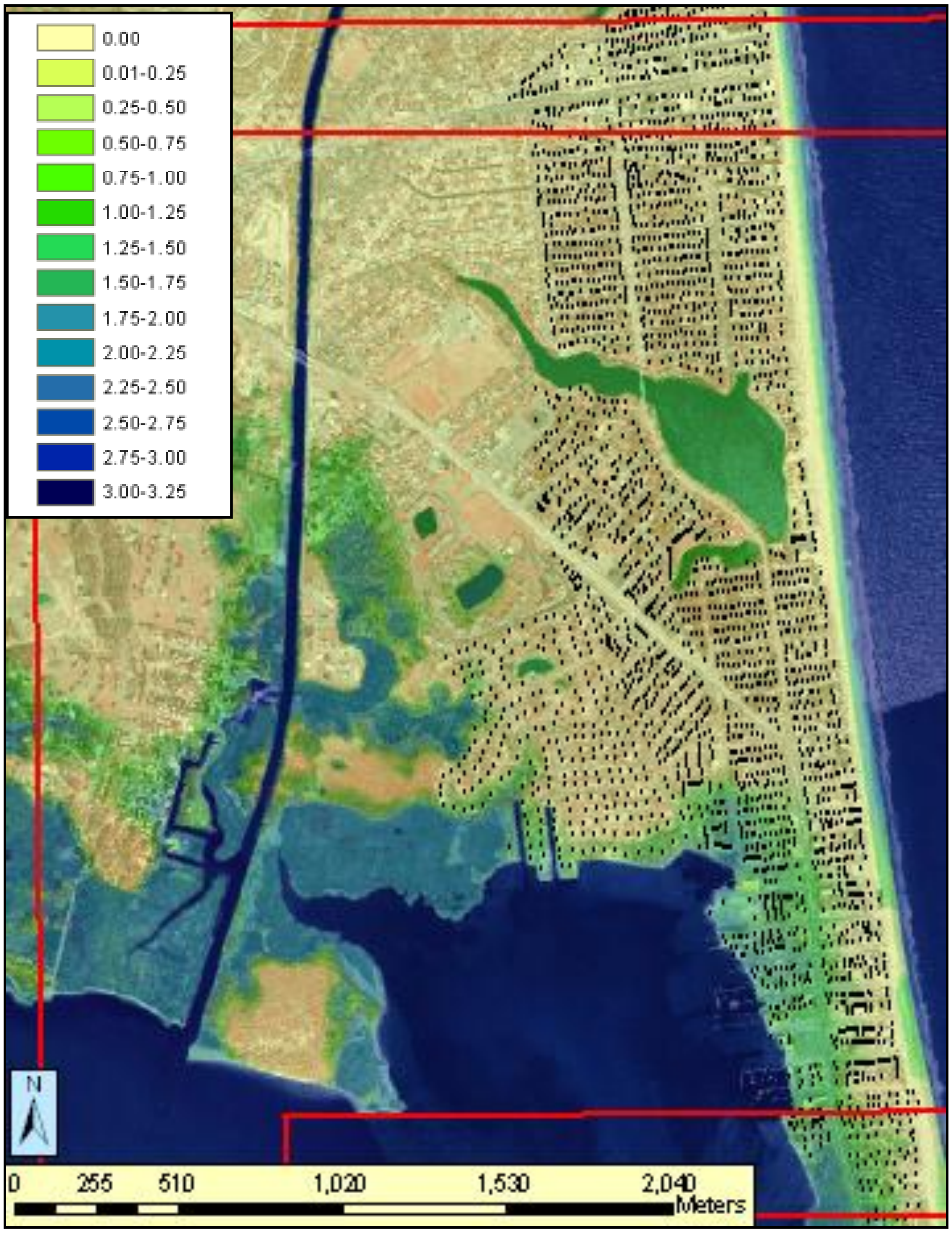

Figure 3.30 Zone 4 LiDAR Inundation Levels. Shows the depth of inundation of the modern shoreline due to a 2.01 m storm surge under conditions similar to those created by the 1962 Northeaster. The black points are the existing buildings and structures. The scale is shown in meters.

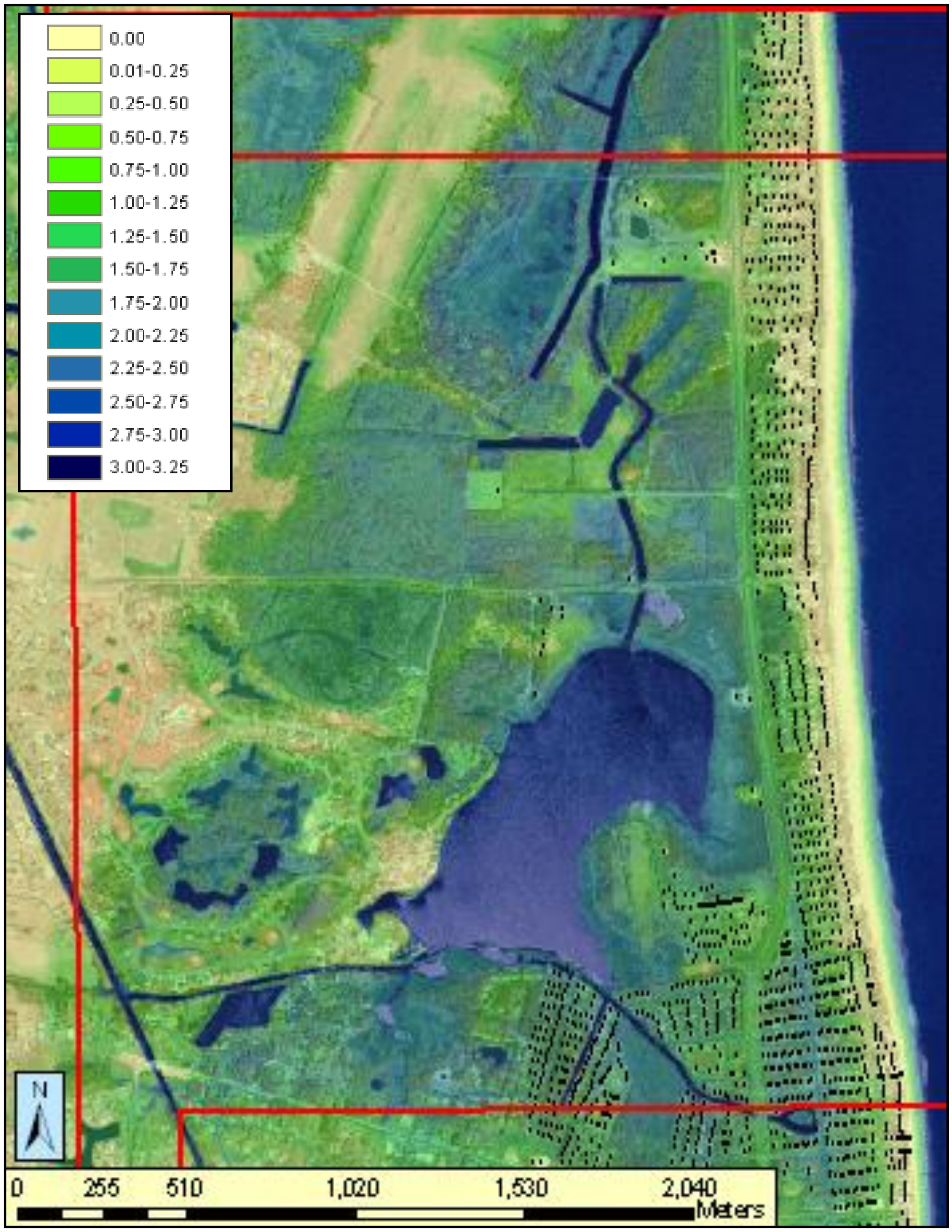

Figure 3.31 **Zone 9 LiDAR Inundation Levels.** Shows the depth of inundation of the modern shoreline due to a 2.01 m storm surge under conditions similar to those created by the 1962 Northeaster. The black points are the existing buildings and structures. The scale is shown in meters.

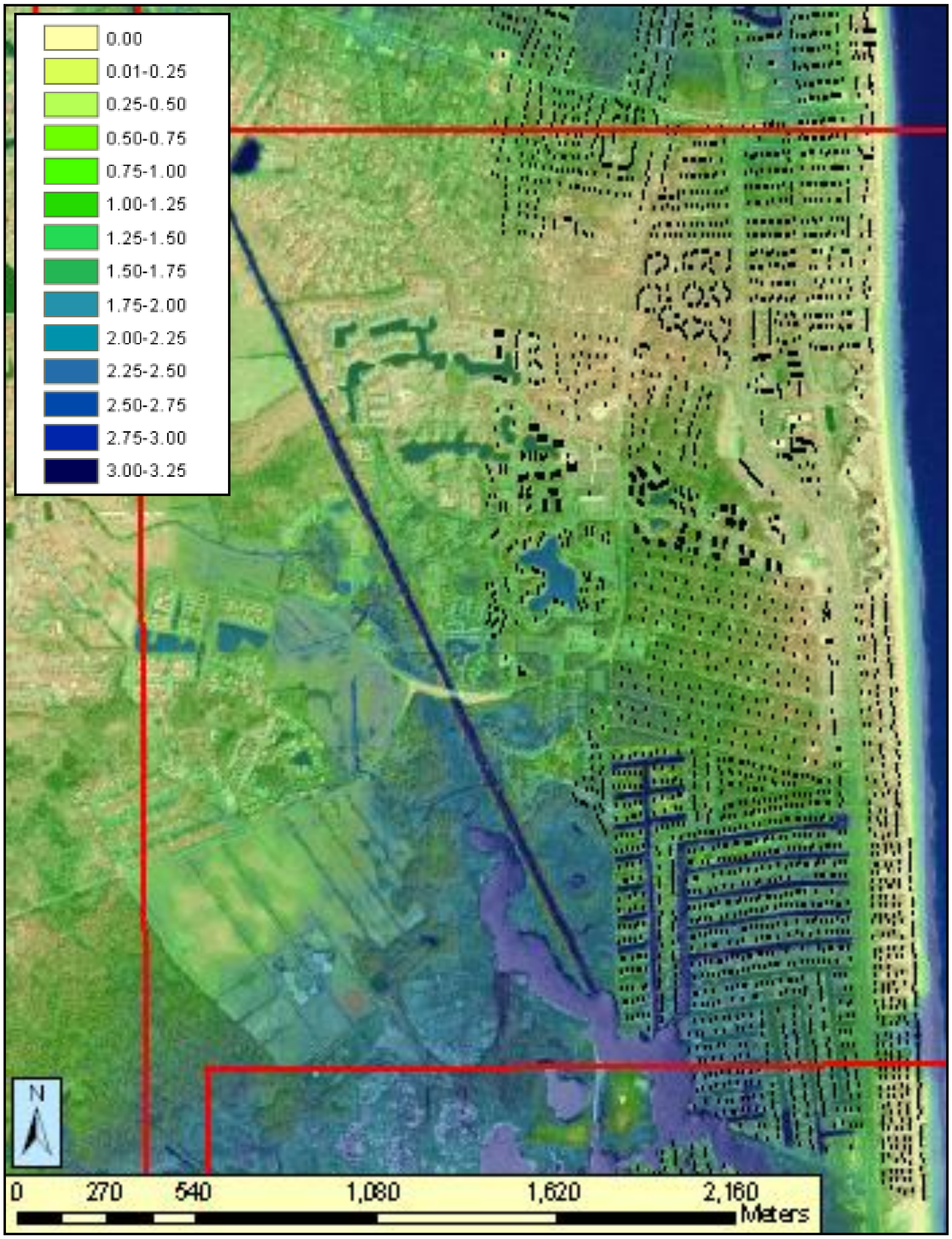

Figure 3.32 **Zone 10 LiDAR Inundation Levels.** Shows the depth of inundation of the modern shoreline due to a 2.01 m storm surge under conditions similar to those created by the 1962 Northeaster. The black points are the existing buildings and structures. The scale is shown in meters.

Chapter 4

CONCLUSIONS

The 1962 Northeaster has maintained its reputation as Delaware's most devastating coastal storm to ever be recorded. In this thesis, the destructive nature of the storm is summarized and aspects of the damage, including shoreline erosion, overwash, and building destruction, were digitally analyzed using a GIS framework. In order to assess the potential effects of another storm of this magnitude on the modern coastline, LiDAR and DEM elevations were used to show areas most at risk to a 2.01 m (6.5 ft) (NAVD88) storm surge, equivalent to that determined for the 1962 storm. As with the 1962 Northeaster, this includes the vast majority of the coastline, as well as tidally influenced inland communities, statewide. When 6-9 m (20-30 ft) wave heights like the ones experienced during the Northeaster are included, inundation is that much deeper and the influenced area expands.

Using an analysis of digitized pre- and post-storm shorelines, the shoreline migrated shoreward in many places over 100 m (328 ft). By 1968, on average across Delaware's coastline, the shoreline recovered seaward most of the way due to renourishment efforts of the USACE; however, following the storm, the barriers appeared to remain somewhat thinner on both sides of the highway. Maximum shoreline migration was observed in the area of approximately 150 m (492 ft) in Zone 6 north of Indian River

Inlet. The double-bar features seen in the 1962 aerial photographs are one of the most striking shoreline features created by the northeaster. These features can be seen all along Delaware's Atlantic coastline, but are most prominent south of Indian River Inlet. The double-bar features, like overwash, are created by the storm and serve to dissipate wave energy before the damaging waves reach the shore (Komar, 1998) . As storm water rises due to storm surge and high waves, portions of the dunes become covered with water and subject to the forces waves exert on the seafloor (Komar, 1998). The sand from the dunes are pulled down the beach-face, flattening out the profile. Some of the sediment is pulled just offshore and deposited as bar features parallel to the coastline. Some of these features can be seen in the southern end of the shoreline as a double-bar feature. Other sediment is deposited behind the beach as overwash (Komar, 1998). Sand that is deposited in offshore bars serves to further protect the beach by dissipating storm waves. In times of low energy, the sediment on these bars returns to the beaches. As pronounced and striking as these features were, however, by 1968 (and probably sooner), these features had disappeared and the 'normal' shoreline re-emerged. There was a difference found in the estimated shoreline erosion rate calculated in this study and that of Honeycutt's study; however the shoreline rate found in this study cannot be used to describe shoreline rates of change due to the lack of data in calculating it. Honeycutt's shoreline erosional rate is not challenged by this study.

Overwash was even more striking than the shoreline changes that occurred due to the 1962 Northeaster. It covered the majority of Rt. 1, all of it in many places, especially south of Indian River Inlet. The total area of overwash along Delaware's shoreline was

8.34 km^2 (3.22 mi^2). The area of greatest lateral displacement of sand was found to be at the southern portion of Zone 6 (also the northern portion of Zone 7, as they overlap), and was as much as 647 m. It was the large amount of displaced sand created by the overwash of the northeaster that the Army Corps used to renourish the beaches following the storm. In fact, all sand that the USACE used to renourish the beaches came from these large overwash fans. The portion of the shore with the greatest volume of sand put back on the beach was from the Coast Guard Station to Indian River Inlet, with almost 222,000 m^3.

Building damage was significant due to the northeaster, especially in areas of extreme overwash. There were four specific areas where the building damage was the greatest, and these coincided with areas of extreme overwash. Some buildings were merely buried, but many others were moved completely from their foundations, or fully demolished. Building density was calculated manually from GIS data for three of the most affected zones along the shoreline (Zones 4, 9, and 10). Between 1960 (pre-storm), and 2002 (close to present) there was an increase in density, and subsequently development of 125%, 278%, and 812%, respectively. These numbers show an increase in development along the coastlines, and therefore an increased necessity for awareness of the effects storms can have on any given shoreline.

Based on the maximum storm surge of 2.01 m (6.5 ft) (as described by Dr. Wendy Carey), if this storm were to occur again, the majority of Delaware's coastal communities would be inundated, with as much as 3 m (10 ft) of water (in low-lying areas and marsh systems). The Rehoboth Beach area seems to be elevated just enough to avoid major inundation. In a storm, however, the water does not just rise and spill over the beach and surrounding area from storm surge, but it is also driven by powerful waves and wind. Therefore, many areas that appear to be safe from inundation would also be flooded because of the churning water and high waves, as well as the destruction of the dune systems protecting the coastal area. Wave heights reached as much as 9 m (30 ft), and added to the storm surge, these levels are more than adequate to overtop the 9 m (30 ft) high dune system. Regardless, based on close observation of the LiDAR data under the 2.01 m (6.5 ft) storm surge level, barrier systems, back-bay and back-barrier systems, and the area of Bethany Beach and Fenwick Island seem to be the most vulnerable to a great deal of inundation and damage due to a similar storm. This is also based on the comparison of the LiDAR images to the aerial photography taken following the 1962 Northeaster, as they parallel one another.

This study shows that shoreline evaluation within the framework of a Geographic Information System can be a very useful aid. The range of analysis that can be done in GIS, particularly in ESRI's ArcMap, are widespread. The shoreline and overwash analysis methods are particularly useful in measuring changes in shorelines because they give a method of accurately, remotely, and quickly making measurements and calculations that would normally take many months and years to take manually. GIS allows one to see a large spatial area all at once, as well as to be able to compare many different types of data all at once. In the case of the overwash caused by the 1962 Northeaster, GIS allowed for the area of overwash to be calculated rather quickly. The fallback, however, with using GIS and aerial photography to measure shoreline changes is that it is only as accurate as the quality and resolution of the aerial photographs being used in the georeferencing process.

Aside from shoreline changes, the GIS interface allows for the comparison of several different years and types of data all at once, one overlaying another. In the analysis of the buildings and structures, GIS allowed for the building layers to be overlain on the aerial photography. This main feature of the GIS software allowed for the easy and direct comparison of the buildings that existed before the storm, and how they fared after the storm. A correlation was able to be made between the extent of overwash and the number of buildings that were destroyed.

Incorporation of LiDAR data into the GIS interface shows the versatility of the GIS software. This software allows for the incorporation of many different types of data that wouldn't otherwise be able to be easily compared without it all being integrated in the same software package. The LiDAR imagery were processed in Fledermaus Software, and then brought into GIS. From here, the LiDAR imagery were able to be superimposed over aerial images for simple and direct comparison. Using software like ESRI's ArcMap for the study of storm events and their effects on coastlines will help to better quantify these impacts and be a tool in emergency response and mitigation.

Coastal communities are booming, and this boom is not likely to die down, as beach homes, retirement, and endless recreational opportunities draw thousands to the shore. With a large interest in the shore, also comes a growing concern in the safety of the people living and visiting there, as well as the properties. Coastal communities are very densely populated, and are only expected to become more dense. Hurricanes and northeasters plague the East Coast of the United States year round. These storms bring a great deal of rain, storm surge, and wind. All of these things cause damage to the beach and to the properties. They are not only a threat to those living directly on the beach, but are also a threat to anyone who lives near any tidally influenced body of water, especially those living in the back-bay area. Therefore, it is crucial to understand how your beach responds to such storm events. It is impossible, in one or even in many studies, to fully analyze the behavior of a complex stretch of shoreline, or a single storm event, and to be able to know how the shoreline will behave during a storm. It is important, however, with the constant increase in development of coastal communities, to attempt to understand how the coastline in which they live will behave during storm events as much as possible. With the aid of smarter technologies being created every day, the daunting task of predicting effects of storms becomes that much faster, easier, and more accurate.

BIBLIOGRAPHY

Blake, E.S., Rappaport, E.N., Jarrell, J.D., & Landsea, C.W. (2005). The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2004 (and other frequently requested hurricane facts). *Technical Memorandum, National Weather Service TPC-4*, National Oceanic and Atmospheric Administration, 51p.

Boak, E.H., & Turner, I.L. (2005). Shoreline definition and detection: A review. *Journal of Coastal Research*, *21*(4), 688-703.

Bosserman, K., & Dolan, R. (1968). The frequency and magnitude of extratropical storms along the Outer Bank of North Carolina. *Technical Report No. 68-4*, Washington D.C, National Park Service, 58p.

Carey, W., & Dalrymple, R. (2003). *Northeasters* (University of Delaware Sea Grant College Program Leaflet). Lewes: University of Delaware.

