# COASTLINE CHANGE AT FOUR SITES IN LOWER MICHIGAN

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**ABSTRACT**

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This study tested a new method of coastline change analysis to examine coastline change at four sites along the Lower Michigan coast. Shoreline position was manually delineated from aerial photography for multiple years between 1938 and 2010. The positional uncertainty associated with each shoreline was calculated in a GIS. A new method was developed to analyze the digitized shorelines. This new method generates a buffer (epsilon band) with radius equal to the positional uncertainty around each shoreline and uses these buffers to visualize and test for significant change. Significant change is determined by comparing a calculated proportion of similarity to a user-defined threshold. A series of transects perpendicular to the shoreline were then used to determine the direction and magnitude of change. Results indicate that shoreline position was most dynamic at the Manistee County site, and was least dynamic at the Sanilac County site. Overall there were more pairs of years with significant shoreline change at the two west coast sites, which suggests that shoreline position is more variable at the two sites along the west coast of Lower Michigan than along the east coast of Lower Michigan. The principle advantage of this dual epsilon method is that it analyzes change along the entire shoreline. This study demonstrates that the dual epsilon band method is feasible along a tideless coast.

## DEDICATION

This work is dedicated to my father, Alan Wernette, and mother, Julie Wernette, for their unwavering and unconditional support during my pursuit of higher education. Additionally, I would like to dedicate this work to my grandmother, Pauline Wernette, who emphasized the importance of never giving up and getting a quality education. I could not have done this without your support and wish you could be here to see me achieve this degree.

## ACKNOWLEDGEMENTS

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Wind and wave data was especially difficult to find. Thanks to Dr. Jeff Andresen and Aaron Pollyea for their assistance in locating meteorological data and direction in how to analyze it.

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# CHAPTER 1: INTRODUCTION

The Great Lakes of North America is collectively the largest body of freshwater in the world. This system covers over 244,000 $km^2$ and contains about 23,000 $km^3$ of freshwater. Approximately 33 million people live in the basin, with 25 million living in the United States and 8 million residing in Canada (U.S. Environmental Protection Agency Factsheet, 2011).

The Great Lakes encompass five major lakes: Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario (Fig. 1.1). Of these, Lake Superior is the largest (82,100 $km^2$) and deepest (mean depth: 147 m) lake and is the only one where lake-level is regulated (Clites and Quinn, 2003). In contrast, Lake Erie is the smallest (18,960 $km^2$) and shallowest (mean depth: 19 m) of the Great Lakes (U.S. Environmental Protection Agency Factsheet, 2011). Lake Ontario has the lowest elevation of the five lakes with its water plane at approximately 243 m above sea level. The deepest parts of Lakes Superior, Michigan, and Ontario are below sea-level (Fig. 1.2). Although Lakes Michigan Huron are commonly considered to be individual water bodies, they actually share the same water plane that is connected at the Straits of Mackinac. Lake Michigan-Huron has the greatest surface area and contains over 8,500 km of U.S. and Canadian coastline.


**Figure 1.1: Map of the Great Lakes region.**
**For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis. (Data from USACE, 2011, Maps and GIS of the Great Lakes Region)**

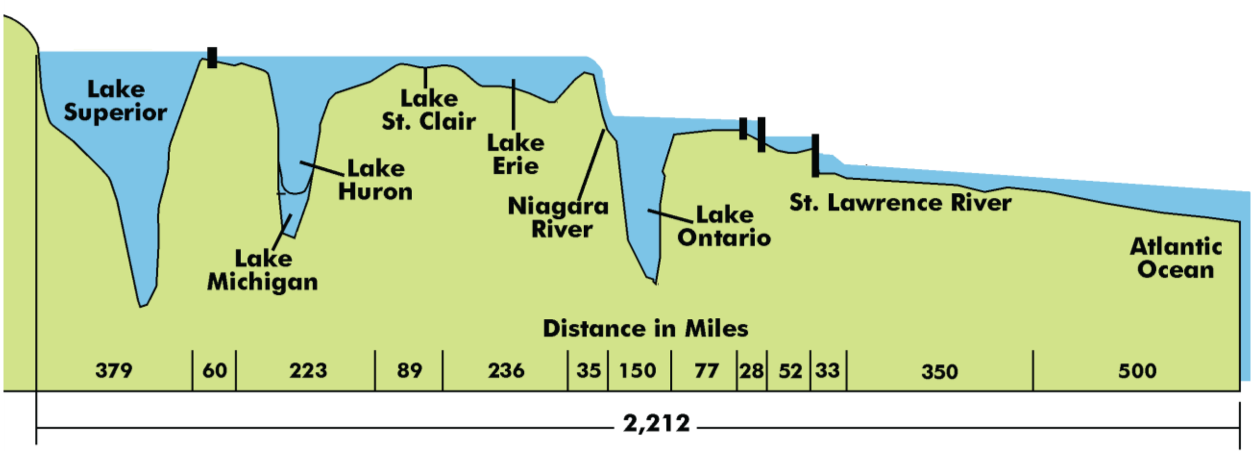



**Figure 1.2: Great Lakes System Profile.**
**(modified from USACE, 2011, Maps and GIS of the Great Lakes Region)**

The Great Lakes coastline has long been an important physical and economic resource. Many of Michigan's early settlements (Detroit, Mackinac, Manistee, Muskegon, St. Joseph) were located along the coast of these lakes because they served as important transportation hubs for commodities such as iron ore and timber. Today, the coastline is important for a variety of reasons, including the fact that a variety of local, state, and national parks occur here (Grand Haven State Park, Ludington State Park, Petoskey State Park, Sleeping Bear Dunes National Lakeshore, Pictured Rocks National Lakeshore). These parks are heavily utilized (Fig.1.3). At Pictured Rocks National Lakeshore, for example, about 421,000 patrons visited the park in 2001, bringing in approximately $14.8 million in revenue (Stynes and Sun, 2003).

**Figure 1.3: Tourism at Ludington State Park.**
**State Parks along Lake Michigan provide ample opportunities for recreation. (photo courtesy of Alan V. Wernette, Park Interpreter at Ludington State Park)**

In addition to the popularity of the coastal parks, the lakeshore is also heavily utilized in other important ways. One such example is the role of sand mining in coastal dunes (Fig. 1.4). There are currently 12 sand mines with active permits along the eastern Lake Michigan coast

(MDEQ, 2012b). In 2010, these mines removed over 1.1 million tons of dune sand (MDEQ, 2012b). Mined sand is used for a variety of purposes, such as foundry molds and glass production. The high melting point, porosity, and uniform grain size makes dune sand ideal for foundry molds and cores. Despite the economic benefits of mining dune sand, environmental groups argue that the natural resource degradation and loss is reason to limit mining of sand dunes (Lake Michigan Federation, 2000).

**Figure 1.4: Looking south at an active sand mine in Ludingotn, MI.**
**This mine, owned and operated by Sargent Sand Co, Inc., has been active off and on since 1937. Note the large rectangular ponds present where large barrier dunes were once present. (photo courtesy of Ludington State Park)**

Another significant human impact along the Great Lakes coastline is expanding residential development. Since 1900 the number of residents along the Lake Michigan coast has more than doubled (Fig. 1.5). This influx of people has created political tension about how the coast should be utilized. Groups such as the Great Lakes Coalition argue that residential development along the coast is protected by the 5th Amendment of the U.S. Constitution (Great Lakes Coalition, 2012). Conversely, environmental groups such as the Alliance for the Great Lakes argue that such developments threaten sensitive coastal ecosystems (Alliance for the Great Lakes, 2011).

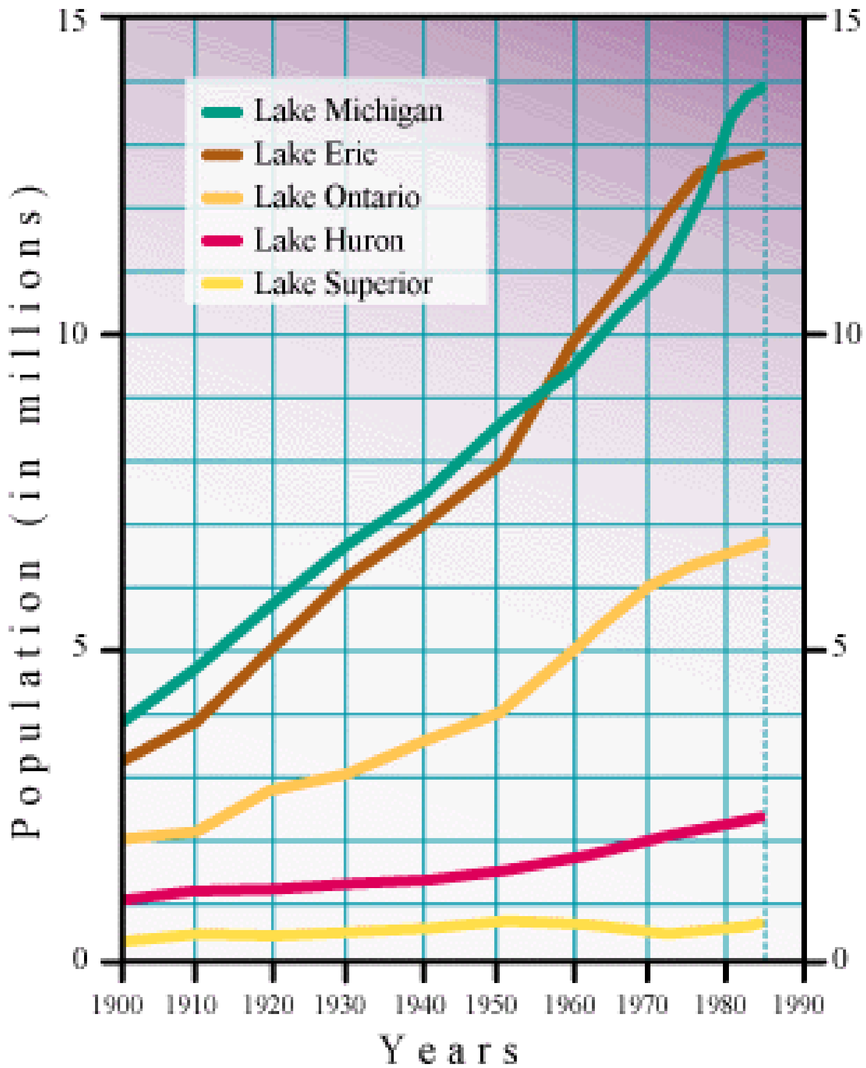



**Figure 1.5: Population growth along the Great Lakes coastlines since 1900. (U.S. Environmental Protection Agency, 2012)**

Given the diverse and extensive human interactions along Lakes Michigan and Huron, a great deal of effort is spent on monitoring coastal change along these water bodies (MDEQ, 2012b). Abundant research (Seibel, 1972; Buckler and Winters, 1983; Jibson, et al., 1994) demonstrates that modifications in the configuration of the coast is most noticeably linked to fluctuating lake levels, with most change occurring during periods of relatively high lake level. A variety of researchers (Thompson, 1992; Thompson and Baedke, 1995, 1997; Baedke and Thompson, 2000) have identified annual and long-term, quasi-periodic lake-level fluctuations that include 33, 150, and 500-year cycles. Johnston, et al (2002) noted that the effects of the cycles are compounded when they overlap.