(CETS) Commission on Engineering and Technical Systems. (1987). *Responding to Changes in Sea Level: Engineering Implications*. Marine Board, National Research Council, Washington D.C: National Academy Press, 148p.

Cooperman, A.I. & Rosendale, H.E. (1962). Great Atlantic Coastal Storm, 1962. *U.S. Weather Bureau Publication Climatological Data,* 337-344.

Davis, R.A., and Fitzgerald, D.M. (2004). *Beaches and Coasts.* United Kingdom: Blackwell Publishing, 405p.

Davis, R.E., & Dolan, R. (1992). All Hallows Eve Storm. *Journal of Coastal Research*, *8*(4): 978-983.

(DEMA) Delaware Emergency Management Agency. (2007). Delaware Emergency Management Agency home page. Retrieved January 10, 2008, from http://dema.delaware.gov/services/disaster_prep.shtml.

(DGS) Delaware Geological Survey. (2002). Metadata for the 2002 aerial photographs. Retrieved October 15, 2007, from http://maps.rdms.udel.edu/metadataexplorer/explorer.jsf.

Dolan, R., & Davis, R.E. (1992). An intensity scale for Atlantic Coast northeast storms. *Journal of Coastal Research*, *8*(4): 840-853.

Dolan, R., Lins, R., & Hayden, B. (1988). Mid-Atlantic coastal storms. *Journal of Coastal Research*, *4*(3): 417-433.

Donnelly, C., Kraus, N., & Larson, M. (2001). Sedimentary evidence of intense hurricane strikes from New Jersey. *Geology*, *29*(7): 615-618.

Gill, S. (2003). National tidal datum epoch (1983-2001) update. Retrieved July 10, 2009 from http://neap.pactide.noaa.gov/hq/datum_update.shtml.

Halsey, S.D. (1986). Proposed classification scale for major northeast storms: East Coast USA, based on extent of damage. *Geological Society of America, Abstracts with Programs (Northeast Section)*, 18, 21.

Hapke, C.J., Reid, D., Richmond, B.M., Ruggiero, P., & List, J. (2006). National assessment of shoreline change: Part 3: historical shoreline changes and associated coastal land loss along sandy shorelines of the California coast. *U.S. Geological Survey Open File Report 2006-1219*, 79.

Hoeke, R.K., Zarillo, G.A., & Snyder, M. (2001). A GIS based tool for extracting shoreline positions from aerial imagery (BEACHTOOLS). *Coastal Engineering Technical Note IV*. Washington, DC: U.S. Army Corps of Engineers.

Honeycutt, M.G. (2003). Spatial variability in shoreline change along the Atlantic Coast of Delaware: influence of the geologic framework. *Doctoral Dissertation, University of Delaware,* 2003, 167p.

Komar, P.D. (1998). *Beach Processes and Sedimentation, Second Edition*. Upper Saddle River: Prentice Hall, Inc.

Kraft, J.C., Chrzastowski, M.J., Belknap, D.F., Toscano, M.A., & Fletcher, C.H. Jr. (1987). The transgressive barrier-lagoon coast of Delaware: morphostratigraphy, sedimentary sequences and responses to relative rise in sea level. *The Society of Economic Paleontologists and Mineralogists, 41*: 129-143.

Lesser, C.R. 2007. Open Marsh Water Management: A Source Reduction Technique for Mosquito Control. *Delaware Mosquito Control Section*. Retrieved January 17, 2009, from http://www.fw.delaware.gov/SiteCollectionDocuments /FW%20Gallery/ Research/OMWM%20Article%2011.05.07.pdf.

(NOAA) National Oceanographic and Atmospheric Administration. (1998). State of the Coasts Report. Retrieved August 1, 2007, from http://oceanservice.noaa.gov/websites/retiredsites/sotc_pdf/PAR.PDF.

(NOAA) National Oceanographic and Atmospheric Administration. (2009). Tides and Currents: Center for Operational Oceanographic Products and Services. Retrieved September 25, 2009, from http://tidesandcurrents.noaa.gov/index.shtml.

Oates, M. (Director). (2007). The ’62 Storm: Delaware’s shared response. *Documentary produced by 302 Stories*. Noted interviewees: Dr. Wendy Carey, Professor, University of Delaware; Tony Pratt, Shoreline & Waterway Management Administrator, Delaware Department of Natural Resources and Environmental Control; and Dr. Louis Uccelini, Director of Meteorology for the National Centers for Environmental Prediction, National Oceanographic and Atmospheric Administration. *In text citation gives the director followed by the interviewee, then the year*.

Overton, M.F., Greenier, R.R., Judge, E.K., & Fisher, J.S. (1999). Identification and analysis of coastal erosion hazard areas: Dare and Brunswick Counties, North Carolina. *Journal of Coastal Research*, Special Issue No. 28: 69-84.

Podufaly, E.T. (1962). Operation Five-High. *Shore Beach,* 30(2): 9-18.

Pries, A.J., Miller, D.L., & Branch, L.C. (2008). Identification of structural and spatial features that influence storm-related dune erosion along a barrier-island ecosystem in the Gulf of Mexico. *Journal of Coastal Research* 4(3): 168-175.

Ramsey, K.W., Leathers, D.J., Wells, D.V., and Talley, J.H. (1998). Summary report: the coastal storms of January 27-29 and February 4-6, 1998, Delaware and Maryland. *Open Report No. 40*. Newark: Delaware Geological Survey, 47p.

Sallenger, A.H. (2000). Storm impact scale for barrier islands. *Journal of Coastal Research*, *16*(3): 890-895.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., & Miller, T.L. (2005). Digital Shoreline Analysis System (DSAS) Version 3.0: An Arc GIS Extension for Calculating Shoreline Change. *Open-File Report 2008-1278*, U.S. Geological Survey.

(USACE) United States Army Corps of Engineers. (1963). Report on operation five-high: March 1962 Storm. *Disaster Recovery Operations under Public Law 875, 81 Congress*.

Zhang, K., Douglas, B., & Leatherman, S. (2002). Do storms cause long-term beach erosion along the U.S. East Barrier coast? *The Journal of Geology*, *110*: 493-502.

APPENDIX A

This appendix contains all digitized shorelines, separated by Zones. The Zone map is also included for reference. Shorelines are superimposed upon the 1962 aerial photographs, and was done so that the damage caused by the storm can be seen and compared to the pre- and post-storm shorelines. Each shoreline is represented by a different color, which is included in the figures. Methods for georeferencing the aerial photographs and digitizing the shorelines are outlined in detail in Chapter 2 of this document. Some of the shoreline segments are discussed in further detail in Chapter 3 of this document.

Table AA.1 Shoreline Measurement Data. This table shows the shoreline measurement data for the coast of DE beginning at Cape Henlopen. This figure is zoomed in on Indian River Inlet for clarity. Lines were set every 500 m along the coastline. Segment data is also given in this table.

Distance from Starting Point (Cape Henlopen)	Segment Length	Segment Start (Easting)	Segment Start (Northing)	Segment End (Easting)	Segment End (Northing)	Segment Centroid (Easting)	Segment Centroid (Northing)
0	255	228173	88881	228416	88959	228294	88920
500	223	228332	88440	228554	88458	228443	88449
1,000	300	228429	87933	228729	87942	228579	87937
1,500	273	228504	87449	228777	87446	228640	87448
2,000	312	228875	86924	228563	86909	228719	86916
2,500	318	228706	86440	229023	86452	228864	86446
3,000	253	229201	85915	228949	85903	229075	85909
3,500	282	228999	85398	229281	85401	229140	85400
4,000	309	228985	84896	229293	84902	229139	84899
4,500	377	229385	84407	229008	84413	229197	84410
5,000	226	229065	83902	229290	83908	229177	83905
5,500	384	229454	83424	229071	83401	229262	83412
6,000	264	229391	82911	229127	82911	229259	82911
6,500	389	229127	82421	229516	82418	229321	82420
7,000	297	229177	81937	229474	81940	229326	81939
7,500	243	229264	81447	229507	81447	229385	81447
8,000	302	229272	80937	229572	80976	229422	80956
8,500	345	229314	80441	229658	80456	229486	80449
9,000	297	229454	79952	229750	79952	229602	79952
9,500	191	229584	79441	229774	79456	229679	79448
10,000	229	229626	78960	229854	78966	229740	78963
10,500	253	229652	78453	229905	78470	229779	78461
11,000	288	229667	77948	229955	77963	229811	77955
11,500	353	229688	77440	230041	77440	229865	77440
12,000	223	229884	76918	230106	76927	229995	76922
12,500	291	229991	76425	230282	76443	230136	76434
13,000	237	230104	75927	230341	75927	230222	75927
13,500	335	230065	75381	230400	75386	230233	75384
14,000	297	230190	74894	230486	74897	230338	74895
14,500	306	230264	74380	230570	74398	230417	74389
15,000	407	230225	73905	230632	73899	230429	73902
15,500	413	230252	73377	230665	73383	230458	73380
16,000	304	230697	72893	230394	72869	230546	72881
16,500	294	230727	72371	230433	72371	230580	72371
17,000	353	230400	71884	230754	71878	230577	71881
17,500	258	230472	71400	230730	71400	230601	71400
18,000	270	230742	70881	230472	70881	230607	70881
18,500	270	230733	70338	230463	70341	230598	70339
19,000	229	230552	69806	230780	69806	230666	69806
19,500	519	230893	69239	230374	69245	230633	69242
20,000	359	230869	68684	230510	68675	230690	68680
20,500	362	230923	68150	230561	68150	230742	68150

Distance from Starting Point (Cape Henlopen)	Segment Length	Segment Start (Easting)	Segment Start (Northing)	Segment End (Easting)	Segment End (Northing)	Segment Centroid (Easting)	Segment Centroid (Northing)
21,000	202	230828	67654	231030	67666	230929	67660
21,500	300	231214	67144	230914	67156	231064	67150
22,000	303	231243	66624	230941	66630	231092	66627
22,500	433	231365	66126	230932	66126	231148	66126
23,000	386	231368	65595	230982	65595	231175	65595
23,500	258	231353	65045	231095	65045	231224	65045
24,000	235	231380	64565	231145	64556	231263	64560
24,500	267	231445	64018	231178	64024	231312	64021
25,000	247	231484	63511	231237	63502	231361	63506
25,500	273	231478	62971	231205	62968	231341	62969
26,000	356	231510	62442	231154	62454	231332	62448
26,500	252	231469	61929	231217	61929	231343	61929
27,000	235	231225	61433	231460	61439	231343	61436
27,500	249	231540	60932	231291	60932	231415	60932
28,000	261	231680	60460	231418	60451	231549	60455
28,500	262	231469	59943	231730	59967	231599	59955
29,000	329	231784	59439	231454	59439	231619	59439
29,500	249	231709	58949	231460	58955	231585	58952
30,000	264	231831	58459	231567	58459	231699	58459
30,500	235	231810	57928	231576	57922	231693	57925
31,000	172	231831	57438	231659	57438	231745	57438
31,500	243	231884	56936	231641	56939	231763	56938
32,000	276	231899	56426	231623	56426	231761	56426
32,500	303	231965	55909	231662	55903	231813	55906
33,000	354	232030	55381	231677	55399	231853	55390
33,500	294	232027	54882	231733	54882	231880	54882
34,000	246	232054	54363	231807	54363	231930	54363
34,500	237	232057	53849	231819	53852	231938	53851
35,000	312	232110	53327	231798	53324	231954	53326
35,500	312	232149	52820	231837	52820	231993	52820
36,000	332	232202	52285	231870	52282	232036	52284
36,500	300	232202	51766	231902	51772	232052	51769
37,000	264	232208	51264	231944	51267	232076	51266
37,500	321	232238	50736	231917	50739	232077	50737
38,000	255	232169	50219	231914	50219	232042	50219

Table AA.1 Shoreline Measurement Data. Continued…

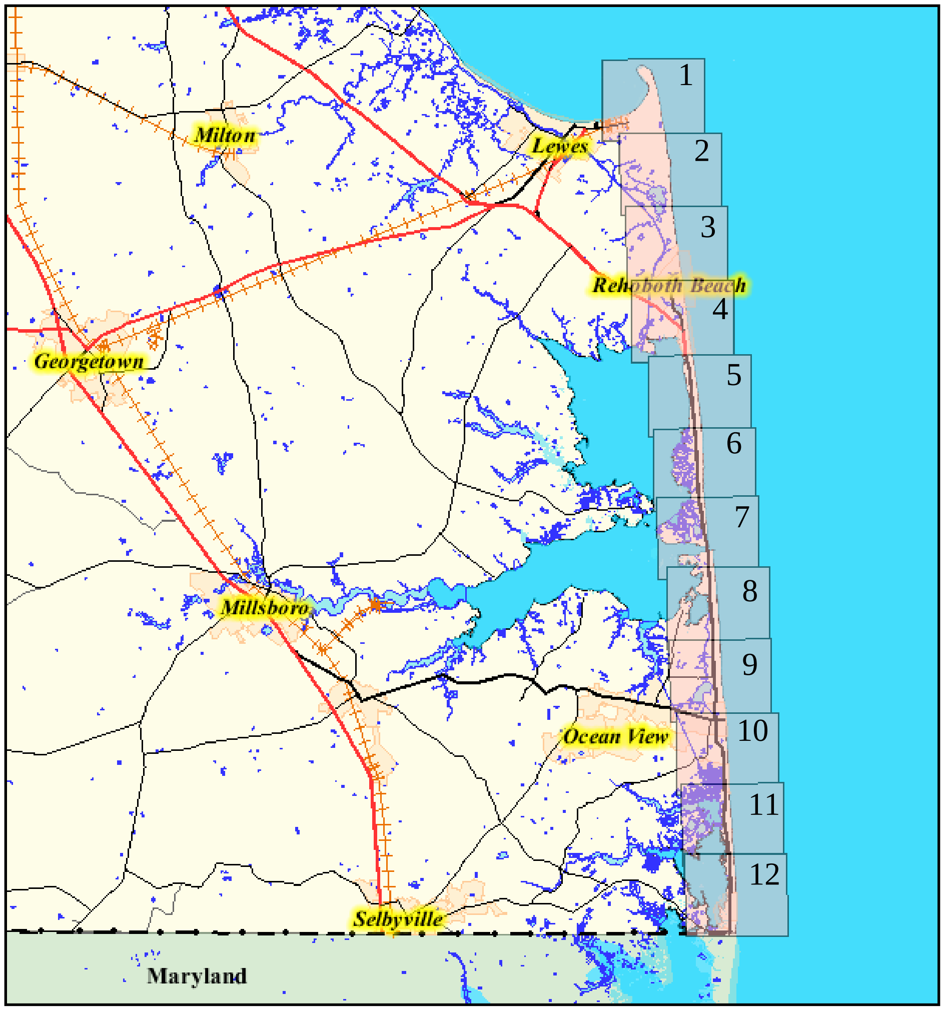

Figure AA.1 Zones of the Study Area. The study area divided into 12 zones so that changes in shoreline, overwash, and building destruction can be seen and compared.

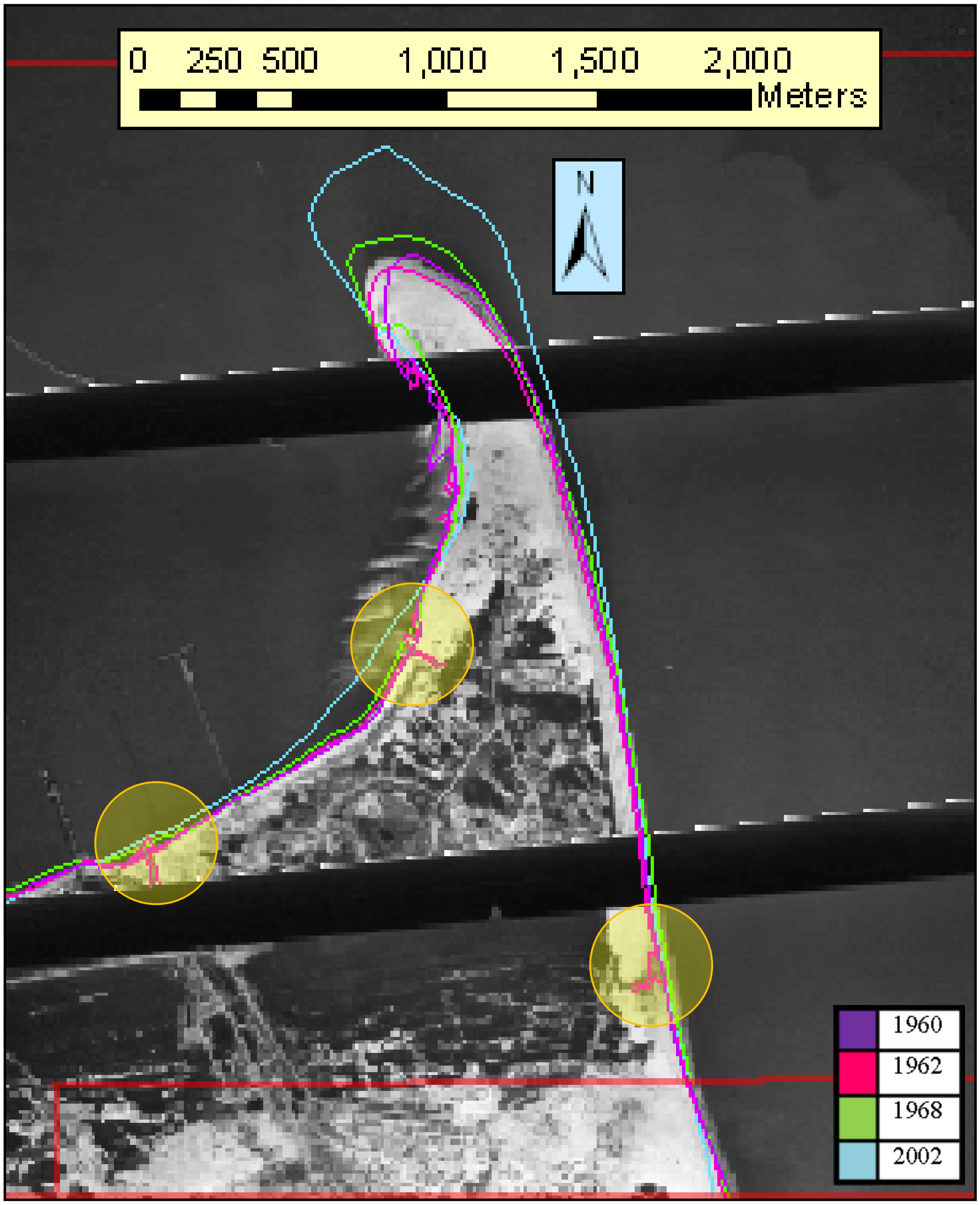

Figure AA.2 Shorelines, Zone 1. Shows the shorelines of Zone 1. As shown by this image, Cape Henlopen has migrated further into the Delaware Bay since 1960. There are few areas here, where the 1962 northeaster has had a significant impact on the shoreline. These areas are highlighted.

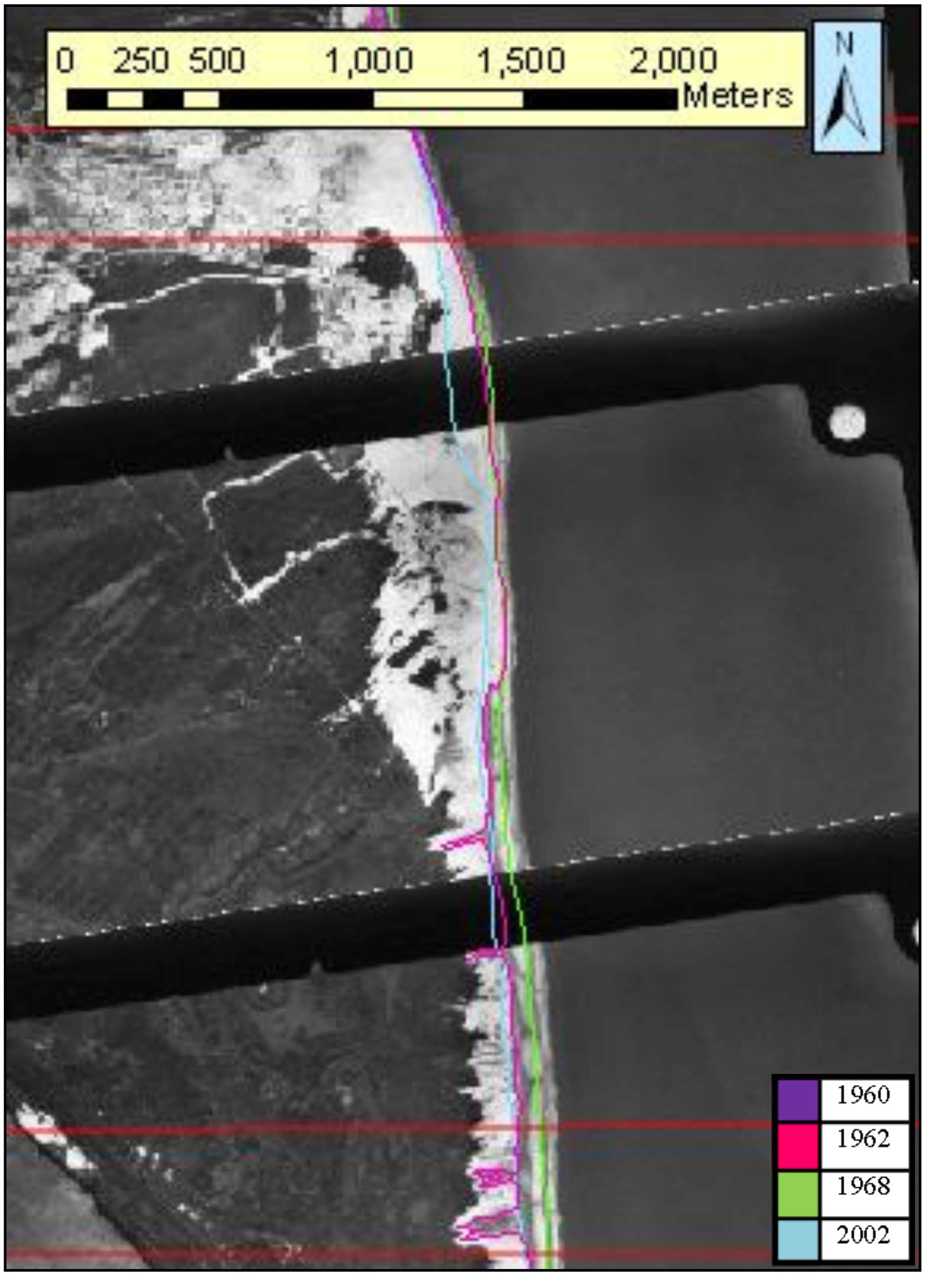

Figure AA.3 Shorelines, Zone 2. Shows the shorelines of Zone 2. As shown by this image, the area at the bottom shows inundation of the shoreline and a potential area of breakthrough. Clearly water reached these areas, and even 7 days after the storm, water was influencing this area.

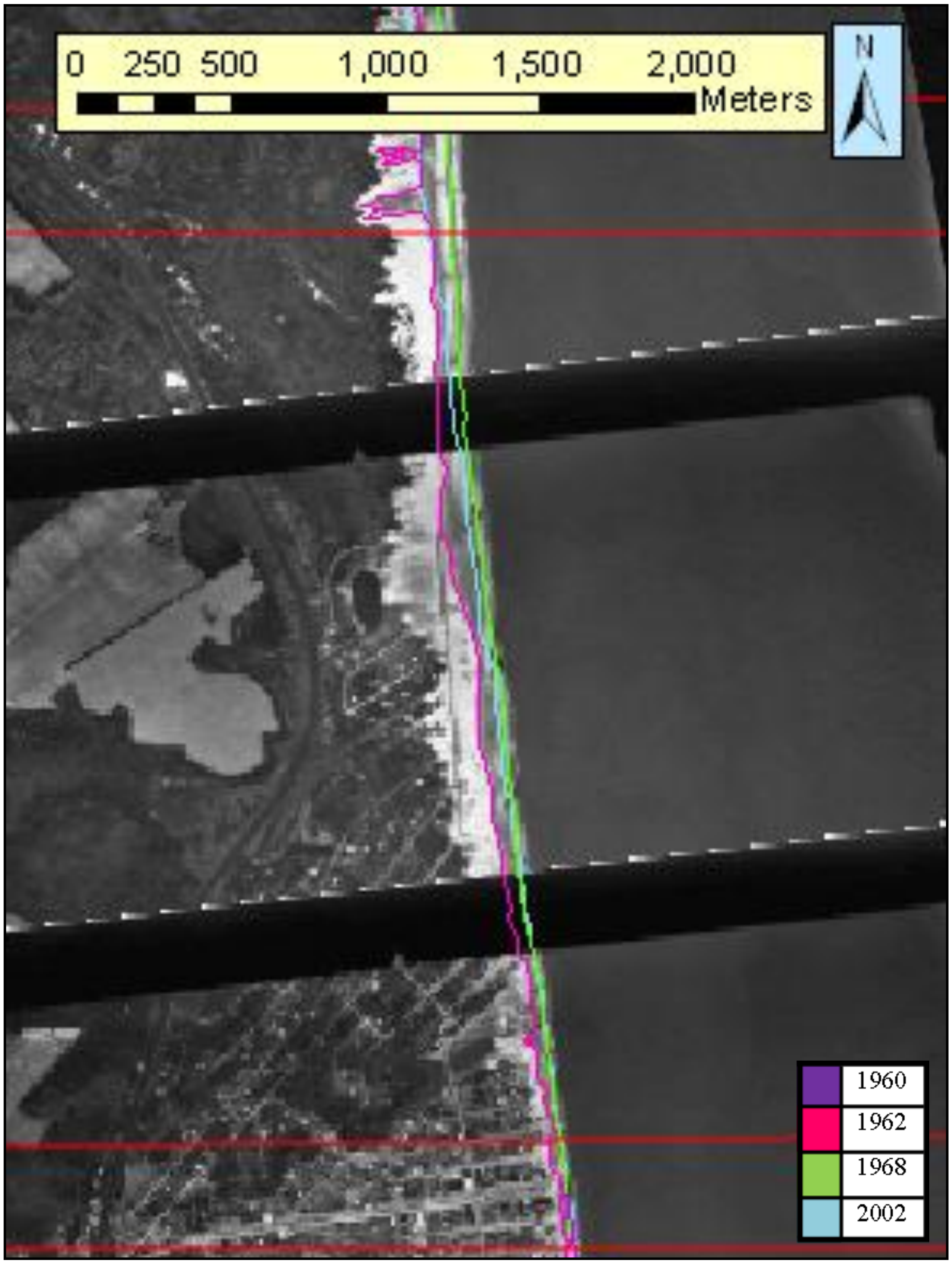

Figure AA.4 Shorelines, Zone 3. Shows the shorelines of Zone 3. As shown by this image, the area at the top shows the same area discussed in the previous figure.

Figure AA.5 Shorelines, Zone 4. Shows the shorelines of Zone 4. As shown by this image, there are no significant anomalies in the 1962 shoreline, although as seen here, the shoreline is still significantly more eroded than the other shorelines. The shoreline rebounded almost completely by 1968.

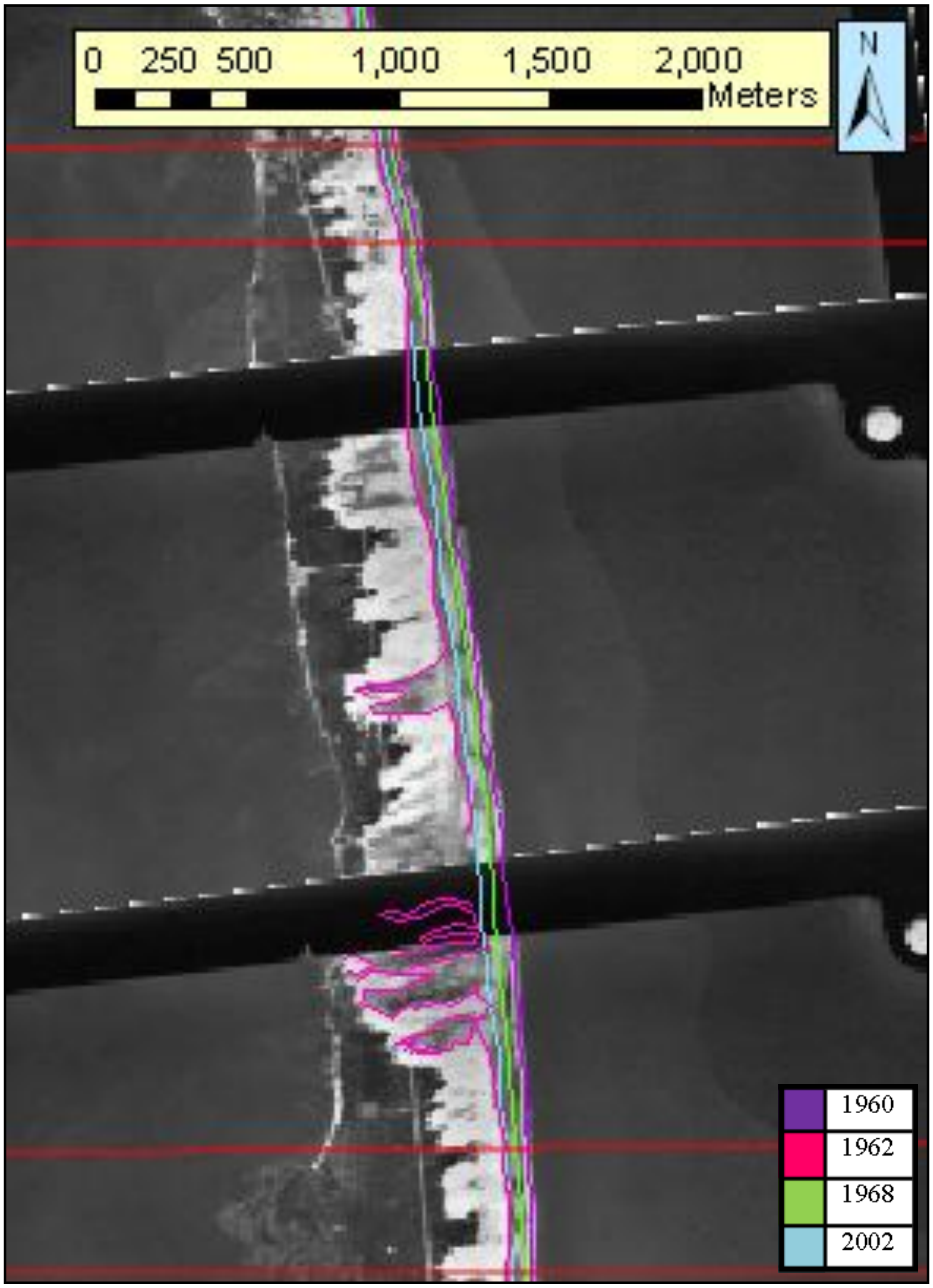

Figure AA.6 Shorelines, Zone 5. Shows shorelines of Zone 5. As shown by this image, there are areas of significant inlet fingering due to the breaching of water through the barrier. This area is the area of most significant breaching on this shoreline, based on available aerial photography.

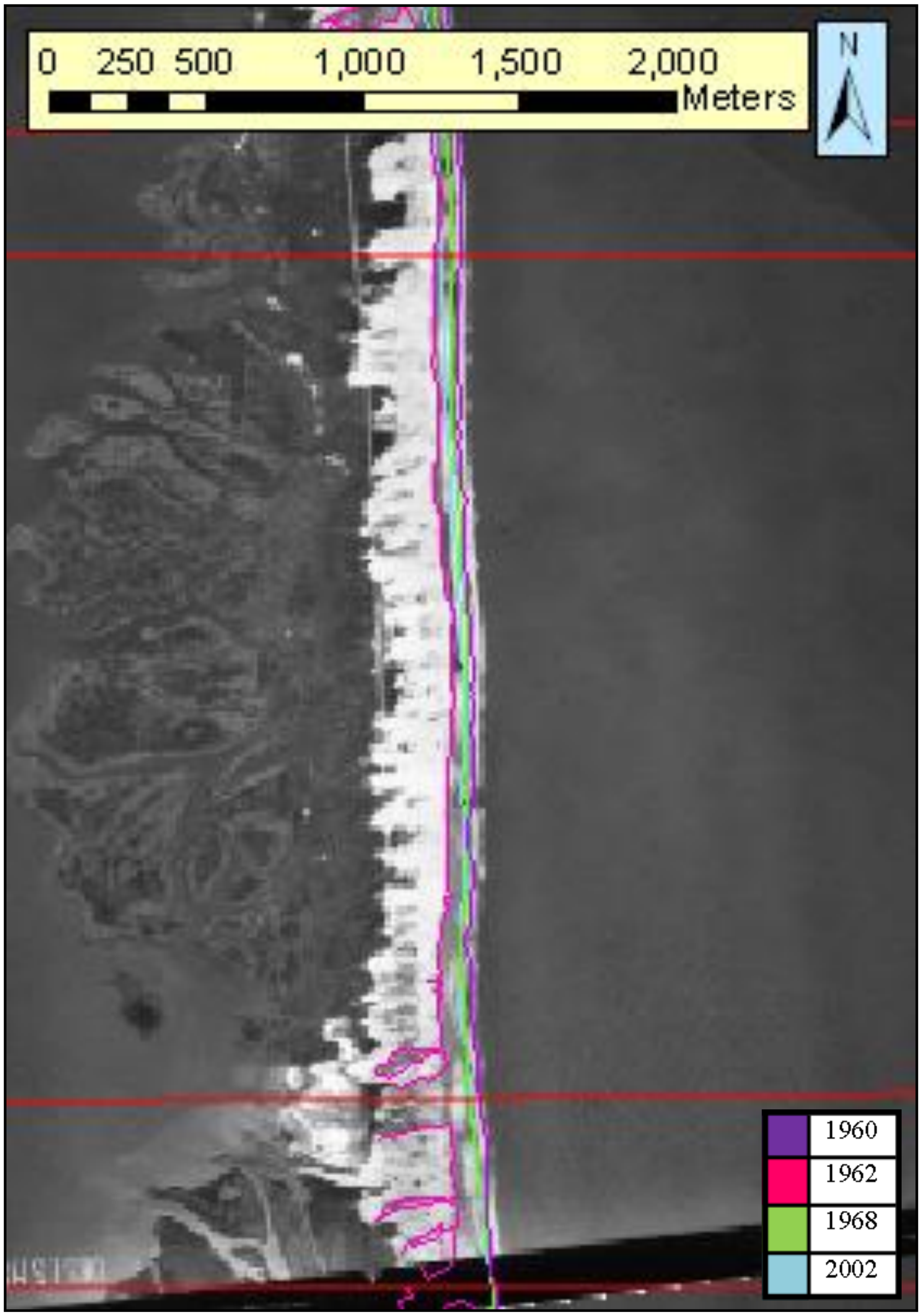

Figure AA.7 Shorelines, Zone 6. Shows the shorelines of Zone 6. As shown by this image, there are areas of significant inlet fingering due to the breaching of water through the barrier. It is also an area of significant breaching on this shoreline, based on available aerial photography.

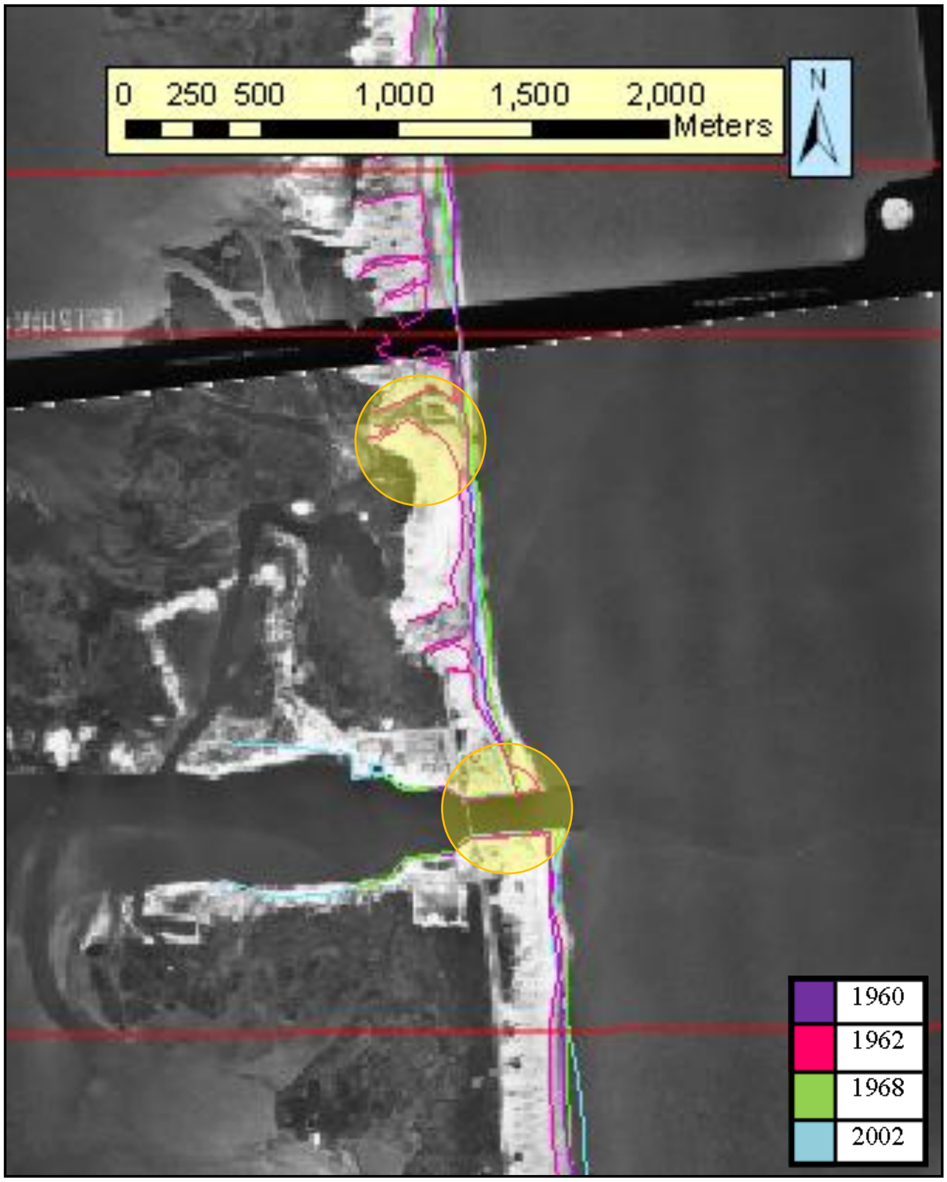

Figure AA.8 Shorelines, Zone 7. Shows the shorelines of Zone 7. As shown by this image, there are areas of significant inlet fingering due to the breaching of water through the barrier. In the uppermost highlighted area, the water from the ocean breached through to the tidal channel. The second area highlighted shows the deposition of sediment on the northern side of the jetty, while to the southern side, there is a great deal of erosion.