In the 20$^{th}$ century, lake-levels for Lakes Michigan-Huron were exceptionally high during the mid-1930s, 1950s, 1970s, and 1980s (Fig. 1.6). The economic importance of understanding coastal dynamics was especially highlighted by rapid bluff recession in the 1970s and 1980s (Fig. 1.7). This erosion destabilized dunes and bluffs and caused extensive property damage and loss (Angel, 1995). Remnants of coastal property damage can still be found along Lower Michigan's western coastline (Fig. 1.8). Conversely, prolonged periods of below average lake-levels increase beach widths and reduce the impact of nearshore processes on the bluffs. During periods of lower lake-levels, dunes and bluffs typically stabilize and erosion is no longer a widespread issue (Anderton and Loope, 1995; Arbogast and Loope, 1999; Arbogast, et al., 2002).

Since 1999, lake-levels for Lakes Michigan and Huron have generally been below average. Although coastal erosion is not currently a prevalent issue, coastal management remains important for Michigan residents and the economy. In 2009-2010 the Michigan Department of Environmental Quality (MDEQ) approved over $1.4 million in grants to help manage Michigan's 3,224 miles of coastline (MDEQ, 2012b). Given this focus on coastal issues, understanding the spatial and temporal patterns of coastline change is key to efficiently managing this important resource.

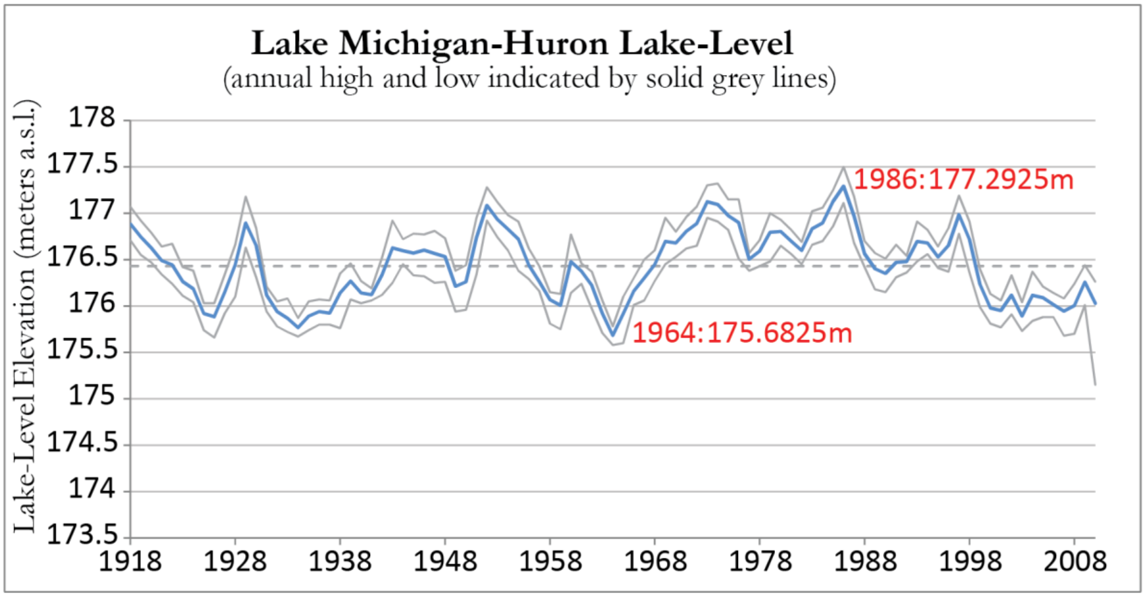



**Figure 1.6: Observed annual high, low, and mean lake-level for Lake Michigan-Huron. Data labels indicate record low (1964) and high (1986) lake-levels. (data from USACE, 2011, Detroit District)**

**Figure 1.7: Property damage due to bluff erosion in Berrien County, MI during high lake-levels.**
**(from Buckler and Winters, 1983, pg. 102)**

**Figure 1.8: Debris scattered across dunes near Manistee, MI.**
**Notice the staircase on the right and concrete foundation protruding from the dune in the center (photo by Phil Wernette).**

Coastal evolution is the product of the interaction of multiple factors, including geologic composition, coastal slope, wave direction and strength, fetch length, and anthropogenic erosion control structures. The nature and intensity of these factors differ on either side of Lower Michigan. One such example is wind strength. The west coast of Lower Michigan receives stronger winds than Lower Michigan's eastern coast (Fig. 1.9). This geographical variability hypothetically leads to differences in coastline change on either side of Lower Michigan.

**STATEMENT OF PROBLEM**

This research explores the spatial variability that hypothetically exists with respect to the degree of coastal change and coastline location on either side of Lower Michigan. Given the dominance of prevailing westerly winds and the associated waves, I hypothesize that portions of the western Lower Michigan coastline have changed more than the eastern Lower Michigan coastline. The degree of change will be investigated through an assessment of a sequence of air photos from 1938 to 2010. This research contributes to our understanding of coastline evolution in Lower Michigan by examining more than 70 years of coastline change along selected portions of Lower Michigan's west and east coasts. This new information will provide valuable information about patterns of coastline evolution along parts of both coasts of Lower Michigan.

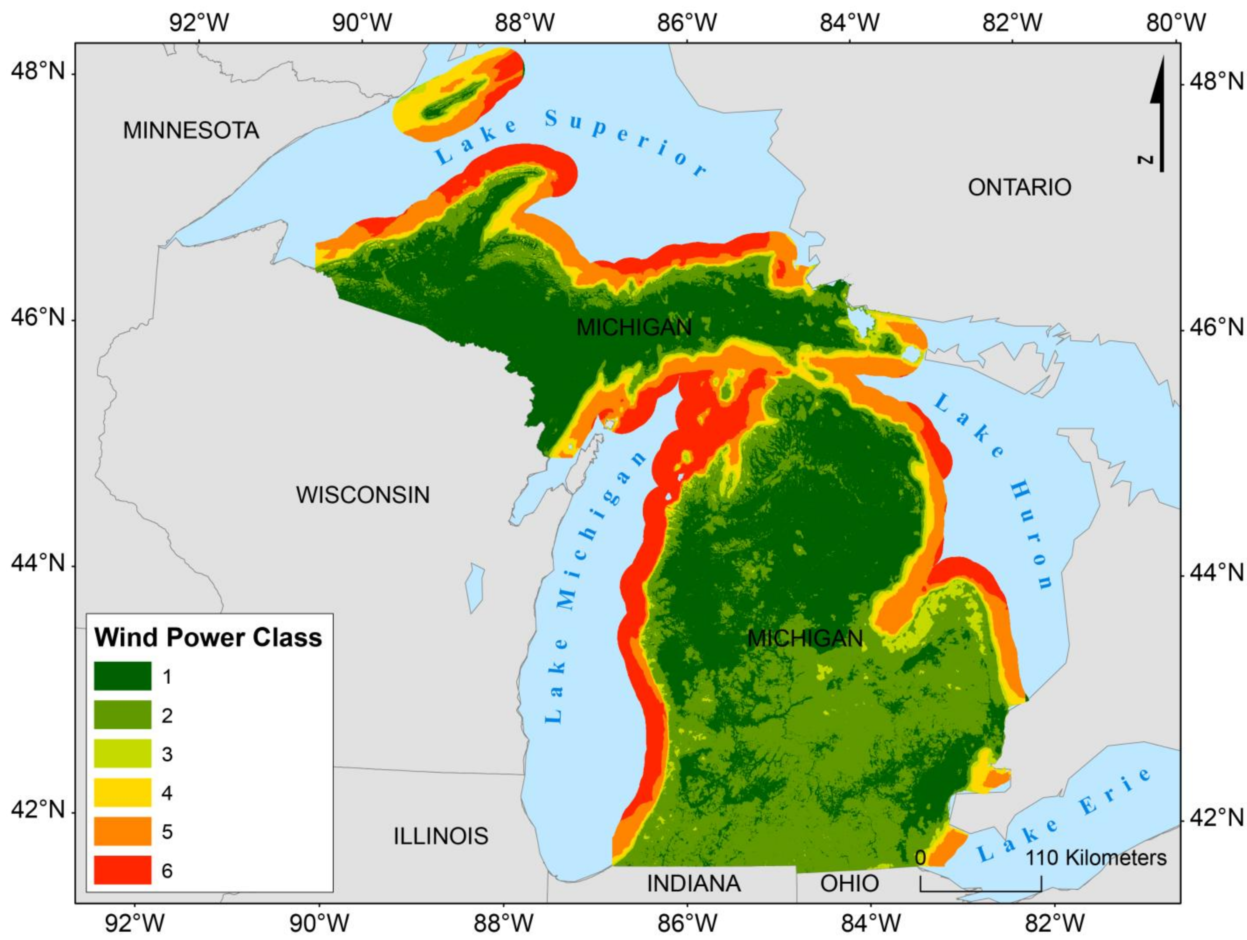



**Figure 1.9: Michigan wind resource map.**
**Note the geographical variability that exists with respect to wind resources across the state. (data from National Renewable Energy Laboratory, 2004)**

# CHAPTER 2: DEFINITION OF TERMS AND LITERATURE REVIEW

## DEFINITION OF TERMS

The coasts examined in this study have similar profile morphologies that can be divided into four distinct zones: offshore, nearshore, foreshore, and backshore (Fig. 2.1). Each zone contains a unique set of landforms which reflect the dominant processes affecting that zone.

The offshore zone extends from deep water parts of the lake to the first sand bar. Mathematically, deep water is defined as the areas where water depth is greater than one half the wave length (Fox and Davis, 1973; Equation 2.1). In other words, this zone is characterized by deep water where wave energy does not reach the lake substrate. The offshore zone ends near the base of the first sand bar where wave energy begins to reach the lake bottom and mobilize the substrate.

$$Water\ Depth > \frac{1}{2} * Wave\ Length \qquad [\ 2.1\ ]$$

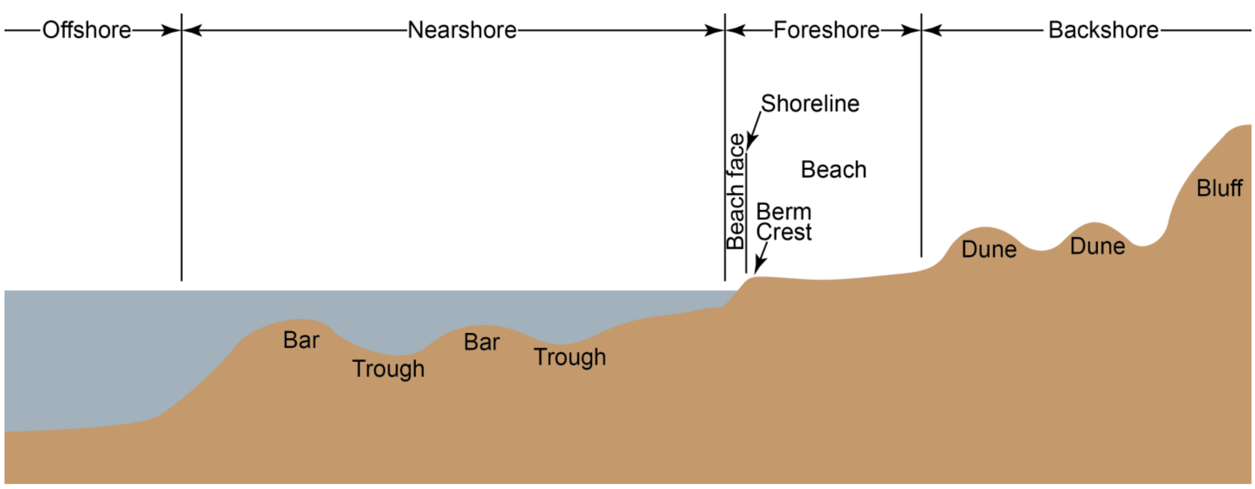



**Figure 2.1: Profile view of the coast with important coastal landforms labeled. (diagram by Phil Wernette)**

Inland of the offshore zone is the nearshore zone. This zone begins at the farthest offshore bar. The nearshore zone is characterized by one or more bar and trough sequences (Fig. 2.1). These bars and troughs typically have their greatest amplitude farther offshore and decrease in amplitude landward. The distance from shore and amplitude of these bars can change seasonally (Fox and Davis, 1973). Landward, the nearshore zone terminates at the base of the oversteepened sediments.

The foreshore zone begins at the point where coastal sediments become oversteepened and can be further subdivided into the beach face and the beach. The beach face begins where coastal sediments begin to become oversteepened and terminates at the berm crest (Fig. 2.1). The primary forces affecting the beach face are wave processes such as swash and backwash. Depending on the angle of approaching waves, the beach face may develop small cusps that are visible from the ground (Fig. 2.2). Additionally, wave processes wet and redistribute coastal sediments which can cause the beach face to have a steeper slope than the adjacent beach.

**Figure 2.2: Looking north at the Alcona County site.**
**Notice the pronounced cusps along the beach face. (photo by Phil Wernette)**

The berm crest is marked by an acute change in slope. This feature marks how far waves reach inland. The berm crest typically coincides with the high water line (HWL). Since this line is visible from the ground and the air (Fig. 2.3), this study defines the shoreline as the HWL. The beach begins at the berm crest and extends to the base of the first dune or bluff. The width and slope of the backshore zone can be highly dynamic and are dependent on the wind and wave climate of the area. Unlike the beach face, aeolian processes are dominant on the beach, which can supply the adjacent dunes and bluffs zone with sediment.

**Figure 2.3: Looking north at the Manistee County site.**
**The HWL is clearly visible along the berm crest as a change in tone between the darker, wetted beach face and the lighter, drier beach. (photo by Phil Wernette)**

The farthest inland coastal zone is the backshore zone. This area frequently contains one or more sand dunes and bluffs (Fig. 2.4). These dunes can vary greatly in size from >1 m high foredunes to large parabolic dunes greater than 10 m tall. They are typically vegetated by dune grasses. The morphology of the dunes and bluffs is greatly affected by aeolian processes and mass movement events (Fig. 2.5). Mass movement is more evident in larger dunes and higher bluffs.

**Figure 2.4: The backshore zone at the Allegan County site (photo by Phil Wernette).**

**Figure 2.5: Evidence of mass movement in the backshore zone at the Allegan County site (photo by Phil Wernette).**

**PREVIOUS LITERATURE**

According to Buckler and Winters (1983), erosional problems along the Lake Michigan shore of Wisconsin and Michigan were first recognized in the 1800s (Lapham, 1847; Whittlesey, 1867; Andrews, 1870; Chamberlin, 1877; Woolridge, 1884; and Leverett, 1899). One of the earliest geomorphic investigation of Lower Michigan coastal features was conducted in the early $20^{th}$ century by Leverett and Taylor (1915). Given the intensive logging that had occurred during the second half of the nineteenth century in Michigan, Leverett and Taylor (1915) were able to interpret much of the state's landscape due to heightened visibility associated with deforested terrain. Along the Lower Michigan shore, they recognized that a series of abrupt escarpments, which they identified as relict shorelines associated with various paleolakes, existed that could be followed for great distances. Additionally, they recognized the role of isostatic uplift in creating these features. Using basic surveying techniques and with remarkable accuracy, given the time, they mapped the extent and elevation of these shorelines, such as the prominent Lake Algonquin shoreline (Fig. 2.6). These shorelines were then related to proglacial and Holocene lake stages. Nearly 100 years later, their interpretations remain largely valid.

During the mid-$20^{th}$ century, Great Lakes' lake levels were relatively stable. Beginning in the 1960s, however, lake levels began to noticeably fluctuate, and Lake Michigan-Huron reached its record low in 1964 (Fig. 1.6). Following this record low, lake levels began to rise at an average annual rate of 0.17 m (based on data from USACE Detroit District, 2011), which resulted in widespread coastal erosion and property damage.

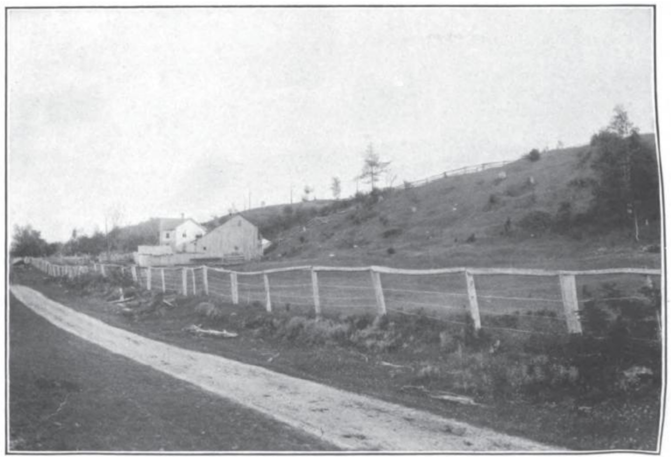


**Figure 2.6: Example of a relict shoreline recognized by Leverett and Taylor (1915, pg. 457). This escarpment, formed by proglacial Lake Algonquin, is located near Black River, MI in Alcona County.**

The extensive impacts associated with this high lake stage (the historic high lake level on Lake Michigan-Huron occurred in 1986) promoted a new wave of coastal research. The first of these studies was conducted by Seibel (1972), who investigated possible relationships between lake-level fluctuations, storm activity, and erosion rates along both coasts of Lower Michigan. Four sites along the Lake Michigan coast and two sites along the Lake Huron coast were selected for detailed analyses. Seibel (1972) interpreted bluff position from aerial photography taken between 1938 and 1972 and calculated coastal erosion rates for each site. The calculated erosion rates varied between all six sites. This variation was attributed to differences in fetch distance and direction due to variations in coastline orientation. The most significant result of this research was the establishment of a link between erosion rates and lake-level fluctuations. Although erosion rates corresponded to periods of higher lake-levels (Fig. 2.7), Seibel (1972) was unable to identify any clear relationship between storm cycles and coastal erosion rates.

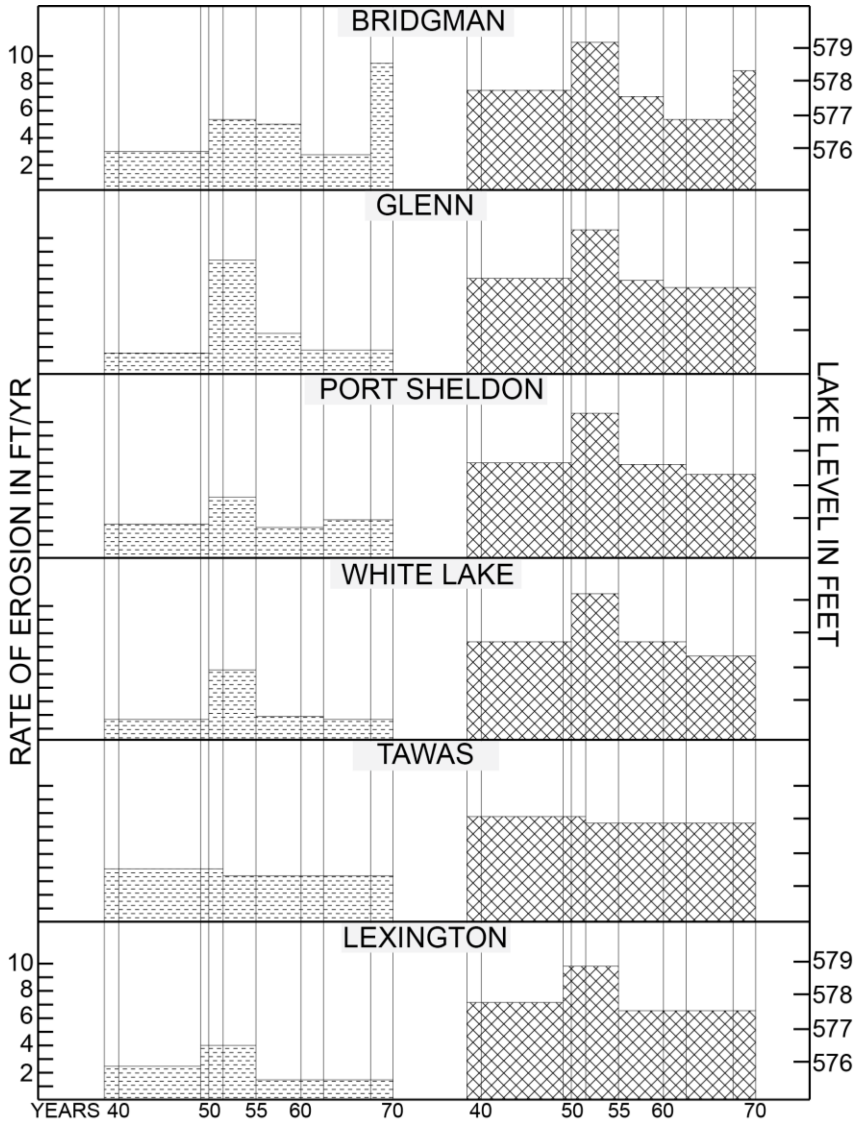



**Figure 2.7: Observed relationship between lake-level (right) and coastal erosion rates (left) at all sites examined by Seibel (1972, pg 104).**

The potential relationship between storm cycles and coastal evolution was further investigated by Fox and Davis (1973). Specifically, they were interested in seasonal beach erosion and nearshore bar migration. Their study examined the general equilibrium profile concept that had been proposed by Bruun (1954) a decade earlier along the U.S. Atlantic coast. Fox and Davis (1973) used observations of barometric pressure and wave data from the summers of 1969 and 1970 as inputs into a mathematical simulation model to calculate wave and longshore currents. Results indicated that nearshore bar distance resulted from the relationship between wave energy and bottom slope. Nearshore bar distance was characterized by the following equation: $Xb = \sqrt{((3Ew)/S)}$, where $E_W$ is wave energy and $S$ is slope (Fox and Davis, 1973, pg. 1785). Nearshore bars were found to be farther from the coastline on a gently sloping coast than a steeper sloping coast with similar wave energy regime. Longshore current velocity and breaker height were the first and second derivatives of the change in barometric pressure over time. These empirical relationships were confirmed by field observations.