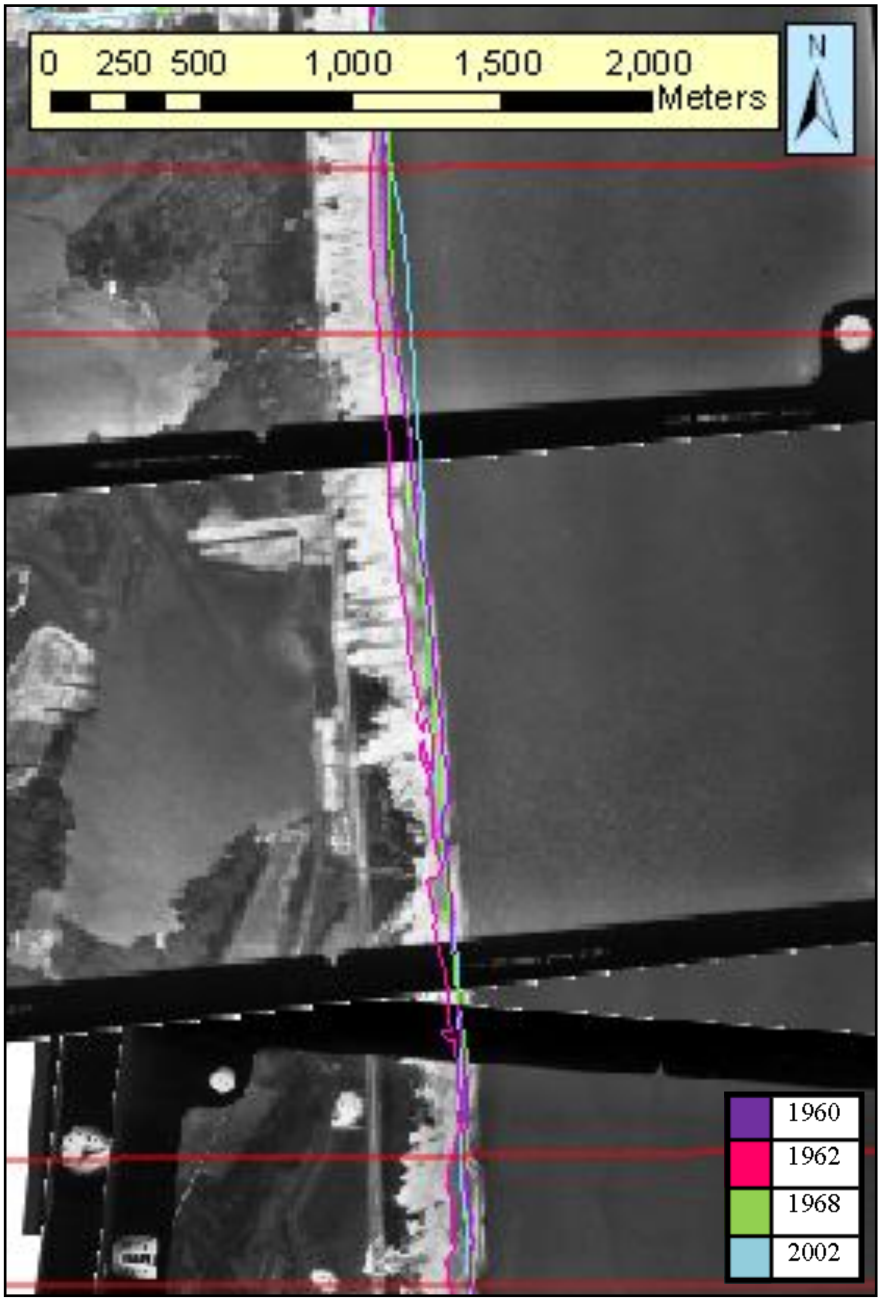

Figure AA.9 Shorelines, Zone 8. Shows the shorelines of Zone 8. As shown by this image, there is no specific area of significant breaching, however, the shoreline is significantly eroded.

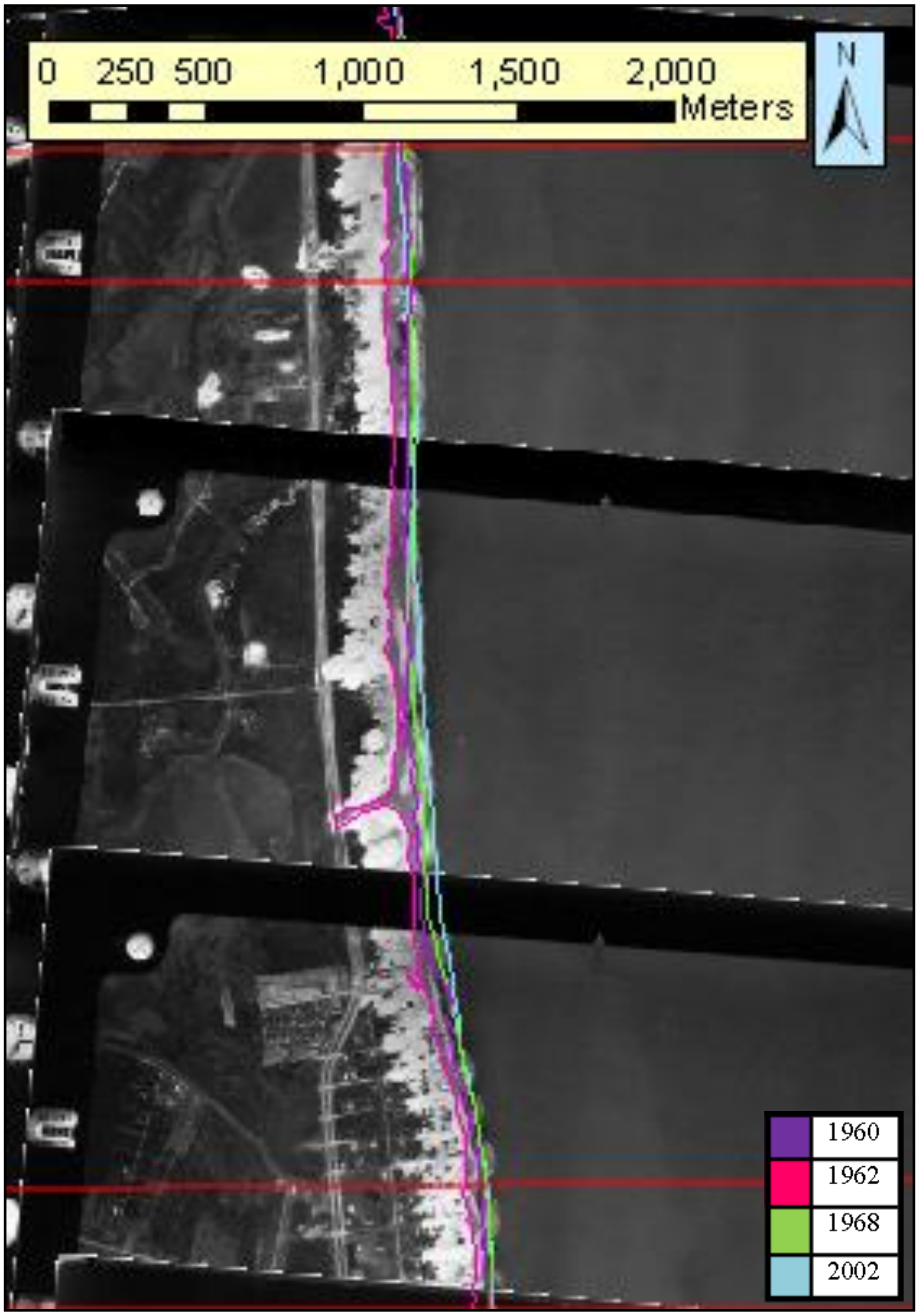

Figure AA.10 Shorelines, Zone 9. Shows the shorelines of Zone 9. As shown by this image, there is an area, mid-photo of significant breaching, with a great deal of erosion throughout the rest of this portion of the shoreline.

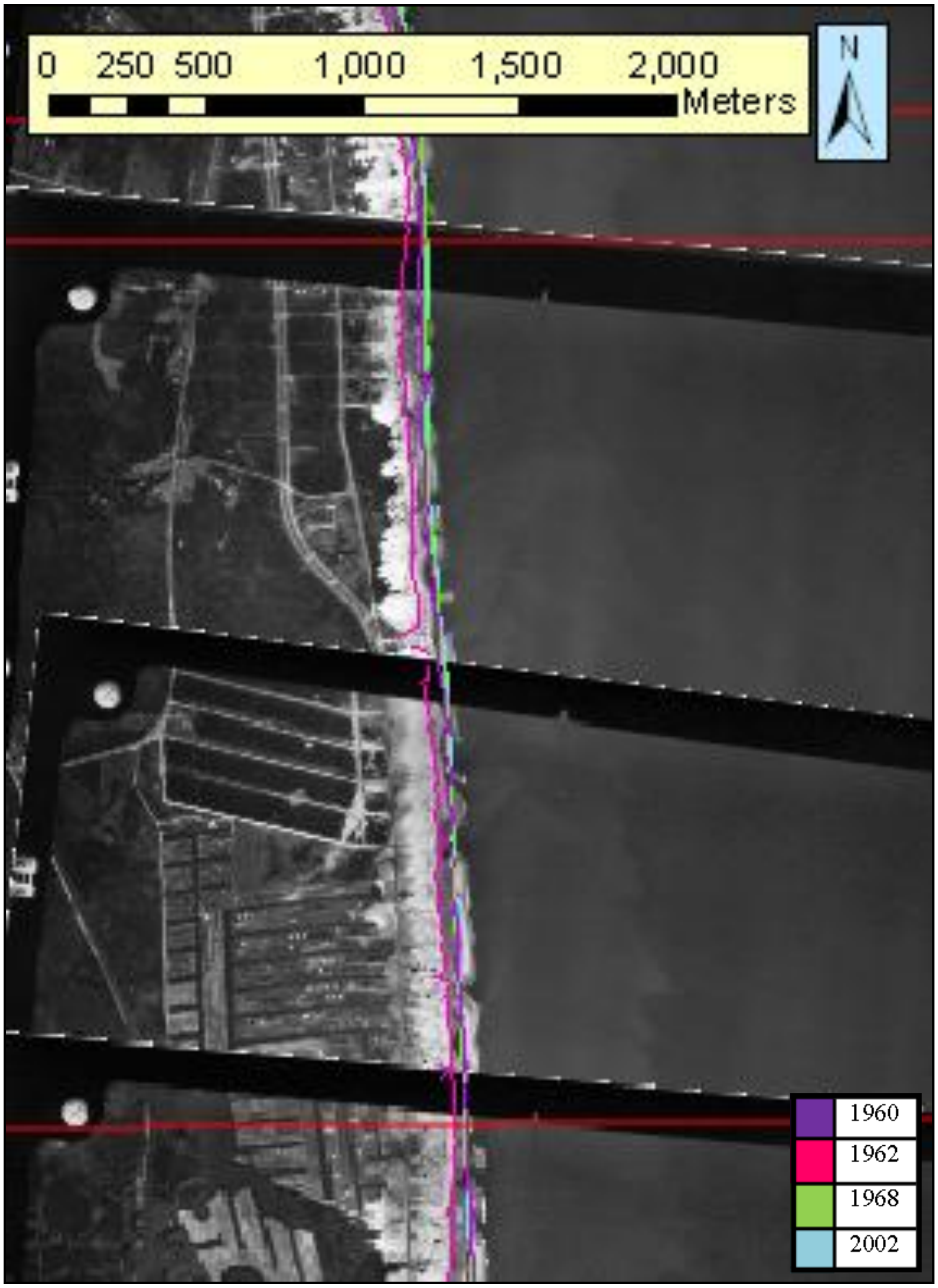

Figure AA.11 Shorelines, Zone 10. Shows the shorelines of Zone 10. Again, there is significant loss of shoreline as shown by this image.

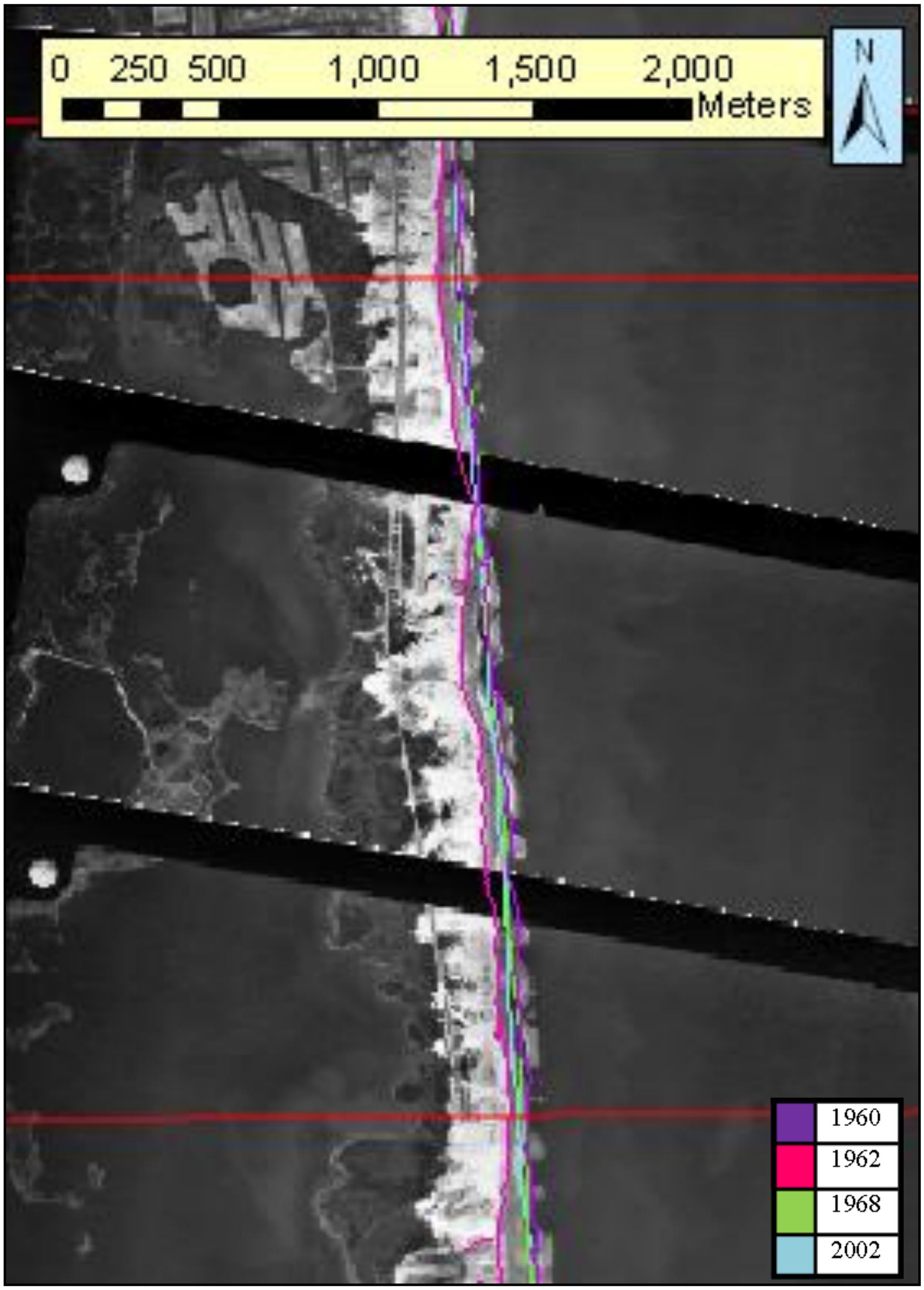

Figure AA.12 Shorelines, Zone 11. Shows the shorelines of Zone 11. As with the other images south of Indian River Inlet, there is significant loss of shoreline as shown by this image.

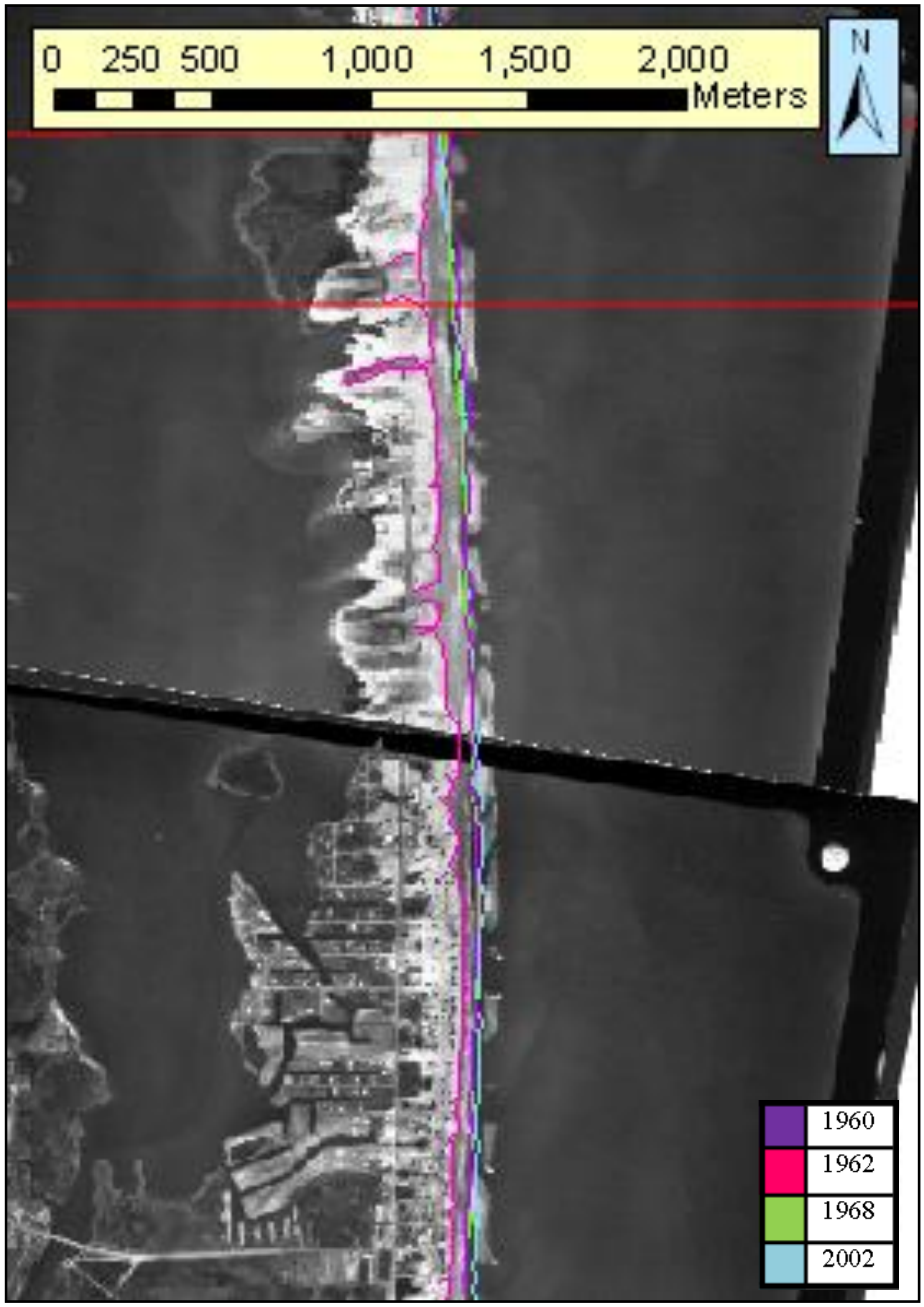

Figure AA.13 Shorelines, Zone 12. Shows the shorelines of Zone 12. As with the other images south of Indian River Inlet, there is significant loss of shoreline as shown by this image. There are also two major breaches at the top of this image, where the ocean meets the bay.

APPENDIX B

This appendix is comprised of digitized overwash fans. The **green** overwash line represents the 1960 overwash fan. Please note that in all places of development, these fans had buildings built directly on top of them. They are remnant of past storms, and also likely areas where sand was placed purposefully for developmental use. The 1960 shoreline was not all that different from the 2002 shoreline. The **yellow** overwash line represents the overwash due to the 1962 Northeaster. Note that there are areas of significant overwash, and buildings would have been covered almost completely. The overwash lines have been superimposed over the 2002 aerial photographs to show the modern shoreline under an overwash fan caused by a storm of the magnitude of the 1962 Northeaster. For a map of where each zone lies in the study area, please see Appendix A, Figure AA.1, page 116. All 2002 aerial photographs were from the DataMIL website, and methods in digitizing the overwash are outlined in detail in Chapter 2 of this document. Some of the overwash shoreline segments are discussed further in Chapter 3 of this document.

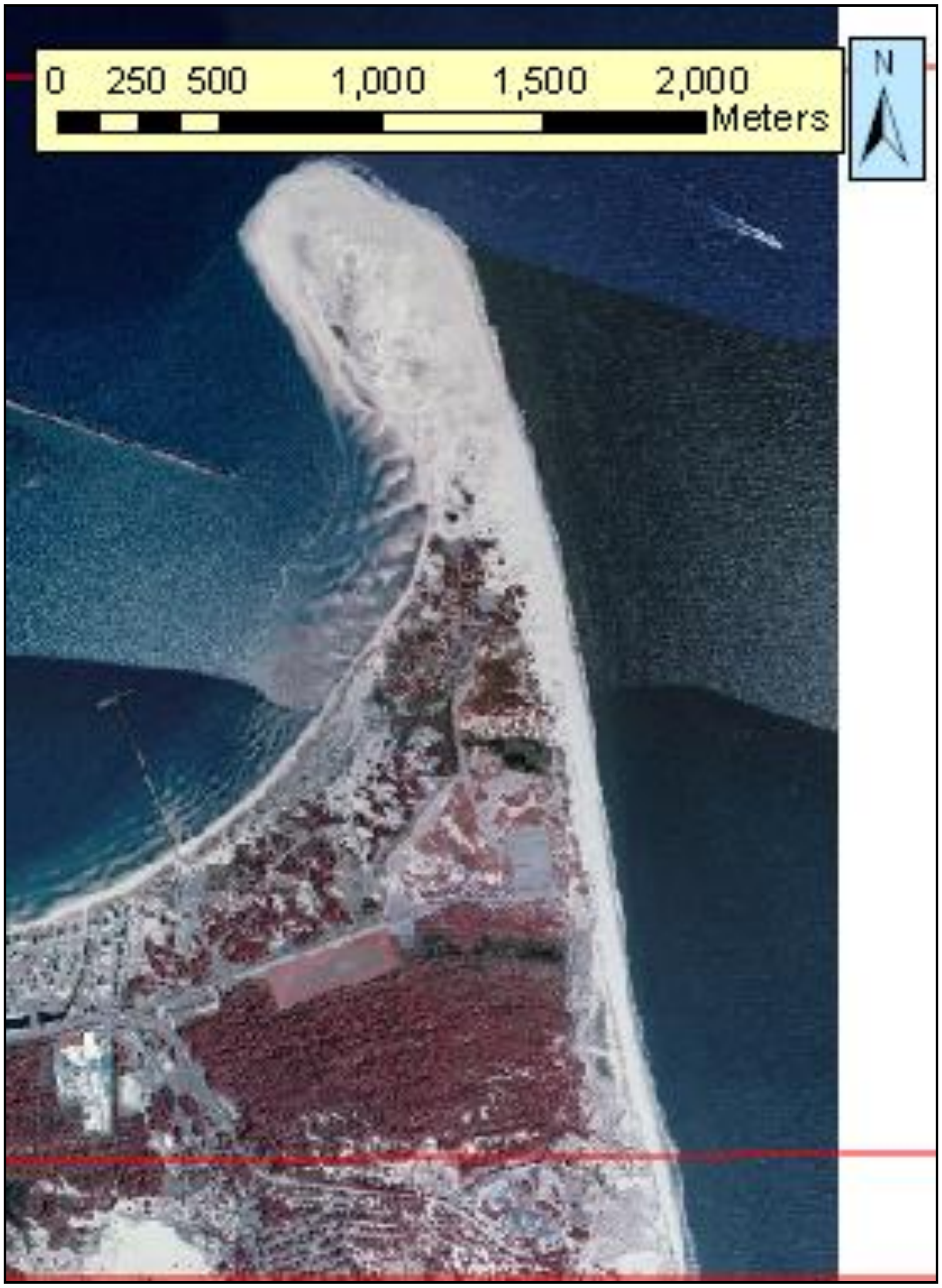

Figure AB.1 **Overwash, Zone 1.** Shows the Overwash of Zone 1. The overwash is not digitized here, because this area is constantly sandy, and it is difficult to determine where the overwash fans are, if there are any. It doesn't appear that there really are any areas of overwash here.

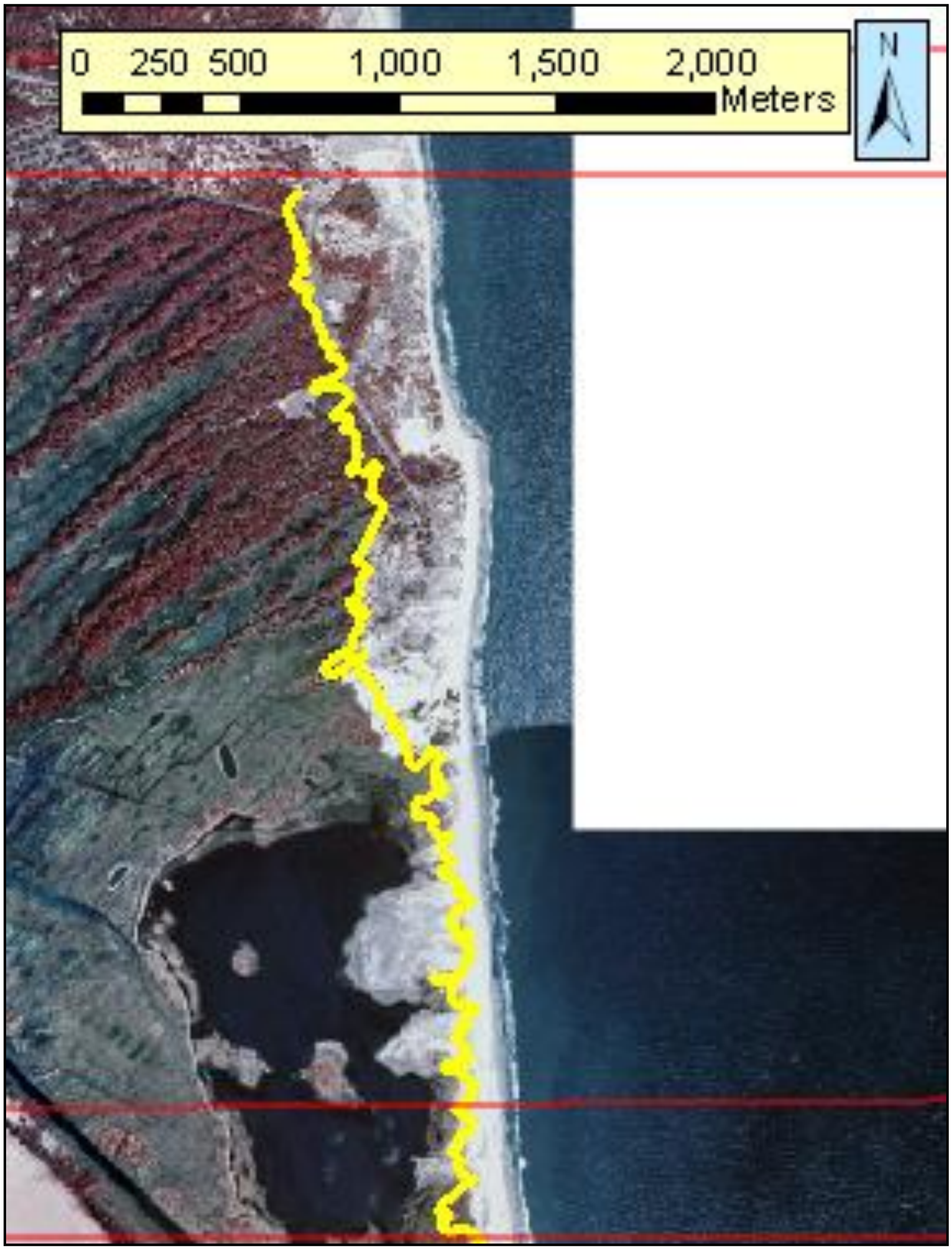

Figure AB.2 **Overwash, Zone 2.** Shows the Overwash of Zone 2. There was overwash due to the 1962 northeaster here, but no real defined overwash for that of 1960.

Figure AB.3 **Overwash, Zone 3.** Shows the Overwash of Zone 3. Overwash for 1960 begins at the very bottom of this image. As this image shows, the 1962 overwash covered a significant part of this shoreline.

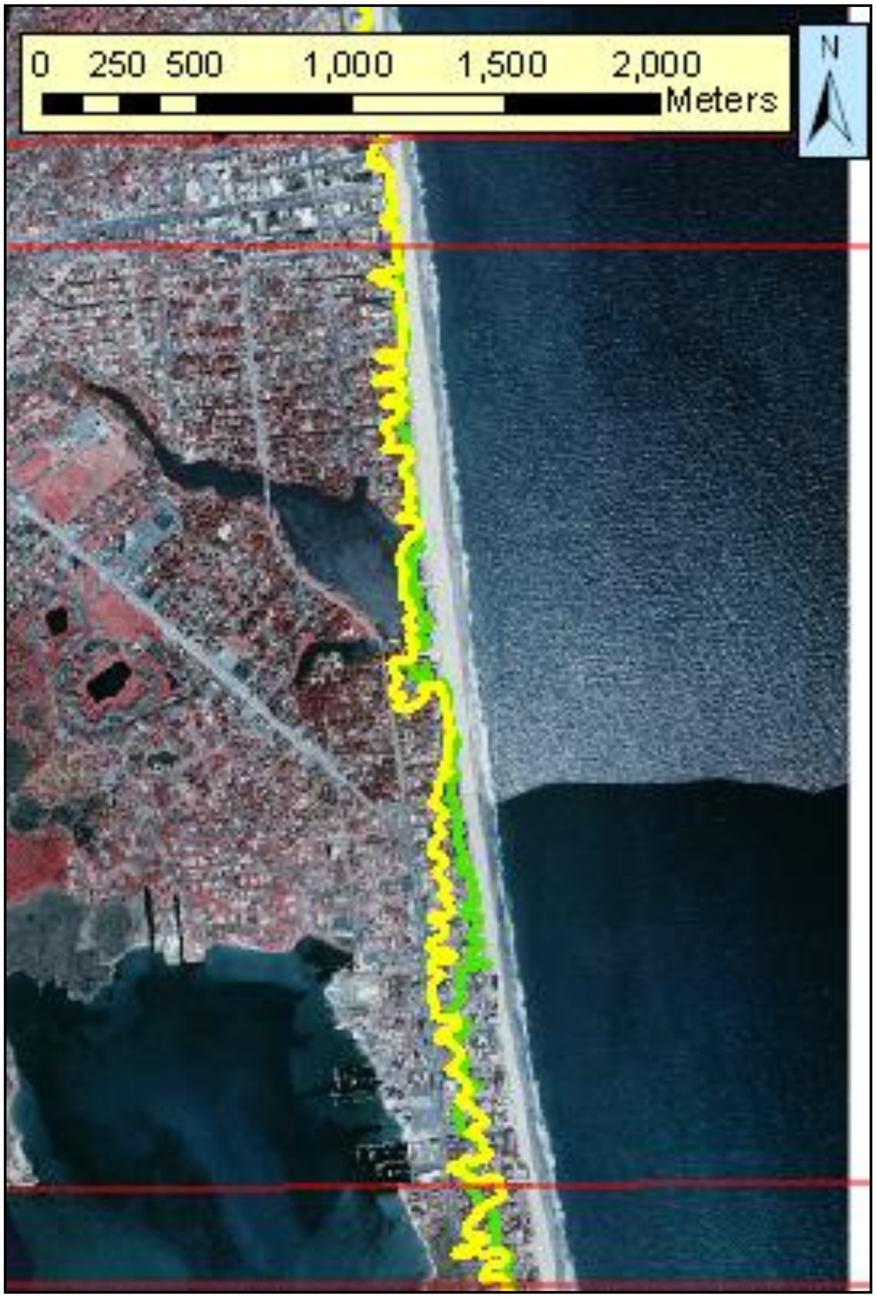

Figure AB.4 **Overwash, Zone 4.** Shows the Overwash of Zone 4. Overwash here with 1960 and 1962 matches up fairly well, however, note that the 1960 overwash was not fresh – it was a previous storm, and buildings were on top of it, while the 1962 overwash was covering homes.

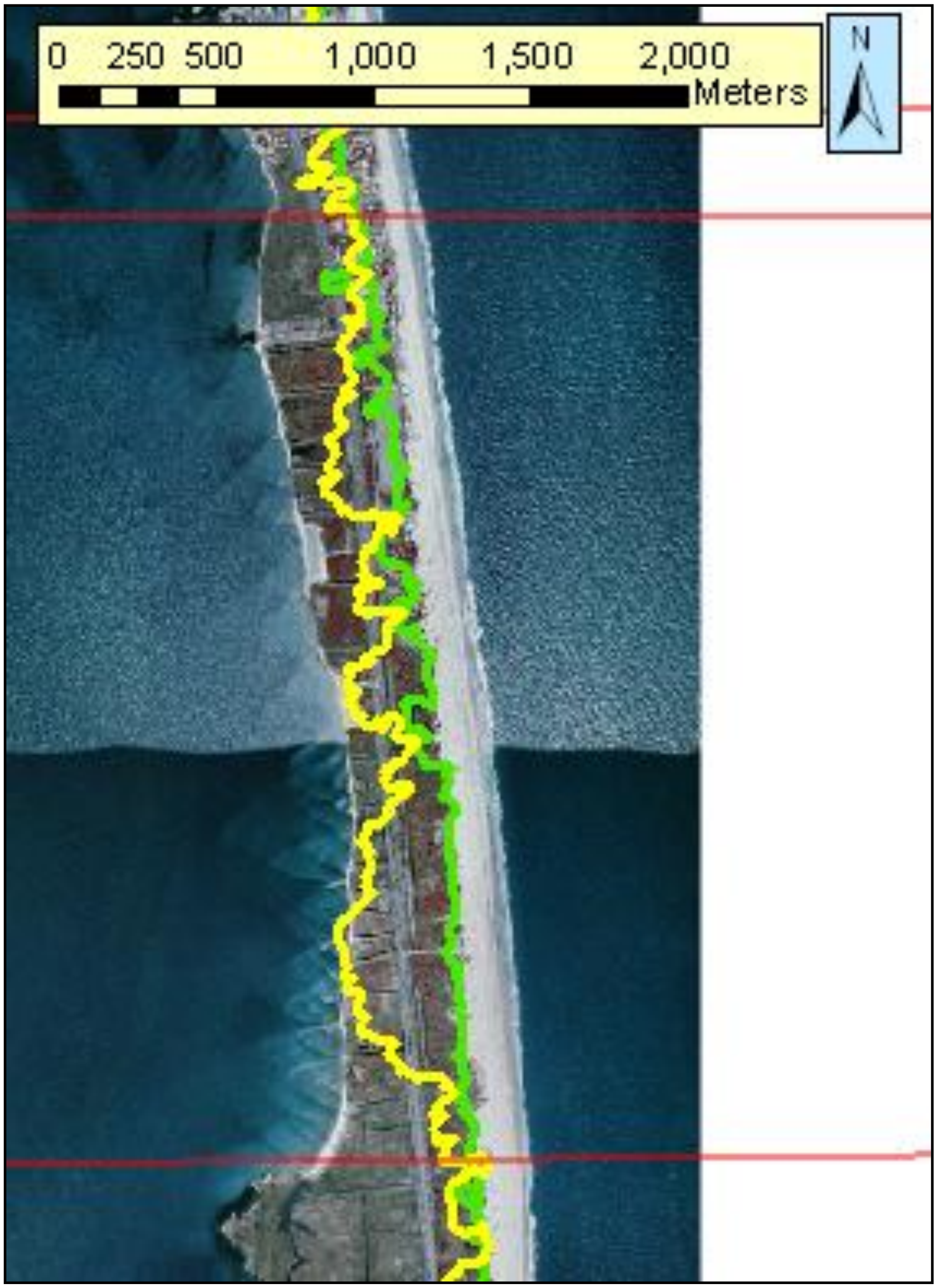

Figure AB.5 **Overwash, Zone 5.** Shows the Overwash of Zone 5. This image shows significant overwash due to the northeaster. It washes completely over the barrier.

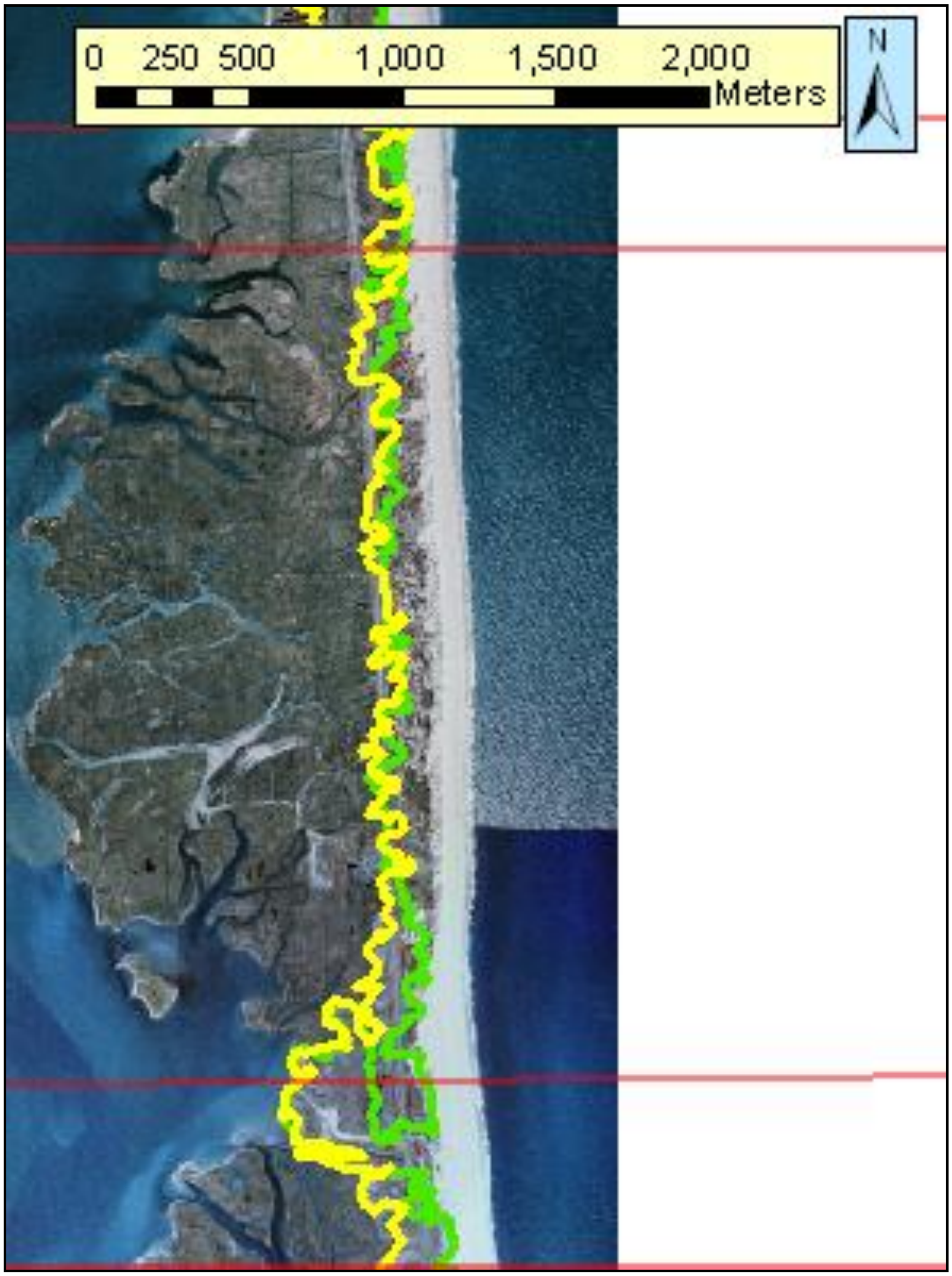

Figure AB.6 **Overwash, Zone 6.** Shows the Overwash of Zone 6. This image shows overwash due to the storm over most of the barrier, with significant overwash toward the bottom of the image. The overwash in most of these photographs completely covers Rt.1.

Figure AB.7 **Overwash, Zone 7.** Shows the Overwash of Zone 7 Again, overwash here breaches the barrier and meets the back-barrier mash.