In a related study, Lee (1973) built on the idea that several factors influence coastal change along the Lake Michigan coast. He challenged the common misconception that coastal erosion was purely a function of lake-level fluctuations and waves by examining bluff recession at three sites along Wisconsin's eastern coast. This research highlighted the importance of several factors working in conjunction with one another in order for erosion to occur. He found that wave undercutting was not extensive because the toe of the bluff was only within the upper limits of the swash zone. High lake-levels and associated wave action only explained a fraction of the observed bluff recession. Recession was attributed to sheer failure of soils due to groundwater flow through the stratified structure. Groundwater seepage weakened underlying sand layers, resulting in mass movement of the overlying sediment. Recession rates were exceptionally high in areas where stratified layers were horizontal or nearly horizontal. This model of bluff failure is essential to coastal bluffs across the region where the bluff is composed of nearly horizontally bedded unconsolidated sediments. Although lake levels were not the sole factor influencing coastal erosion, Lee (1973) acknowledged that fluctuating lake levels did play a role in this widespread issue.

From 1977 to 1986 lake levels increased at an average annual rate of 0.09 m (based on data from United States Army Corps of Engineers, Detroit District, 2011, personal correspondence). This increase in lake level (Fig. 2.8) led to another wave of coastal erosion and associated property damage (Fig. 1.7). As a result, it prompted another pulse of Great Lakes coastal studies.

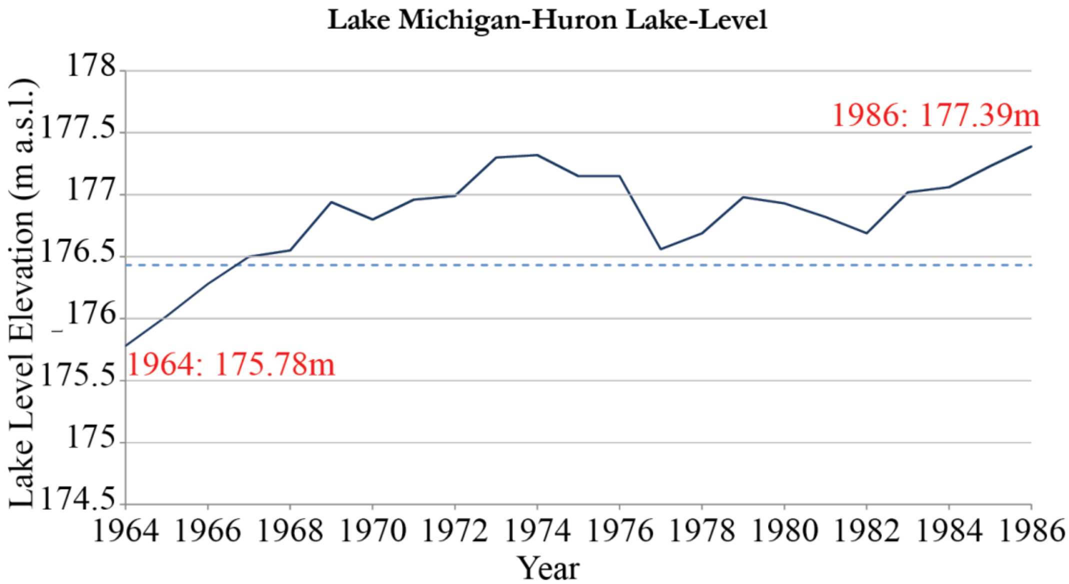



**Figure 2.8: Observed annual mean lake-level for Lake Michigan-Huron for 1964 – 1986. Data labels indicate record low (1964) and high (1986) lake-levels. (data from USACE Detroit District, 2011)**

The first of these studies was conducted by Gray and Wilkinson (1979), who investigated spatial patterns of coastal bluff recession in relation to lake level fluctuations along eastern Lake Michigan. Other variables examined were nearshore bathymetry and lithology. Recession rates were calculated from bluff positions interpreted from repeat aerial photography. Gray and Wilkinson (1973) were able to systematically relate nearshore bathymetry and lithology to each other and to observed bluff recession rates. Specifically, they found that generally coarser, gravelly areas develop gently sloping wave-cut benches and that the upper shoreface in such circumstances is covered with boulders. The gravel and boulders armor the coast from high energy waves and reduce coastal erosion. Conversely, recession was more pronounced in areas composed of finer, sandier sediments where sediment is more mobile. Additionally, differences in bathymetric profiles influenced waves reaching the coast and were correlated to spatial variation in recession rates. This nearshore bathymetric profile is influenced by sediment characteristics in the littoral substrate, which, in turn, is correlated to the lithology of the exposed onshore bluff. Gray and Wilkinson (1979) found that coastal erosion rates were heavily influenced by a combination of nearshore bathymetry and lake-level fluctuations.

The relationship between lake levels and enhanced coastal erosion along the central eastern Lake Michigan coast was further explored in two studies by Hands (1979, 1980). In the first of these investigations, Hands (1979) intensively explored the relationship between lake-level fluctuations and shoreline recession by using data collected from 1967-76 as part of a study by the U.S. Army Corps of Engineers Coastal Engineering Research Center. Using lake-level observations, coastal profiles (engineering surveying data), and multitemporal aerial photography, these studies sought to determine the importance of lake-level fluctuations on shore change rates. Plotting these variables against each other yielded important relationships. Hands (1979) concluded that 80 percent of shoreline erosion was a direct result of elevated lake levels, but that less than 20 percent of shoreline retreat was attributed to direct inundation by waves. These findings supported the conclusions of Gray and Wilkinson (1979) that wave action is not the only factor modulating shoreline retreat and that wave action may be a less significant variable than originally thought. In his follow-up study, Hands (1980) concluded that shoreline recession was directly linked to higher lake levels. In this study, he explored nearshore equilibrium profiles and changes resulting from due to lake level fluctuations. Hands (1980) proposed that shorelines respond to rising lake levels in a predictable way.

Following the work by Hands (1979, 1980), Buckler and Winters (1983) were the first to examine bluff recession rates throughout most of the Lake Michigan basin. They were particularly interested in long-term bluff recession rates over the past 127 to 147 years (dependent on data availability). Buckler and Winters (1983) evaluated coastal bluff recession rates at 118 sites in the Lake Michigan basin (56 in Michigan and 62 in Wisconsin). Observed trends in bluff recession rates were related to shorezone characteristics such as composition, shoreline orientation, and fetch distance. Retreat rates were calculated using historical General Land Office (GLO) surveys, which recorded the distance to the bluff edge along the section line from the nearest section corner or quarter-corner and then resurveying these same lines in the late-1970s. They observed that the majority of sites (106 of 118 sites) were retreating an average of 0.4 m per year. Bluffs on both sides of Lake Michigan exhibited similar retreat rates, although northern Wisconsin had lower rates than southern Wisconsin. When sediment composition was included, they found that dune-covered bluffs, common along the west coast of Lower Michigan, had lower recession rates. No relationship was found between bluff height and recession rate; however, groundwater seepage, shoreline orientation, fetch, and anthropogenic shoreline structures were correlated with variations in recession rates.

Groundwater seepage and fetch were positively correlated to recession rates. Buckler and Winters (1983) found that, along eastern Lake Michigan, shorelines oriented to the northeast retreated almost twice as fast compared to northwesterly shorelines. They attributed the high retreat rates of northeasterly oriented shorelines to a combination of northwesterly winds from large storms and the large fetch. This dichotomy supported the findings of Seibel (1972). Additionally, Buckler and Winters (1983) found that shoreline structures were extremely important in coastal progradation and erosion. Groins and jetties perpendicular to the shoreline interrupted longshore sediment transport and caused large volumes of sediment to accumulate updrift of these structures. Consequently, the downdrift zones were starved for sediment and experienced increasingly rapid shoreline retreat. Irregular distribution of these structures increased shoreline irregularity and lead to increased bluff recession in areas lacking structures. Buckler and Winters (1983) projected bluff recession rates along eastern Lake Michigan to remain high (meters per year) until lake levels decreased or erosion control structures are erected on a massive scale.

Weishar and Wood (1983) examined shorezone changes along the southeastern coast of Lake Michigan at Indiana Dunes National Lakeshore. Beach and offshore profiles were evaluated to determine the relationship between wind-wave forcing, long-term lake level fluctuation, and bathymetric profile changes. They observed a narrow, highly eroded profile during the winter, which was offset by a broader deposition-dominated profile during the summer. More than 85% of the profile variability was explained by a mean beach function, closely approximated by a smooth profile. This study concluded that the outermost nearshore bar directly varied in response to lake-level fluctuations.

Following the two previous studies, the Great Lakes region experienced several years of above average precipitation, which resulted in even higher lake-levels. Coastal erosion rates and property damage peaked in 1984 and 1985 (Angel, 1995). By October 1986, Lake Michigan-Huron reached its historical record high of 177.5 m above sea level (Fig. 2.8), after which lake levels began to decline.

The relationship between coastal bluff recession and storm events during this most recent high lake stage was investigated by LaMoe and Winters (1989) along southeastern Lake Michigan. The goal of this research was to determine the relative importance of different storm magnitudes (5-, 10-, 20-, 50-, and 100-year storms) on bluff recession rates. Recession rates at 23 sites were examined using similar methods to those employed by Buckler and Winters (1983); however, data was only collected back to 1977 and deep water wave energy probabilities were closely examined. This study by LaMoe and Winters (1989) was the first to explicitly examine how important different events are to Great Lakes coastal change. Overall, they found that recession rates were most variable between sites at shorter time scales. Results indicated that wave energy explained less than 50 percent of the variation in bluff crest recession, supporting the findings of previous research (Seibel, 1972). In other words, the cumulative effects of lower magnitude, higher frequency events are greater than rare, high-magnitude storms. This conclusion by LaMoe and Winters (1989) was employed by later studies to support the assumption that measurements taken at any particular time are not the product of a single rare high-energy event.

By 1990, historical maps and aerial photographs were widely used to investigate coastal change (Seibel, 1972; Gray and Wilkinson, 1979; Hands, 1979, 1980; Buckler and Winters, 1983; LaMoe and Winters, 1989). Anders and Byrnes (1991) investigated how errors in historical maps and aerial photographs adversely impact conclusions about shoreline change rates. This was the first comprehensive investigation of how error propagation influences results of a study. They found that historical maps and air photos were both prone to multiple sources of error. The accuracy of historical maps is most notably impacted by initial measurement errors and georeferencing inaccuracies. Air photos suffer from horizontal and vertical distortion due to radial displacement and relief distortion, as well as georeferencing inaccuracy. Interpretation of shoreline position from historical maps and air photos introduces another important error into shoreline change studies. Anders and Byrnes (1991) advocated for qualitative and quantitative discussion of error propagation when using historical maps or aerial photography to examine shoreline change. Although error propagation was seldom discussed, the information sources examined by Anders and Byrnes (1991) continued to be applied in coastal change studies throughout the Great Lakes region.

Using historical charts, maps, and aerial photographs, Jibson, et al. (1994) investigated spatial patterns of bluff recession along a 30 km section of the Lake Michigan coast in Illinois. A key component of this study was to investigate differences and similarities for two time periods: 1872 through 1937 and 1937 through 1987. The key difference between these two periods was the construction of shore-protection structures during the early 1900s. They found that erosion rates became more spatially uniform over time, but that erosion control structures had minimal impact on the overall erosion rate. Additionally, Jibson, et al (1994) concluded that spatial patterns of long-term bluff retreat rates were not due to lake-level fluctuations, as proposed by Hands (1979, 1980), but rather due to variations in shore face erosion rates. This was the first study to highlight the link between bluff retreat and shore face erosion rates.

Although previous coastal research had highlighted the importance of several factors on shore face evolution (Fox and Davis, 1973; Hands, 1979, 1980), no Great Lakes study had discussed the effects of ice cover on coastal change. The common assumption was that ice cover armors the coast and reduces coastal erosion. Barnes, et al (1994) aimed to dispel the belief that ice protects the coast against erosion, previously proposed by Davis (1973). Instead, Barnes, et al (1994) proposed that coastal ice enhances coastal erosion. They tested this hypothesis by examining several different types of ice. Great Lakes wave energy was known to be greatest during the winter (Saulesleja, 1986). Barnes, et al (1994) developed a model of nearshore erosion due to ice rafting. They proposed that ice cover along the coast displaced wave energy from the beach into nearshore sediments. Ice formation subsequently entrained coastal sediment, which was rafted alongshore and offshore by currents. Warmer spring temperatures melted the rafted ice and released the entrained sediment offshore. Detailed analysis of several types of ice indicated that more sediment was transported offshore than along the shore. This supported their hypothesis that ice cover can be an erosive force. This was the first study to demonstrate the importance of winter ice cover in long-term beach stability.

The first study to assess potential Great Lakes coastal area changes due to future lake-level change was Pendleton, et al. (2005). This study assessed change potential at three national lakeshores throughout the Great Lakes: Sleeping Bear Dunes National Lakeshore, Indiana Dunes National Lakeshore, and Apostle Islands National Lakeshore. They recognized that changes due to rising lake-levels are different than those from falling lake-levels. To account for this difference in response, the study was limited to submergent coasts where lake level was expected to drop. A change potential index (CPI) was developed to quantify a coast's susceptibility to physical change resulting from falling water levels. The CPI was based on a coastal vulnerability index (CVI) developed by Theiler and Hammar-Klose (1999). The CPI was used to quantify the importance of multiple variables contributing to coastal change. To apply the CPI to an emerging lakeshore, Pendleton, et al (2005) made the assumption that the most important factors influencing coastal change remain constant regardless of the changes in water level. They included six key factors in their analysis: geomorphology (geologic form and composition), shoreline change rate, coastal slope (extending 5 km lakeward and landward), relative lake-level change, mean annual ice cover, and mean significant wave height. Variables were normalized to a common ordinal scale, from 1 to 5, based on prior knowledge of how likely each one was to influence coastal change.  Pendleton, et al (2005) used the CPI to identify the most important variables at each of the three sites.

According to Pendleton, et al. (2005), geologic composition and coastal slope were the two most important variables at all three sites.  Mean significant wave height and coastal erosion or accretion rate were also key variables.  This was the first study to incorporate multiple variables into a predictive model of coastal change in the Great Lakes.  Results indicated that areas characterized by unconsolidated material with a low coastal slope and high wave energy were most likely to experience the greatest change (Fig. 2.9).  Pendleton, et al (2005) concluded that the CPI methodology was applicable to the Great Lakes region.

In summary, modern understanding of coastal erosion processes is the cumulative product of nearly a century of research, from the more descriptive foundations of Leverett and Taylor (1915) to the highly quantitative predictive modeling of Pendleton, et al (2005). Collectively, these studies demonstrate that coastal evolution is the product of geologic composition and stratigraphy (Buckler and Winters, 1983; Lee, 1973), lake-level fluctuations (Seibel, 1972; Hands, 1979, 1980), coastal ice dynamics (Barnes, 1994), wind and wave regime (Weishar and Wood, 1983), nearshore bathymetry (Fox and Davis, 1973; Gray and Wilkinson, 1973), and anthropogenic erosion control structures (Jibson, et al., 1994).

My research falls within the context of this body of work.  To date, only one study has compared shoreline change on both sides of Lower Michigan (Seibel, 1972), and it was limited to sites in the southern half of Lower Michigan.  Additionally, no study has applied GIS to assess coastal change on both sides of Lower Michigan.  My research will further explore spatial and temporal patterns of coastal change in Lower Michigan by employing modern GIS software and techniques.  With approximately $1.4 million spent annually on Michigan coastal management

(MDEQ, 2009), this research has the potential to provide valuable insights concerning coastal change patterns.  The methods from this study provide a framework that can be used to identify areas with the greatest historical change, and the geomorphic information can assist coastal managers to determine long-term trends in coastal evolution at these four sites.

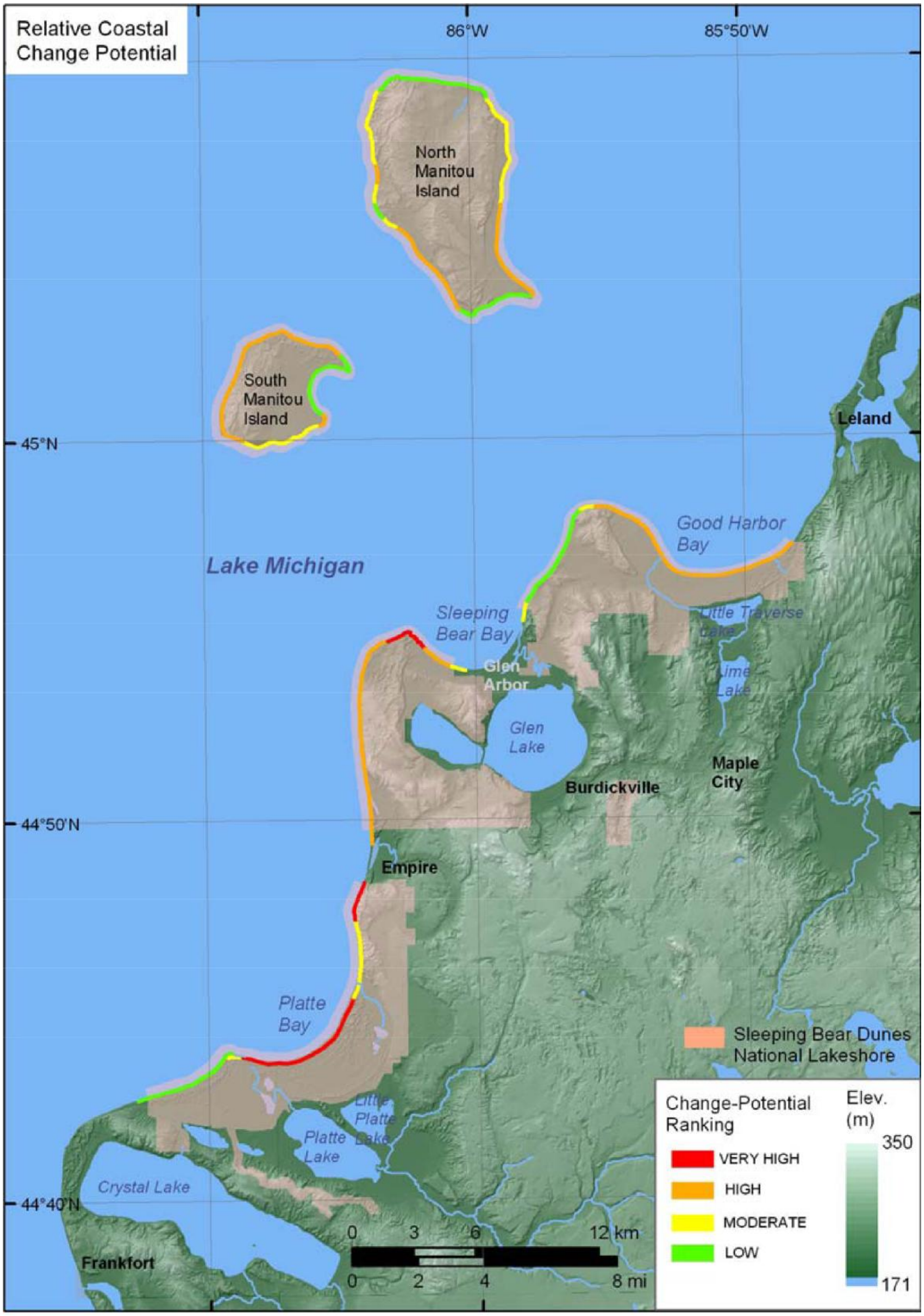



**Figure 2.9: Geography of the relative coastal change potential for Sleeping Bear Dunes National Lakeshore (Pendleton, et al. (2005).**

# CHAPTER 3: STUDY AREA

This research compares shoreline change along both sides of the Lower Michigan. Sites were selected based on their geologic composition, depth to bedrock, juxtaposition to river outlets and prominent bays, and large-scale coastline orientation. Each of the four sites was 1.5 km long, composed of sandy sediment with bedrock at a depth of more than 18 m, more than 2 km from any prominent river outlet or bay, and generally trending north-south. Sandy sediments that are not rock-defended are more prone to redistribution by wave action. Additionally, river outlets and prominent bays tend to alter the sediment budget of the surrounding coastline. Two sites were located along the Lake Michigan coastline and two sites along the Lake Huron coastline of Lower Michigan (Fig. 3.1).