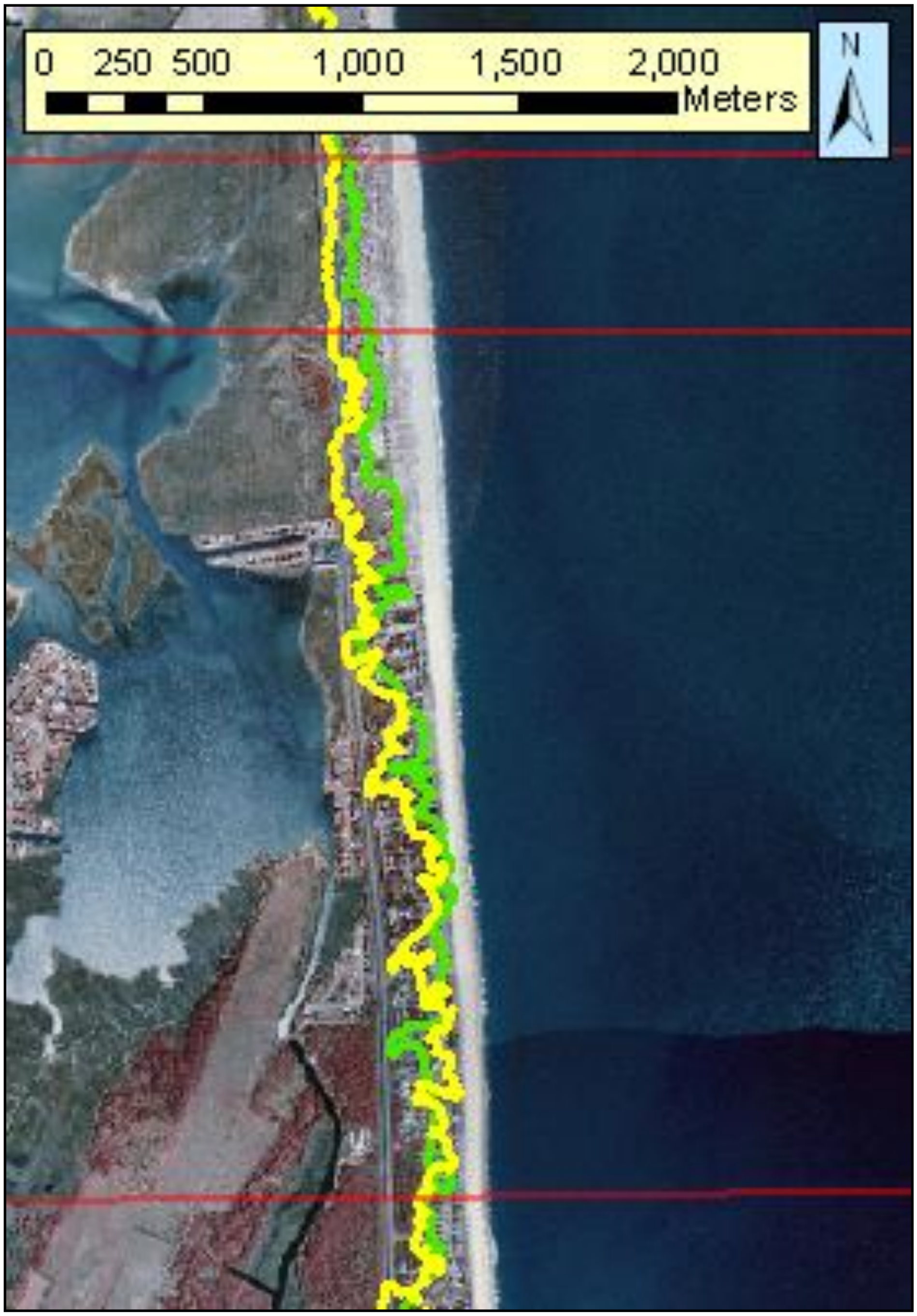

Figure AB.8 **Overwash, Zone 8.** Shows the Overwash of Zone 8. Significant overwash due to the storm fills buildings and homes with feet of sand.

Figure AB.9 Overwash, Zone 9. Shows the Overwash of Zone 9.

Figure AB.10 Overwash, Zone 10. Shows the Overwash of Zone 10.

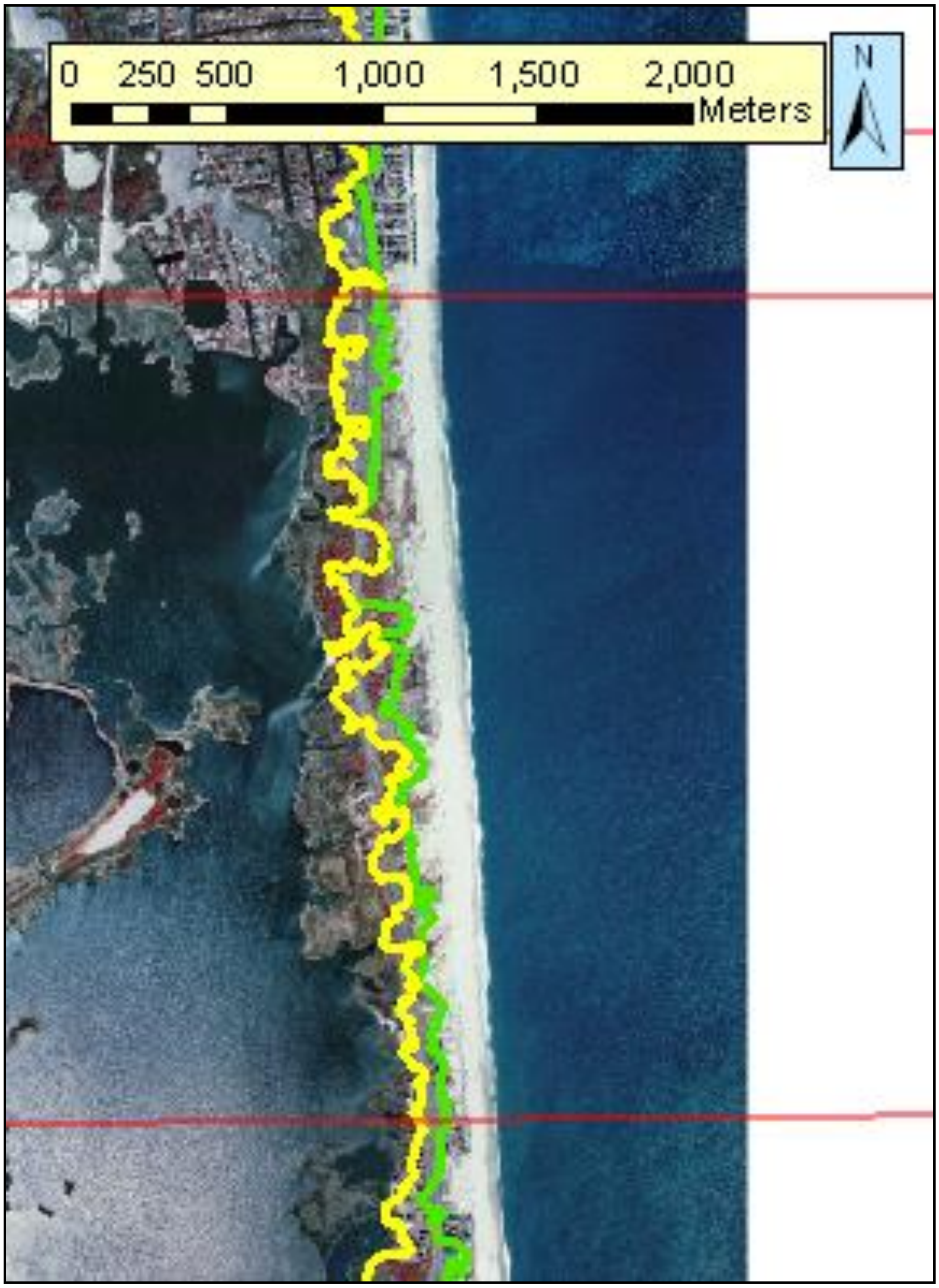

Figure AB.11 Overwash, Zone 11. Shows the Overwash of Zone 11. As in many of the other images, here, overwash covers most of the island, as well as the highway, Rt. 1.

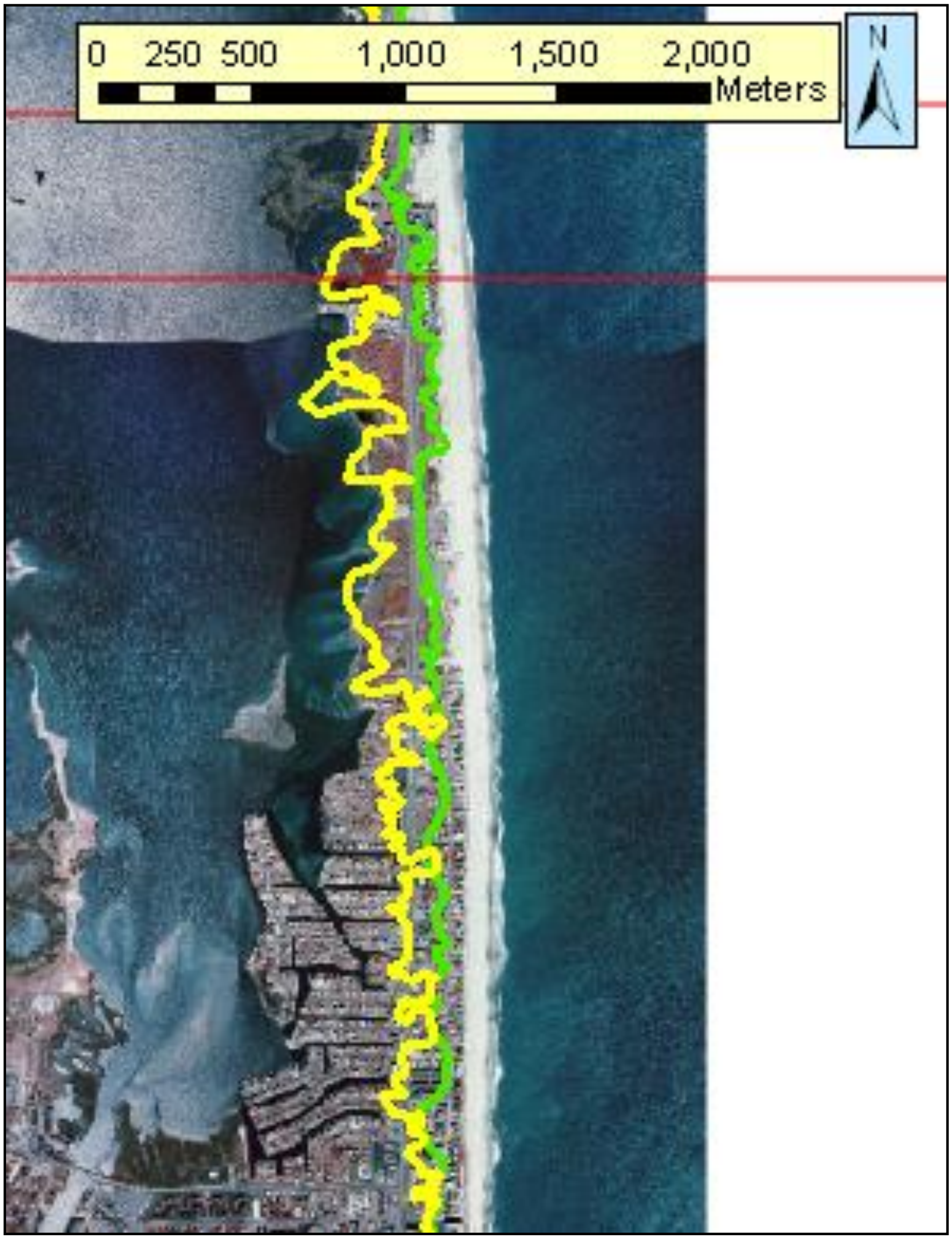

Figure AB.12 Overwash, Zone 12. Shows the Overwash of Zone 12. Overwash is so significant in this area that on the modern shoreline, many homes and buildings would be covered in sand.

APPENDIX C

This appendix is comprised of LiDAR images of the inundation of Delaware's coastline. LiDAR images were set to be approximately 50% transparent, and overlain on the modern, 2002 shoreline of Delaware, for comparison. The color ramp is meant to show the depth of inundation across the shoreline when a 2.9 m storm surge level is applied. As these images show, there is very little of the populated shoreline that is not inundated with water. As mentioned before in this study, when a 6-9 m average wave height is included, the dune areas that appear not to be inundated in these images would be destroyed and flooded, leaving back-dune areas vulnerable just as in the 1962 Northeaster. Several of these images have been described in this paper previously.

Figure AC.1 LiDAR Inundation, Zone 1. Shows the depth of inundation for Zone 1. As shown by this image, there is a large linear area, just above the scale and perpendicular to the beach that is not inundated. This is the Great Dune at Cape Henlopen State Park. The scale is shown in meters.

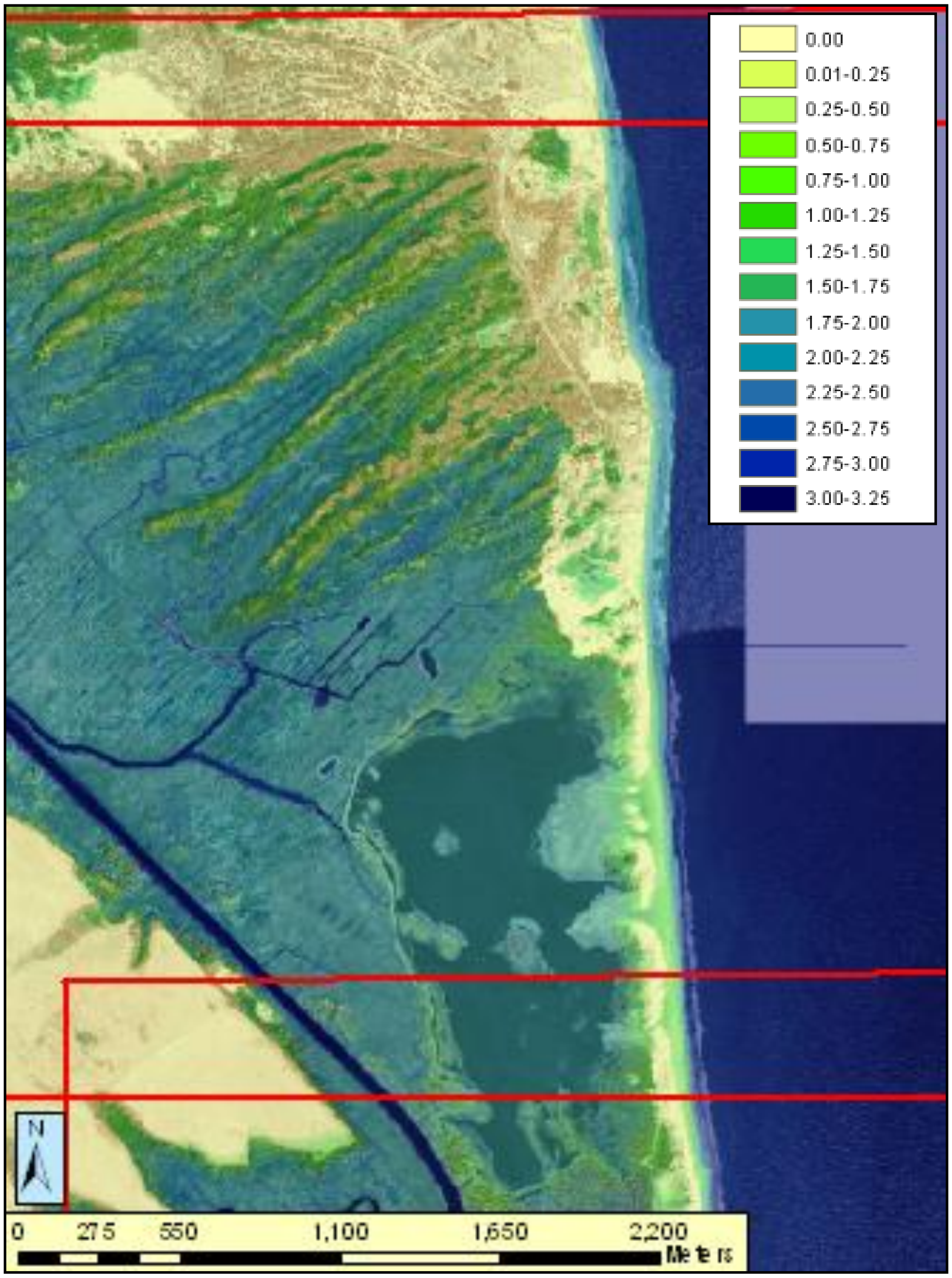

Figure AC.2 LiDAR Inundation, Zone 2. Shows the depth of inundation for Zone 2. The scale is shown in meters. The lower half of Great Dune is shown in a light sandy color at the top of this image.

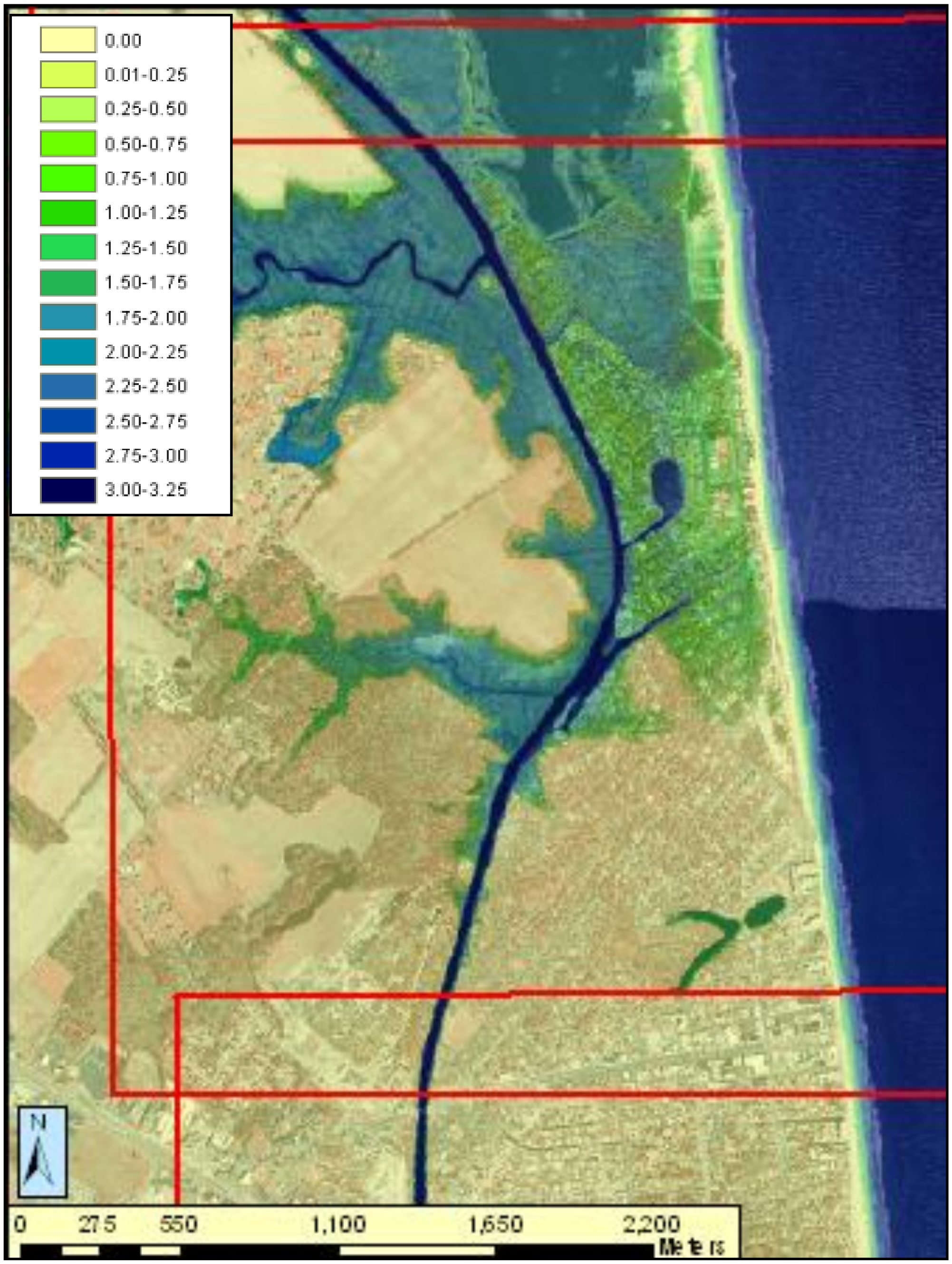

Figure AC.3 LiDAR Inundation, Zone 3. Shows the depth of inundation for Zone 3. The scale is shown in meters.