## WESTERN LOWER MICHIGAN COASTLINE SITES

The northern site along the west coast of Lower Michigan (Fig. 3.1) is located approximately 6 km north of Manistee, MI in Manistee County (Fig. 3.2). This site generally lies perpendicular to the direction of onshore winds. A variety of sand dunes occur at this site, including a combination of large parabolic dunes and smaller foredunes. The beach is (Fig. 3.3) composed of sandy sediment. The depth to debrock surface in this vicinity exceeds 61 m (MDEQ, 2005).

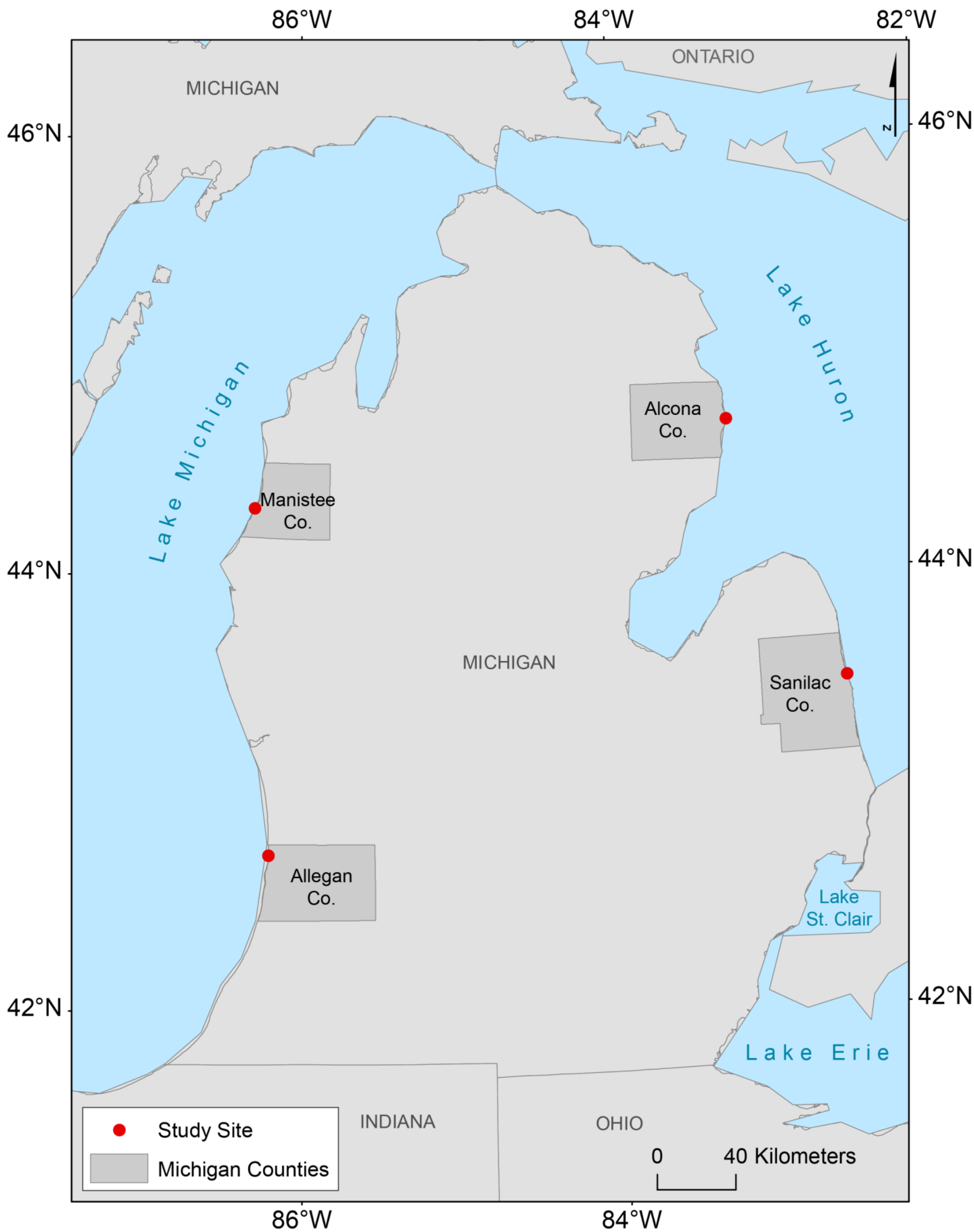



**Figure 3.1: The location of sites investigated in this study.**

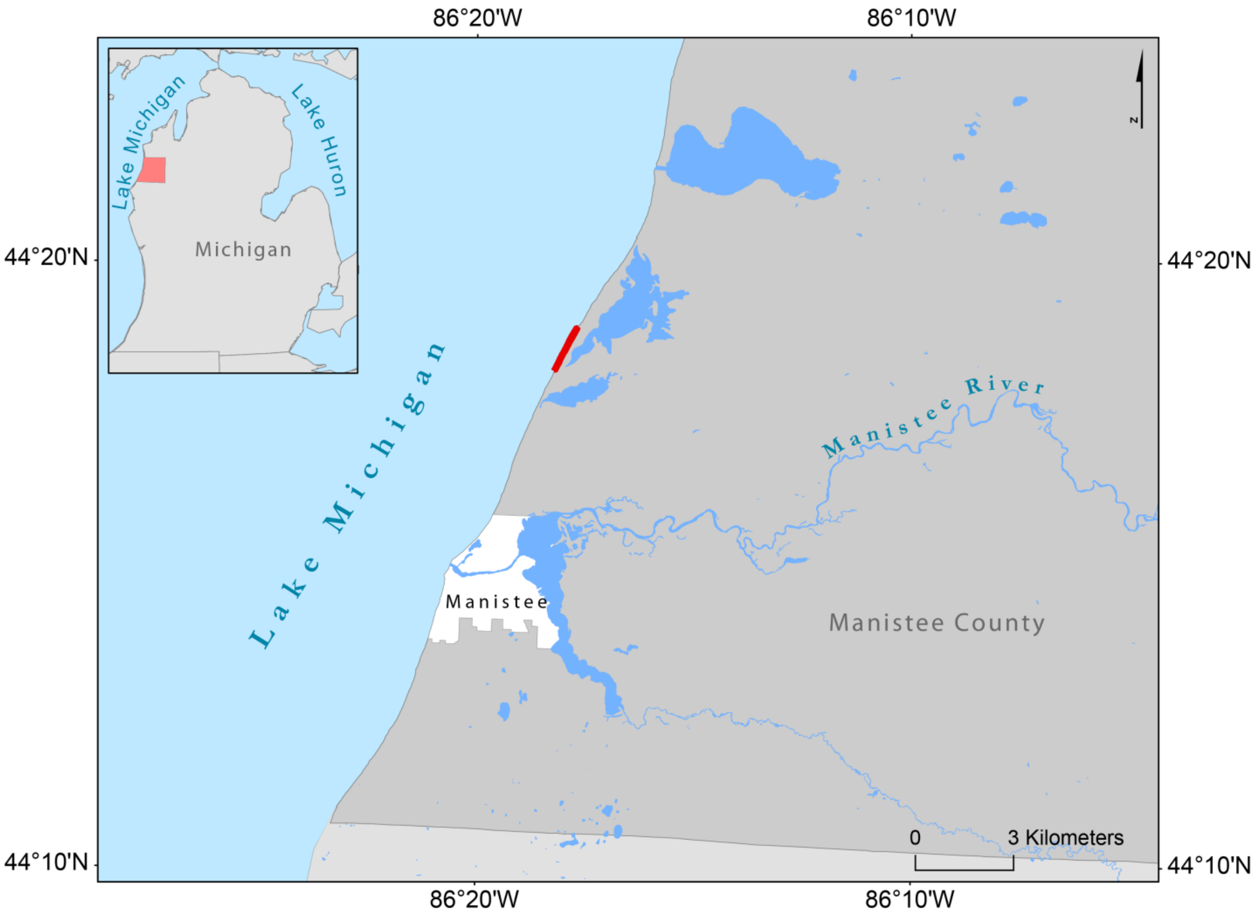



**Figure 3.2: The location of the Manistee County study site (red line).**

**Figure 3.3: A view of the beach at the Manistee County site.**
**(photo by Phil Wernette)**

The southern site along the western coast of Lower Michigan (Fig. 3.1) is centered 4.5 km south of Holland, MI in Allegan County (Fig. 3.4). Most of the coastal zone at the Allegan County site has at least one foredune (Fig. 3.5). In addition, large parabolic dunes are common along the entire stretch of coast. In places, the shoreline is directly at the toe of the parabolic dunes (Fig. 3.6). Fallen trees and slumping sands suggest recent mass movement at this site (Fig. 3.7). The depth to the bedrock surface in this area exceeds 56 m (MDEQ, 2005)

The closest weather station to the Allegan County and Manistee County sites was at the Muskegon County International Airport. The annual resultant wind direction is westerly (Fig. 3.8) with an average annual wind speed of 4.82 m/s. Wind direction and frequencies also vary by month (Fig. 3.9). The most significant easterly winds occur in the fall and early spring. Rare wind gusts up to 88.51 kph have been documented (NOAA National Climatic Data Center, 2012). Based on the geography of the Lake Michigan basin I would expect more northwesterly winds at the Manistee County site than the Allegan County site.