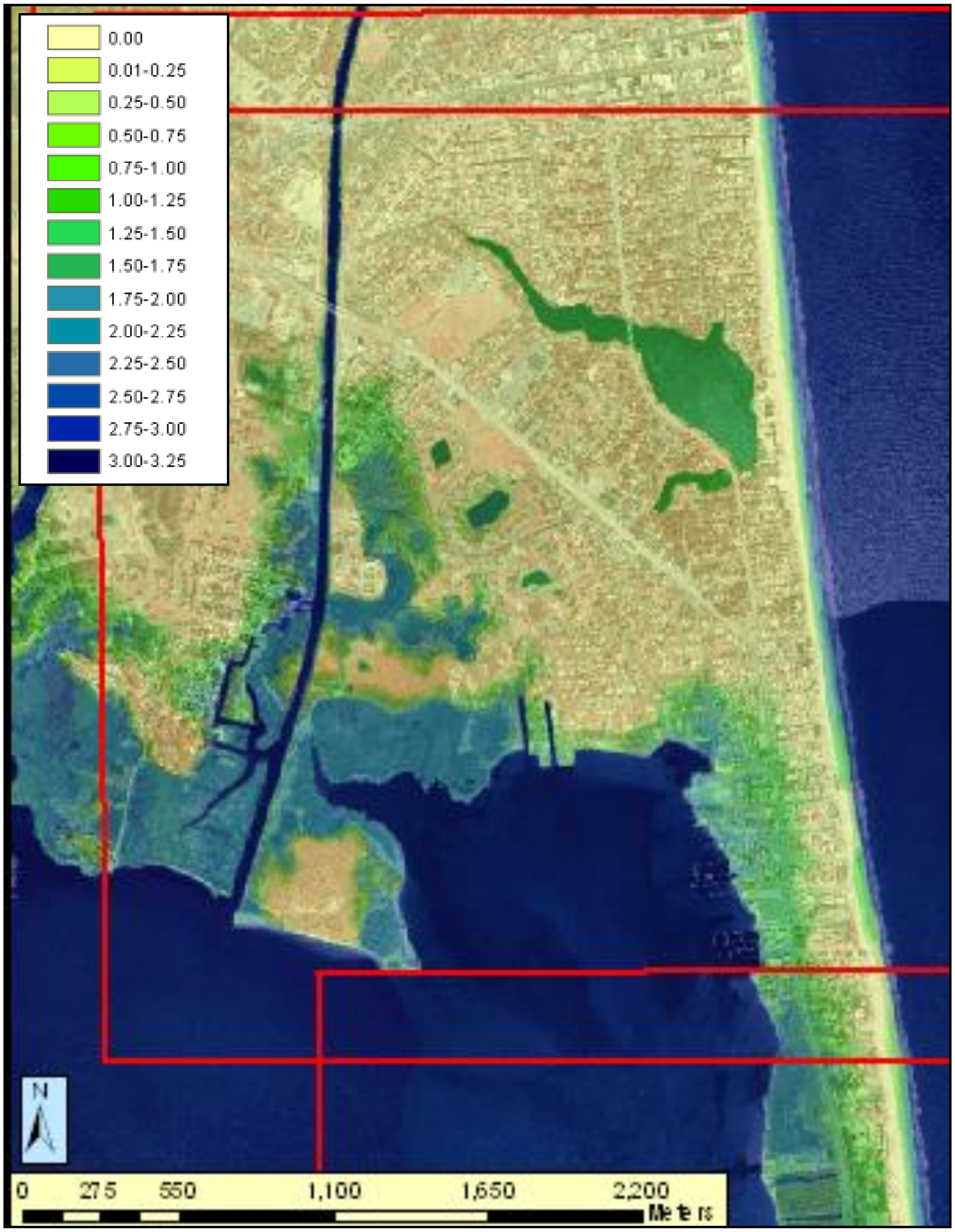

Figure AC.4 LiDAR Inundation, Zone 4. Shows the depth of inundation for Zone 4. The scale is shown in meters.

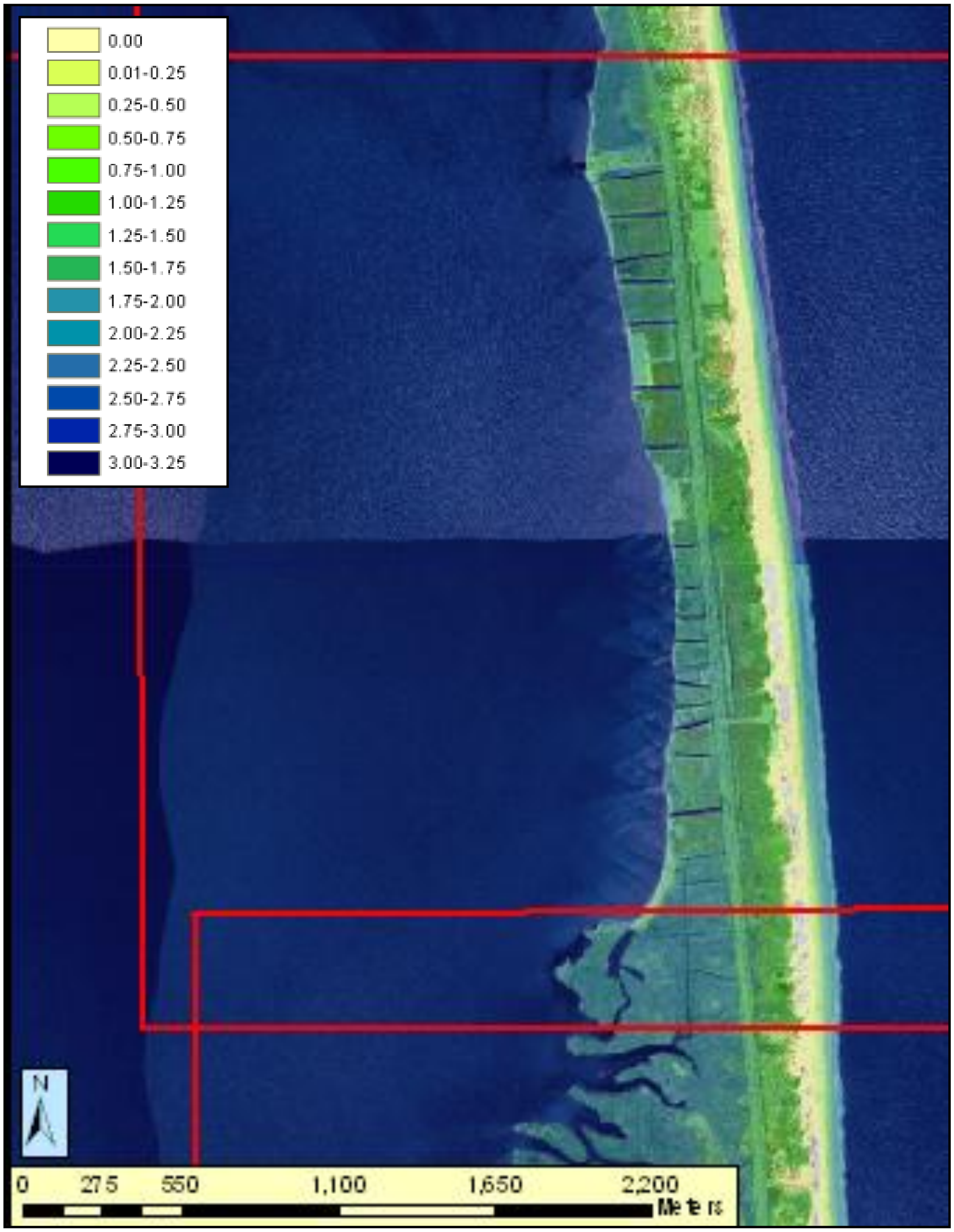

Figure AC.5 LiDAR Inundation, Zone 5. Shows the depth of inundation for Zone 5. The scale is shown in meters.

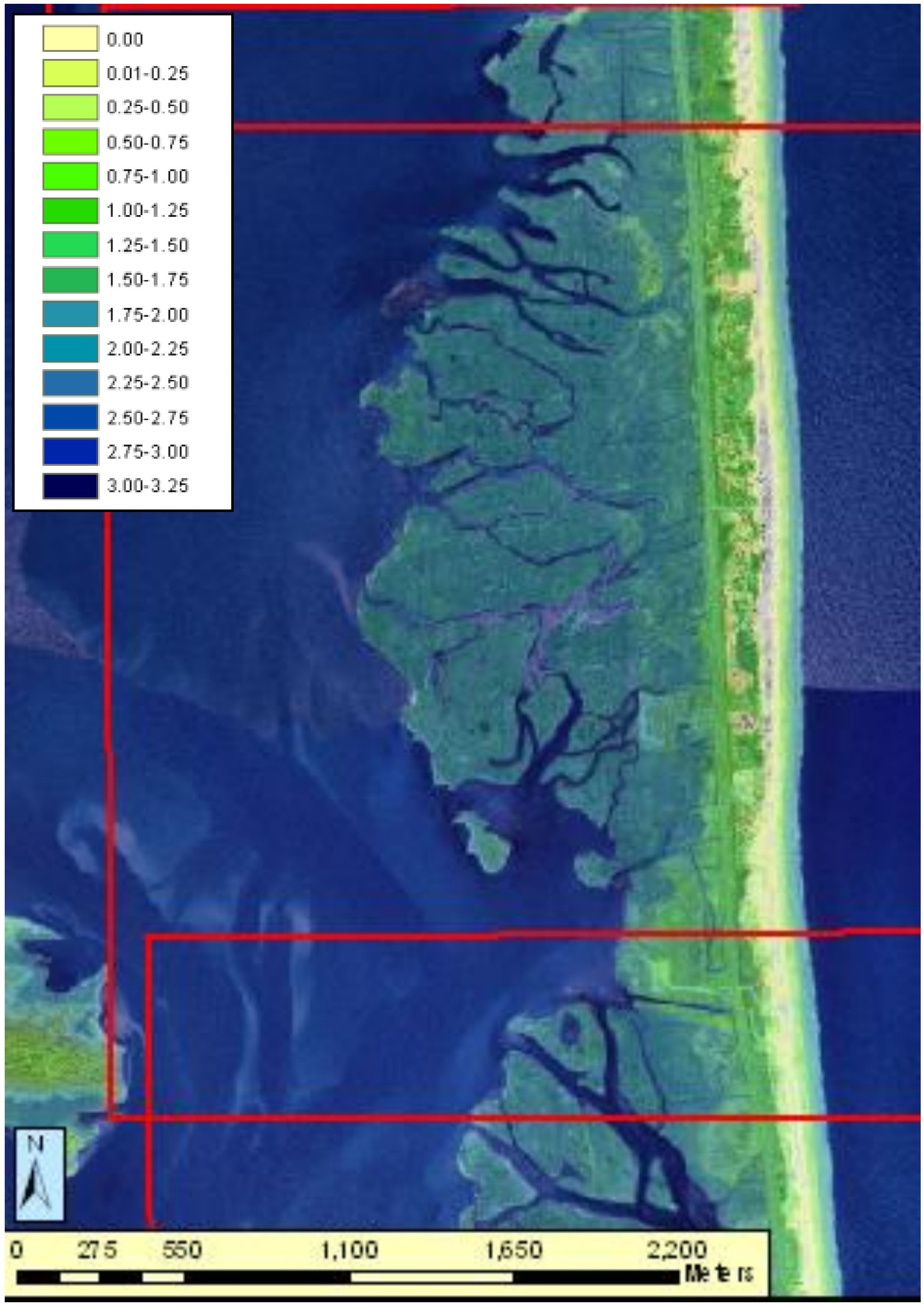

Figure AC.6 LiDAR Inundation, Zone 6. Shows the depth of inundation for Zone 6. The scale is shown in meters.

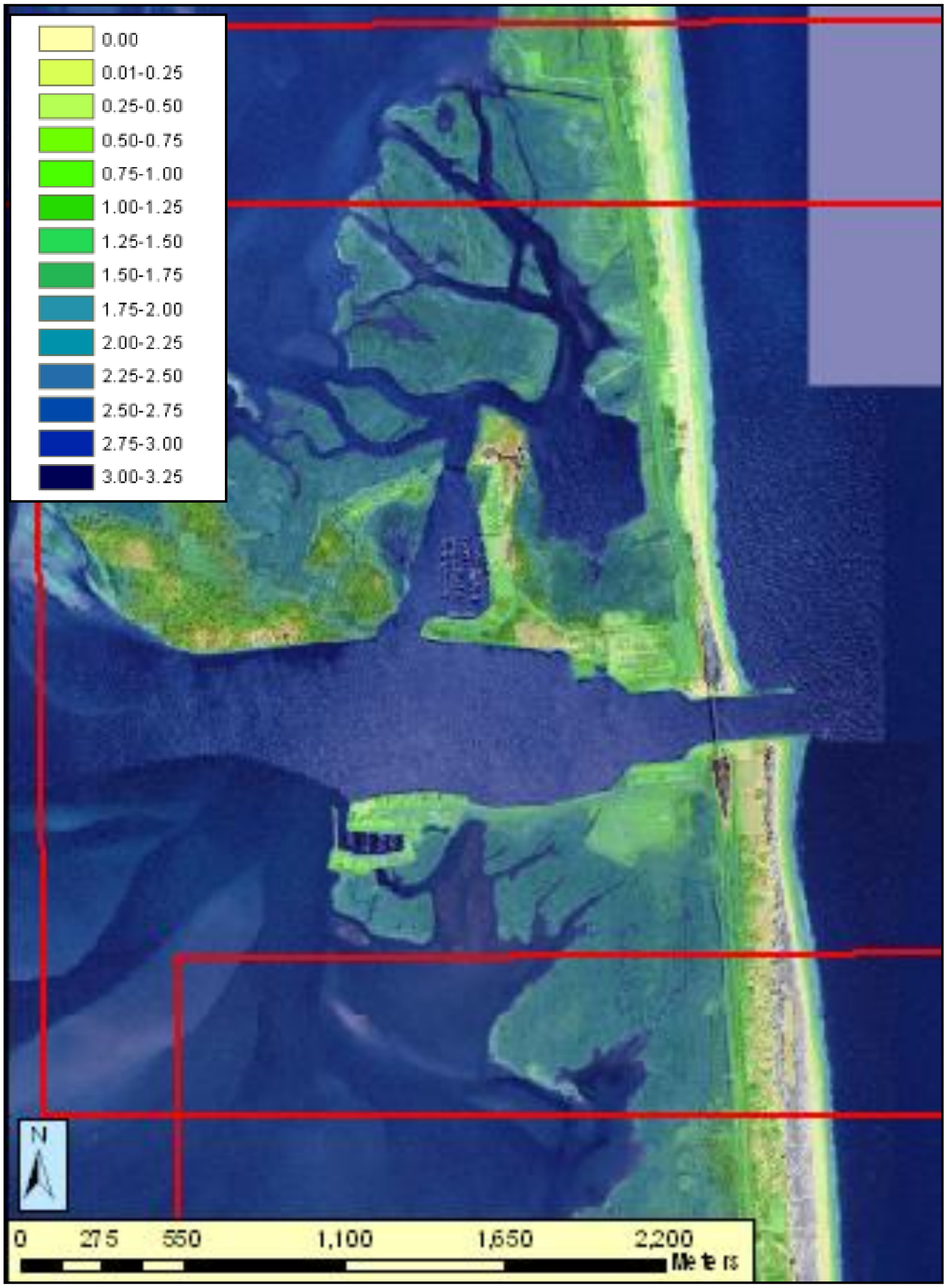

Figure AC.7 LiDAR Inundation, Zone 7. Shows the depth of inundation for Zone 7, Indian River Inlet. The scale is shown in meters.

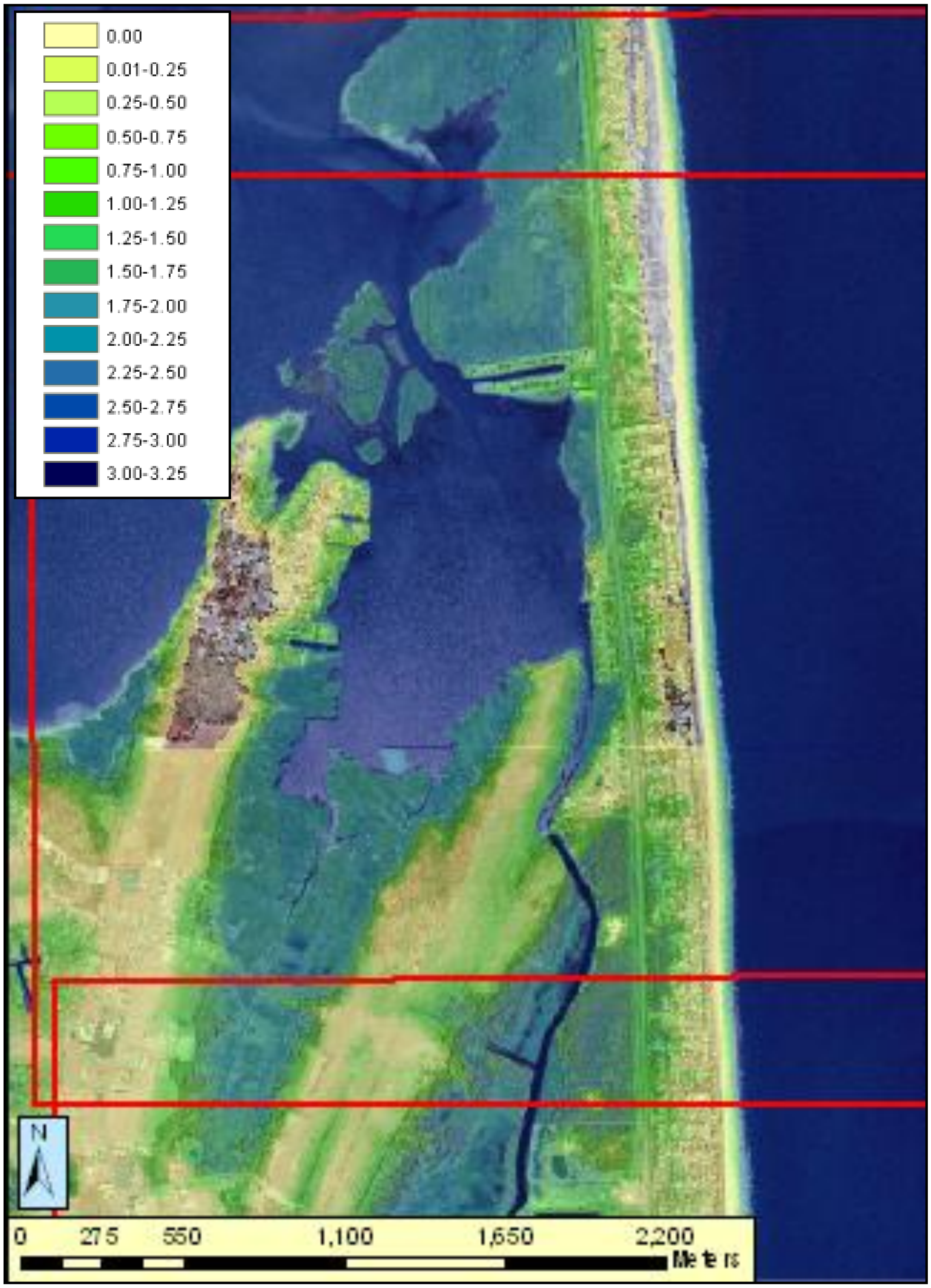

Figure AC.8 LiDAR Inundation, Zone 8. Shows the depth of inundation for Zone 8. The scale is shown in meters.

Figure AC.9 LiDAR Inundation, Zone 9. Shows the depth of inundation for Zone 9. The scale is shown in meters.