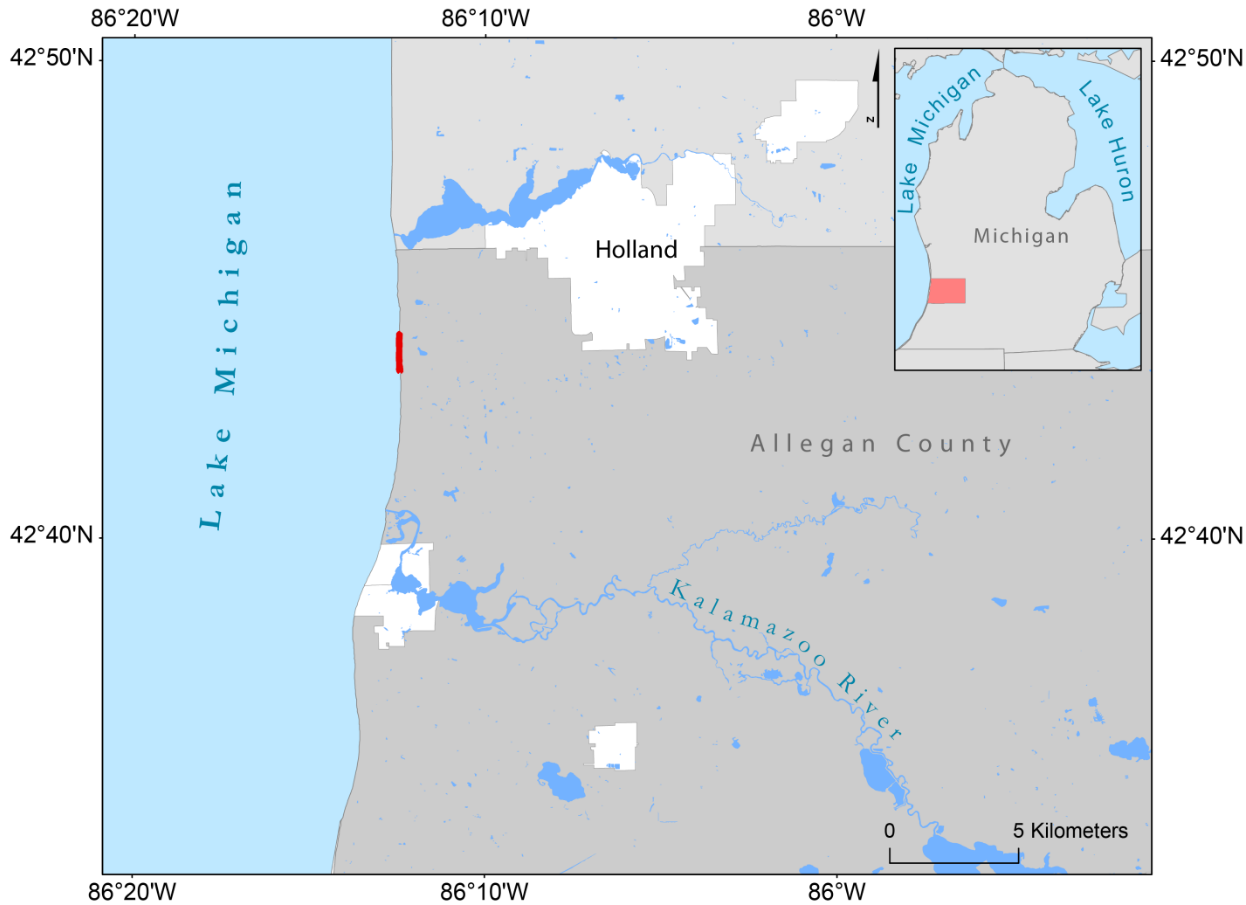



**Figure 3.4: Location of the Allegan County site (red line) in the southwest Lower Michigan (inset).**

**Figure 3.5: View of the beach at the Allegan County site.**
**(photo by Phil Wernette)**

**Figure 3.6: Example where the shoreline is directly at the toe of the large parabolic dunes. (photo by Phil Wernette)**

**Figure 3.7: Evidence of recent mass movement at the Allegan County site. (photo by Phil Wernette)**

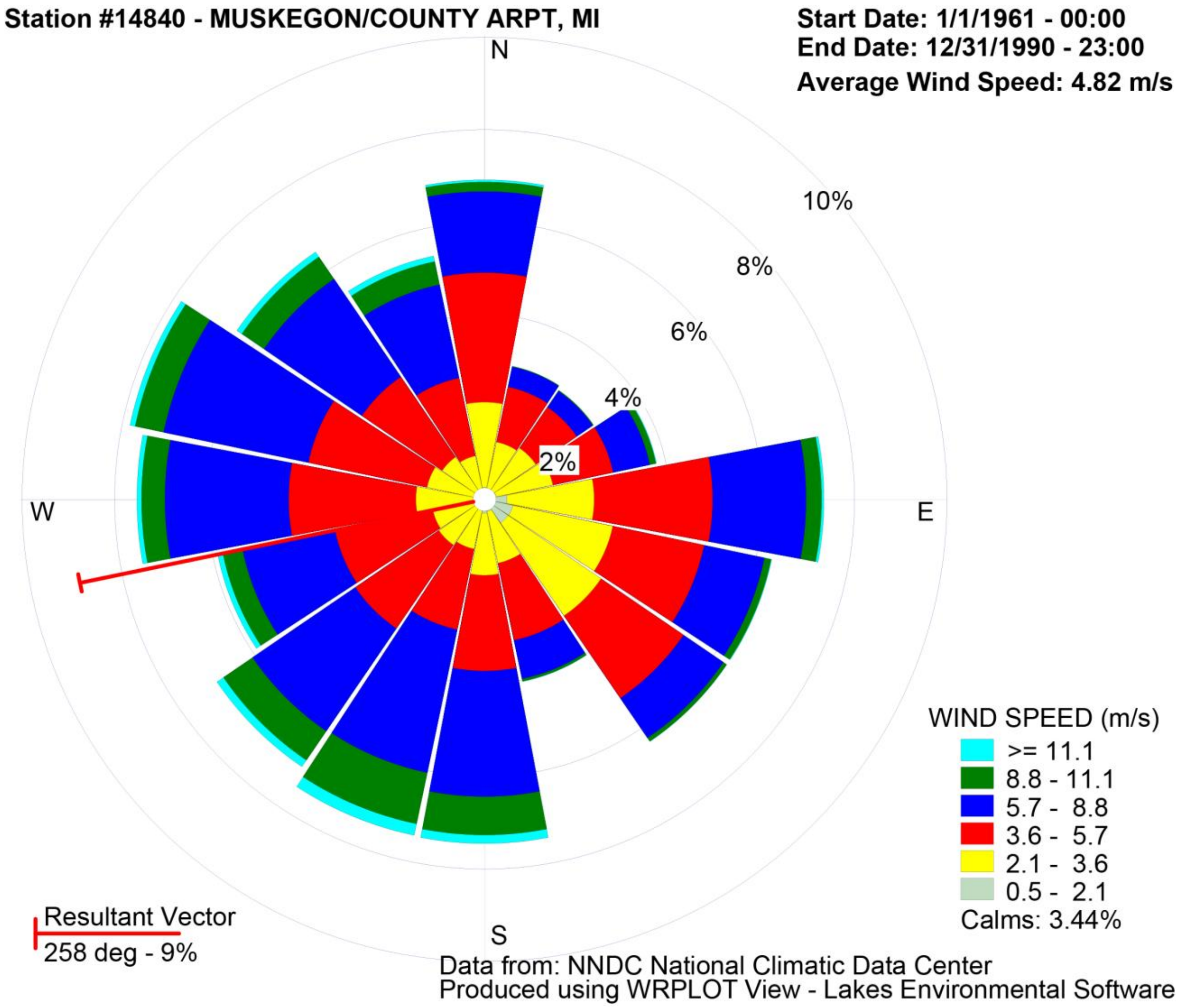



**Figure 3.8: Wind rose for Muskegon International Airport.**
**Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

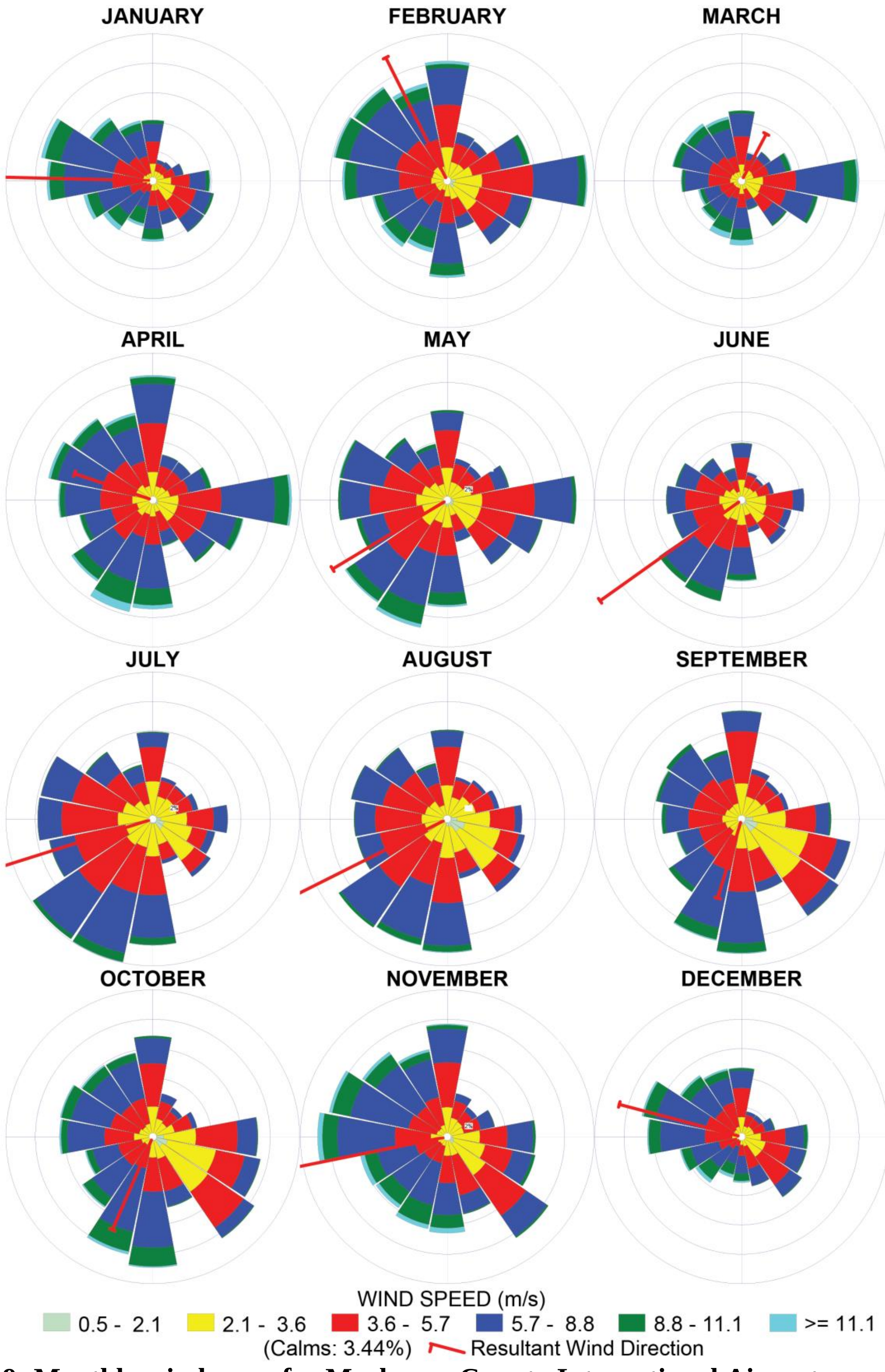



**Figure 3.9: Monthly wind roses for Muskegon County International Airport. Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

## EASTERN LOWER MICHIGAN COASTLINE SITES

The northern site along the eastern coast of Lower Michigan (Fig. 3.1) is located approximately 3 km north of Harrisville, MI in Alcona County (Fig. 3.10). Similar to the two west coast sites, foredunes were present at the Alcona County site. This site had the most extensive foredune complex of any of the four sites (Fig. 3.11). Unlike the two west coast sites, large parabolic dunes were not present at the Alcona County site. The beach was composed of sandy sediment (Fig. 3.12). In the vicinity of this site, the depth to the bedrock surface exceeds 90 m (MDEQ, 2005).