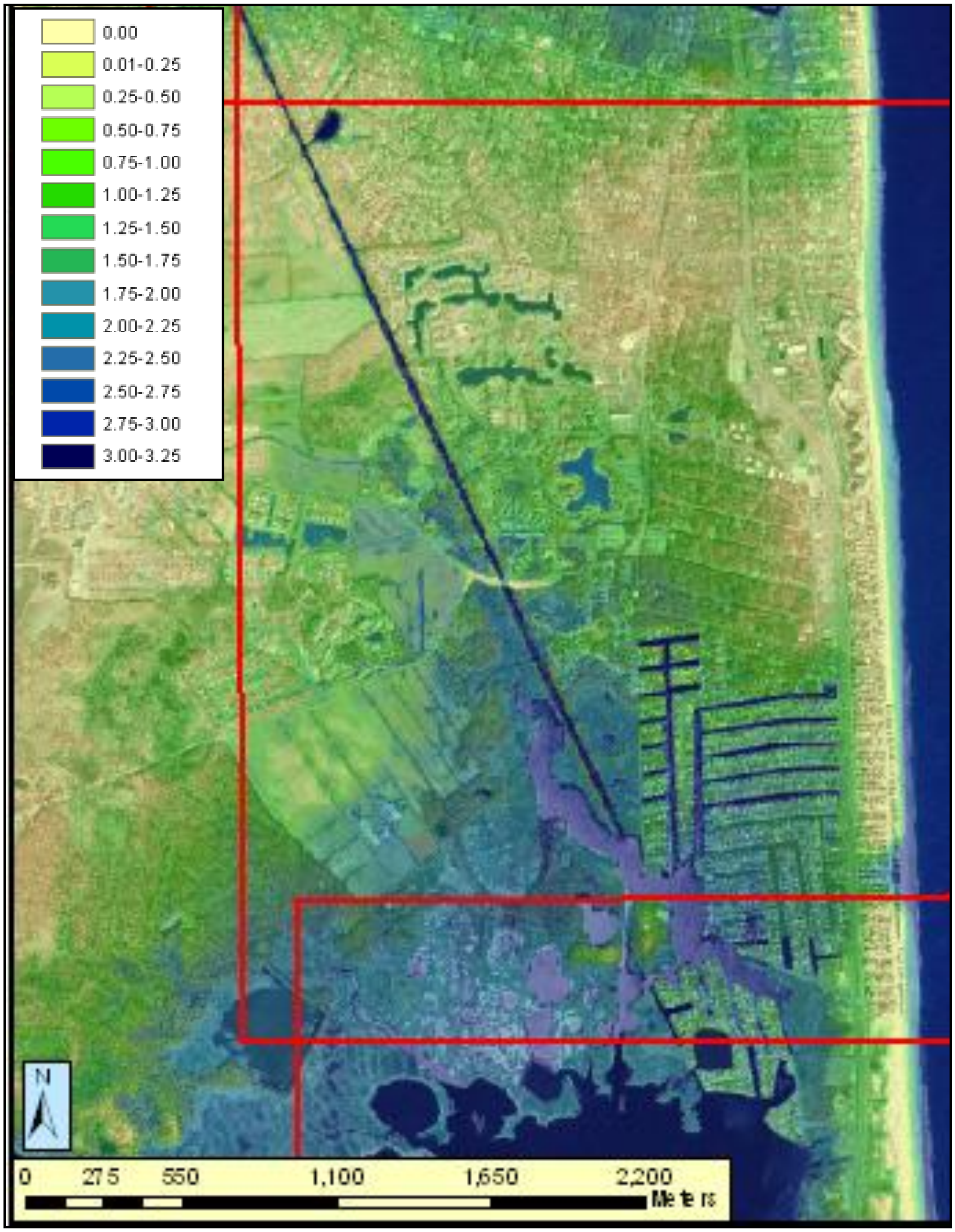

Figure AC.10 LiDAR Inundation, Zone 10. Shows the depth of inundation for Zone 10. The scale is shown in meters.

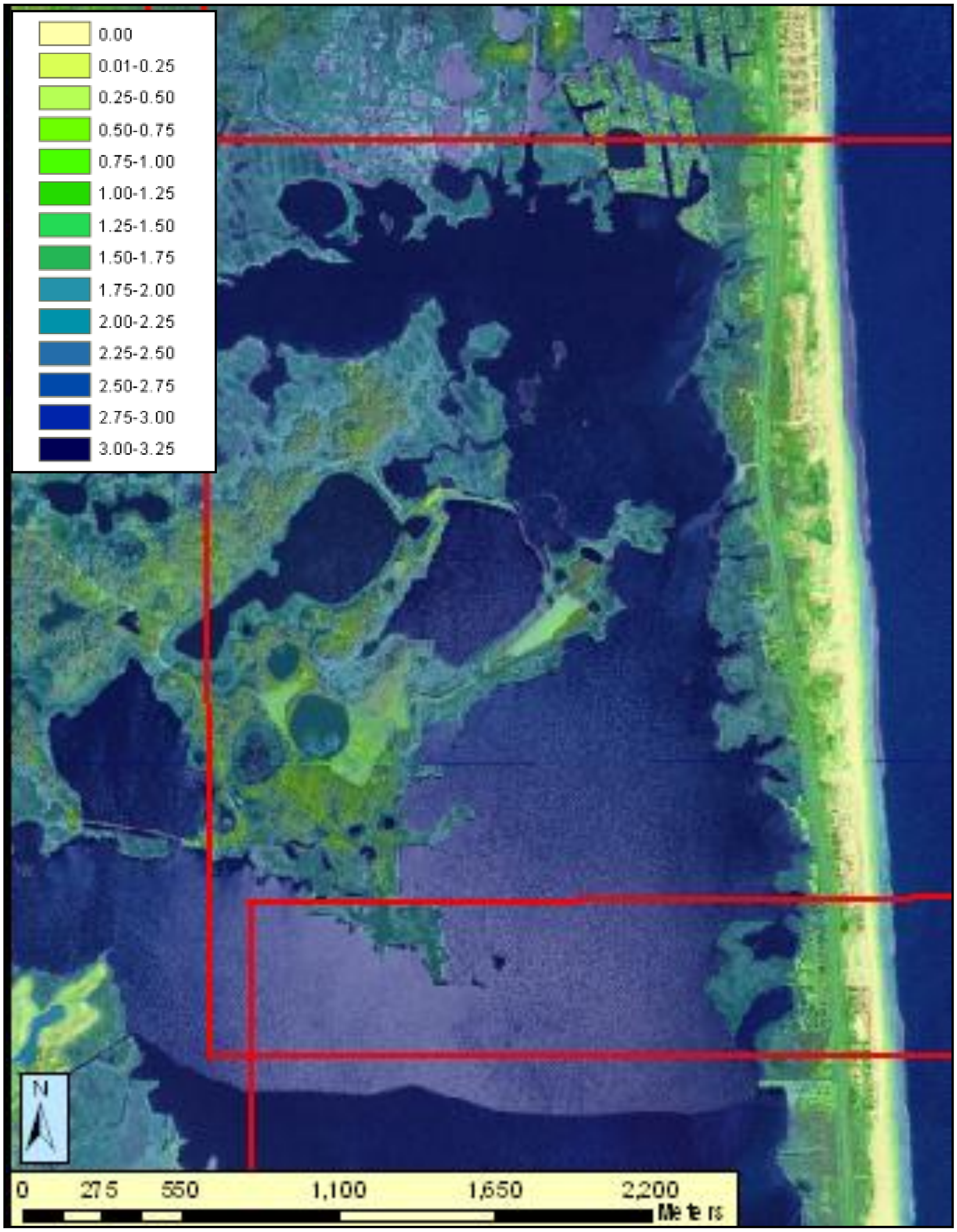

Figure AC.11 LiDAR Inundation, Zone 11. Shows the depth of inundation for Zone 11. The scale is shown in meters.

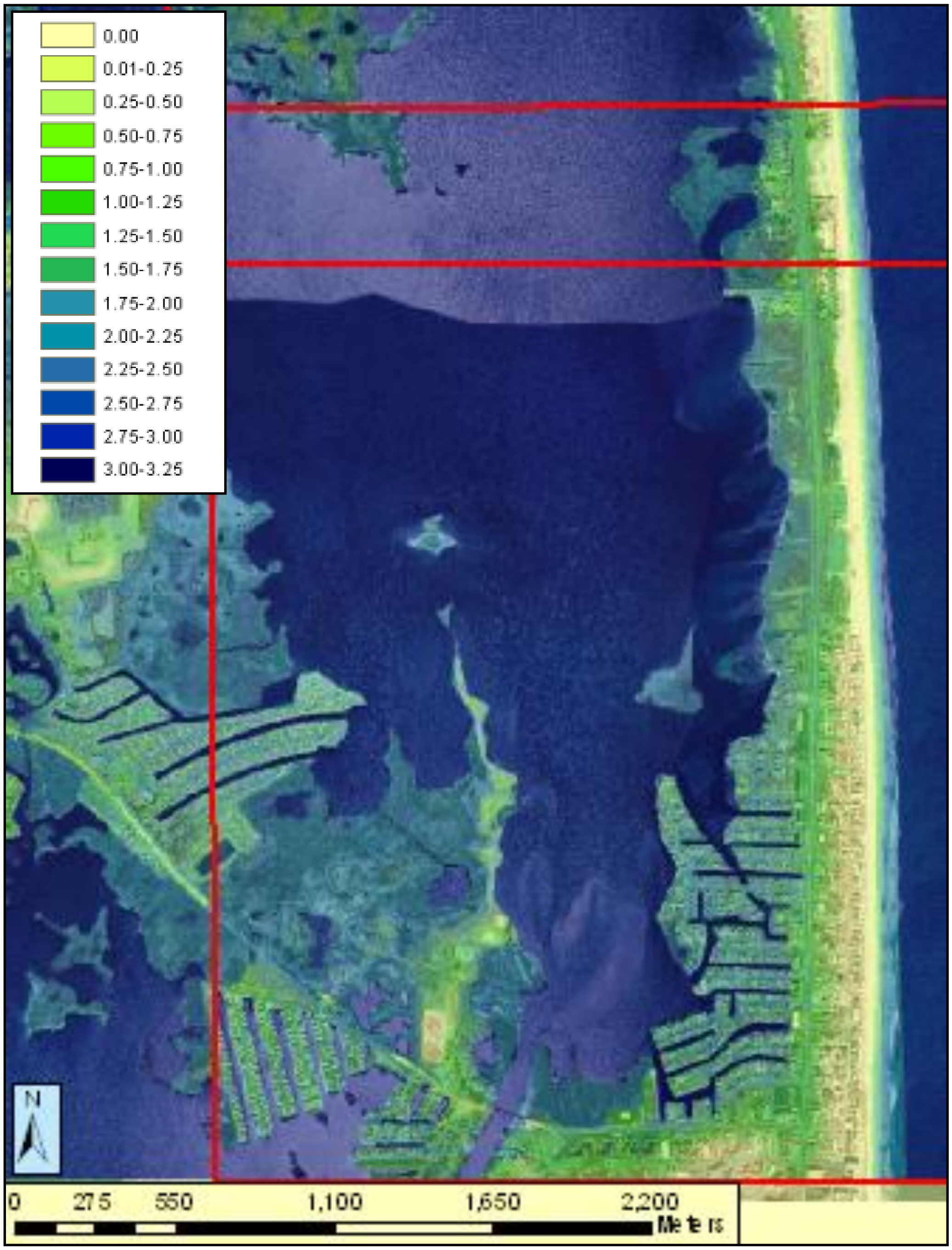

Figure AC.12 LDIAR Inundation, Zone 12. Shows the depth of inundation for Zone 12. The scale is shown in meters.

APPENDIX D

This appendix contains the ESRI GIS Metadata and file. Since the files are so large and complex, they have not been included in this document. In order to manipulate any of the data, one would need to access the project and its folders. Therefore, they have been stored in the University of Delaware, in order to ensure that the data are available. The first table in this section shows where the files are stored, and the contact information necessary to access them. They are stored on the servers that they each have, and is stored in the folder entitled "McCarty." The second table shows, in the left column the GIS table of contents as it appears within the project itself. In the next column over, it has their file names, and in the last column the file path. This was done to ensure that the names of the files and the names within the table of contents could be easily located in their respective file folders, as GIS tends to be finicky about files becoming moved. If you have any comments or questions, you can contact Dr. John Madsen listed in the first table of this appendix.

File Loc.	Contact	Phone	Email	Address
University of DE, Dept. of Geology	Dr. John Madsen	(302) 831-1608 (302) 831-2569	jmadsen@udel.edu	101C Penny Hall Newark, DE

ESRI Name	File Name	File Location
Quadrants	Quadrants2.shp	McCarty_Thesis > Data > My Shapefiles
Points of Interest	Points of Interest.shp	McCarty_Thesis > Data > My Shapefiles
Distances	Distances.shp	McCarty_Thesis > Data > My Shapefiles
SHORELINES		
• 1954_Shoreline	1954_Shoreline.shp	McCarty_Thesis > Data > My Shapefiles
• 1960_Shoreline	1960_Shoreline.shp	McCarty_Thesis > Data > My Shapefiles
• 1962_Shoreline	1962_Shoreline.shp	McCarty_Thesis > Data > My Shapefiles
• 1968_Shoreline	1968_Shoreline.shp	McCarty_Thesis > Data > My Shapefiles
• 2002_Shoreline	2002_Shoreline.shp	McCarty_Thesis > Data > My Shapefiles
• Shoreline Measurement Lines	Shoreline Measurement Lines.shp	McCarty_Thesis > Data > My Shapefiles
• Shoreline_DSAS		
o DSAS_Shoreline Transects	DSAS_Transect_2	McCarty_Thesis > Data > DSAS Analysis > DSAS Analysis 1.mdb
o DSAS_Shoreline & Overwash Baseline	AppendedShapefiles_Buffer_Po_Baseline.shp	McCarty_Thesis > Data > My Shapefiles
o Appended Shoreline_Buffer	AppendedShapefiles_Buffer.shp	McCarty_Thesis > Data > My Shapefiles
o Appended Shoreline_BufferPo	AppendedShapefiles_Buffer_Po.shp	McCarty_Thesis > Data > My Shapefiles
o Appended Shorelines	Appended Shapefiles.shp	McCarty_Thesis > Data > My Shapefiles
OVERWASH		
• Area of Overwash	Overwash Area_02.shp	McCarty_Thesis > Data > My Shapefiles
• Overwash_Reference	Overwash_Reference.shp	McCarty_Thesis > Data > My Shapefiles
• 1960_Overwash	1960_Overwash.shp	McCarty_Thesis > Data > My Shapefiles
• 1962_Overwash	1962_Overwash.shp	McCarty_Thesis > Data > My Shapefiles
• Overwash_DSAS		
o DSAS_Overwash Transects	DSAS_Overwash_Transect	McCarty_Thesis > Data > DSAS Analysis > DSAS Overwash Analysis1.mdb
o Appended Overwash_Buffer	AppendedOverwash_Buffer.shp	McCarty_Thesis > Data > DSAS Analysis
o Appended Overwash_BufferPo	AppendedOverwash_Buffer_Poly.shp	McCarty_Thesis > Data > DSAS Analysis
o Appended Overwash	Appended Overwash.shp	McCarty_Thesis > Data > DSAS Analysis

ESRI Name	File Name	File Location
BUILDINGS		
• 1960_Buildings	1960_Buildings.shp	McCarty_Thesis > Data > My Shapefiles > Buildings
• 1962_Buildings	1962_Buildings.shp	McCarty_Thesis > Data > My Shapefiles > Buildings
• 2002_Buildings	2002_Buildings.shp	McCarty_Thesis > Data > My Shapefiles > Buildings
• Building Density Analysis		
○ 1960_Density Analysis	sixtydensity	McCarty_Thesis > Data > My Shapefiles > Buildings
○ 1962_Density Analysis	sixty2density	McCarty_Thesis > Data > My Shapefiles > Buildings
○ 2002_Density Analysis	naut2_density	McCarty_Thesis > Data > My Shapefiles > Buildings
LIDAR		
• LIDAR_Elevations		
○ 4804290_2mAsciiArcGrid1.img	4804290_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
○ 4904250_2mAsciiArcGrid1.img	4904250_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
○ 4904260_2mAsciiArcGrid1.img	4904260_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
○ 4904270_2mAsciiArcGrid1.img	4904270_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
○ 4904280_2mAsciiArcGrid1.img	4904280_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
○ 4904290_2mAsciiArcGrid1.img	4904280_2mAsciiArcGrid1.img	McCarty_Thesis > Data > LIDAR > Elevation
• LIDAR_Inundation		
○ SUSSEX LIDAR_coast1_111.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation
○ SUSSEX LIDAR_coast1_121.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation
○ SUSSEX LIDAR_coast1_131.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation
○ SUSSEX LIDAR_coast1_141.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation
○ SUSSEX LIDAR_coast1_151.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation
○ SUSSEX LIDAR_coast1_161.img	SUSSEX LIDAR_coast1_111.img	McCarty_Thesis > Data > LIDAR > Inundation

ESRI Name	File Name	File Location
Aerial Photographs		
• 1960 Aerials		
○ Rectify1960_121	RectifyANH_5AA_121_1960.tif	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_76	RectifyANH_5AA_76_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_78	RectifyANH_5AA_78_1960.tif	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_80	RectifyANH_5AA_80_1960.tif	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_82	RectifyANH_5AA_82_1960.tif	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_84	RectifyANH_5AA_84_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_86	RectifyANH_5AA_86_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_88	RectifyANH_5AA_88_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_90	RectifyANH_5AA_90_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
○ Rectify_1960_92	RectifyANH_5AA_92_1960.TIF	McCarty_Thesis > Data > Aerial Imagery > 1960_Rectified
• 1962 Aerials		
○ Rectify_1962_2260	Rectify15Mar62BethanyBeach2260.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2261	Rectify15Mar62BethanyBeach2261.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2262	Rectify15Mar62BethanyBeach2262.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2263	Rectify15Mar62BethanyBeach2263.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2264	Rectify15Mar62BethanyBeach2264.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2265	Rectify15Mar62BethanyBeach2265.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2266	Rectify15Mar62BethanyBeach2266.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2267	Rectify15Mar62BethanyBeach2267.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2268	Rectify15Mar62CapeHenlopen2268.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2243	Rectify15Mar62CapeHenlopen2243.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2244	Rectify15Mar62CapeHenlopen2244.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2245	Rectify15Mar62CapeHenlopenStatePark2245.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2246	Rectify15Mar62CapeHenlopenStatePark2246.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2271	Rectify15Mar62FenwickIsland2271.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2255	Rectify15Mar62IndianRiverInlet2255.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2256	Rectify15Mar62IndianRiverInlet2256.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2269	Rectify15Mar62LittleAssawomenBay2269.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2270	Rectify15Mar62LittleAssawomenBay2270.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2253	Rectify15Mar62NorthIndianRiverInlet2253.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2247	Rectify15Mar62NorthRehobothBeach2247.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2251	Rectify15Mar62RehobothBay2251.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2252	Rectify15Mar62RehobothBay2252.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2248	Rectify15Mar62RehobothBeach2248.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15
○ Rectify_1962_2249	Rectify15Mar62RehobothBeach2249.tif	McCarty_Thesis > Data > Aerial Imagery > 1962_Rectified > New1962_15

ESRI Name	File Name	File Location
Reference Maps_DataMil		
• Delaware Map_DataMil	Delaware Map_DataMil.lyr	McCarty_Thesis > Data > Aerial Imagery > DataMil_Imagery
○ USGS DRG		
Aerials_DataMil		
• 1954_DataMil_Aerials	1954_DataMil_Aerials.lyr	
• 1961_DataMil_Aerials	1961_DataMil_Aerials.lyr	
• 1968_DataMil_Aerials	1968_DataMil_Aerials.lyr	McCarty_Thesis > Data > Aerial Imagery > DataMil_Imagery
• 1992_DataMil_Aerials	1992_DataMil_Aerials.lyr	
• 1997_DataMil_Aerials	1997_DataMil_Aerials.lyr	
• 2002_DataMil_Aerials	2002_DataMil_Aerials.lyr	
If for some reason, the DataMil Aerial Images are corrupted, and cannot be re-loaded into ArcMap, then they can be easily accessed via the following website: http://datamil.delaware.gov/		