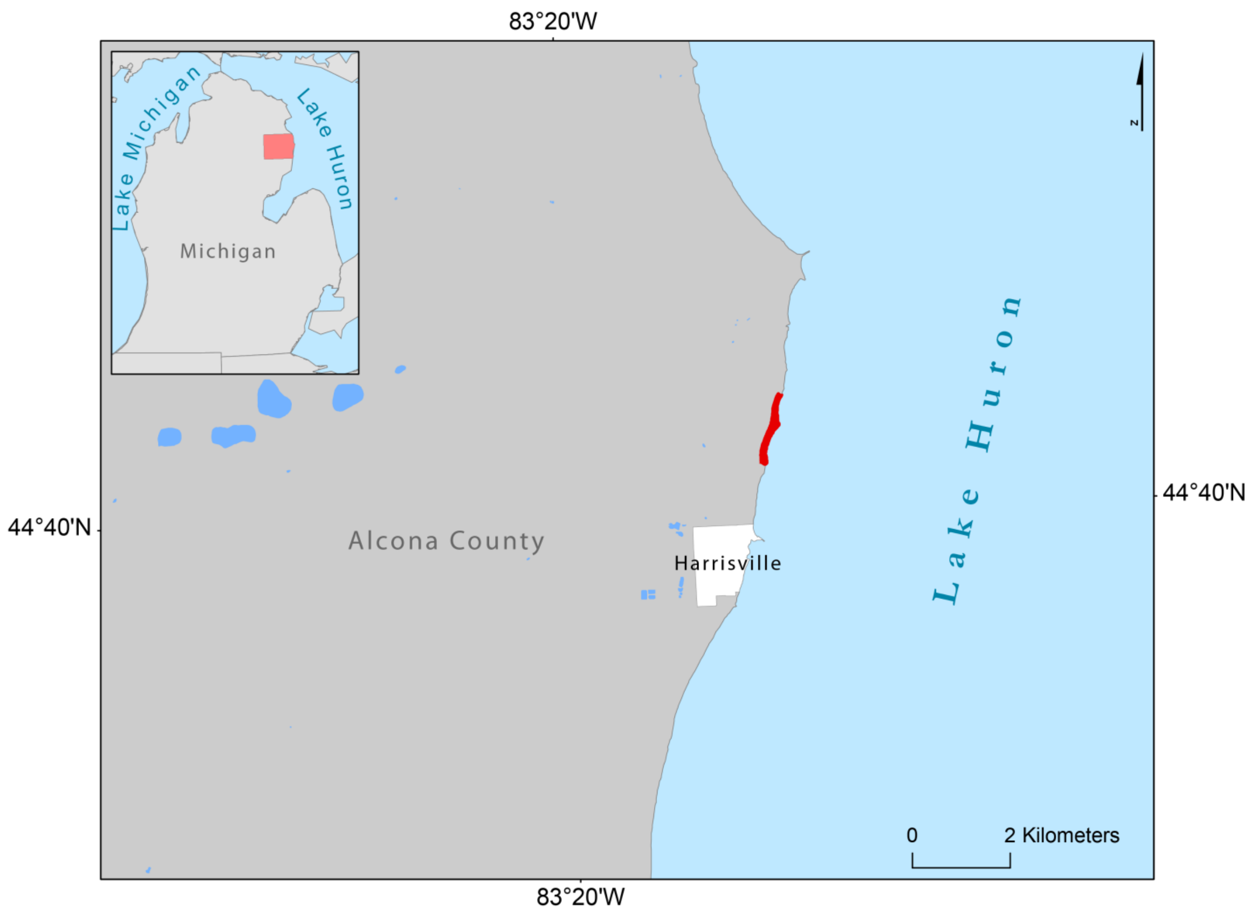



**Figure 3.10: Location of the Alcona County site (red line) in northeastern Lower Michigan (inset).**

The closest tier one weather station to the Alcona County site is located approximately 40 km north in Alpena, MI. The annual prevailing wind direction is westerly (Fig. 3.13) with a wind speed of 3.77 m/s. Wind direction and frequency vary by month and the strongest and most frequent easterly winds occur during March and April (Fig. 3.14). Rare wind gusts up to 61.15 kph have been reported at this station (NOAA National Climatic Data Center, 2012).

**Figure 3.11: Looking south along the beach at the Alcona County site. Note the extensive foredune complex present. (photo by Phil Wernette)**

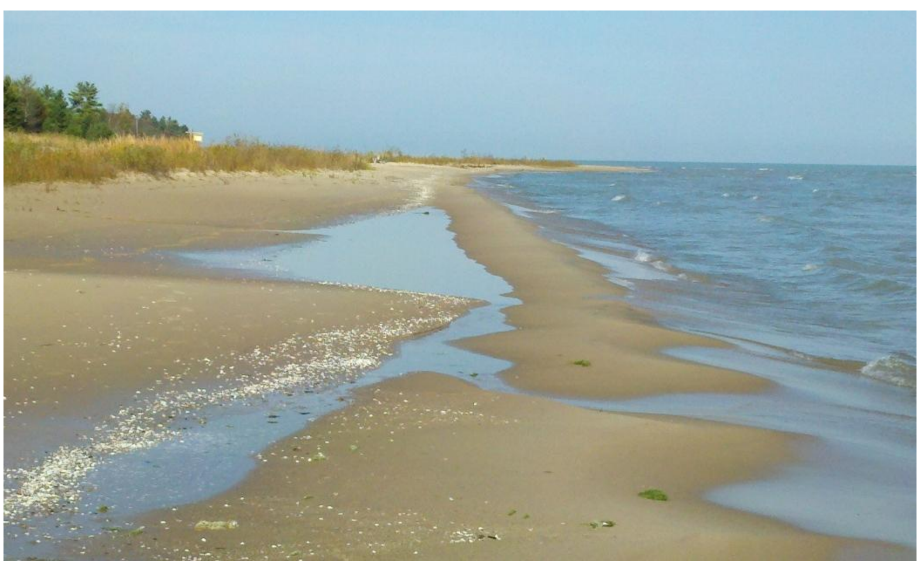


**Figure 3.12: Looking north along the beach at the Alcona County site. (photo by Phil Wernette)**

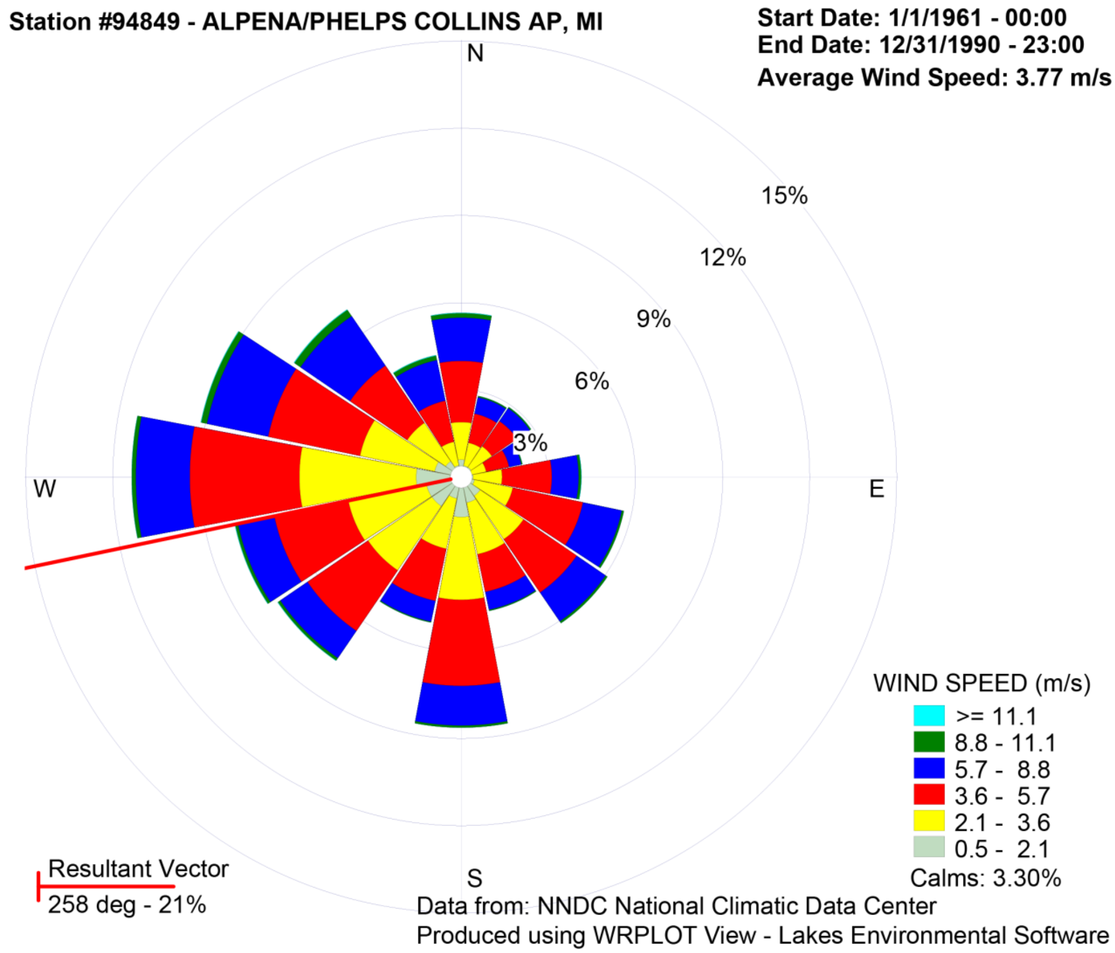



**Figure 3.13: Wind rose for Alpena, MI.**
**Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

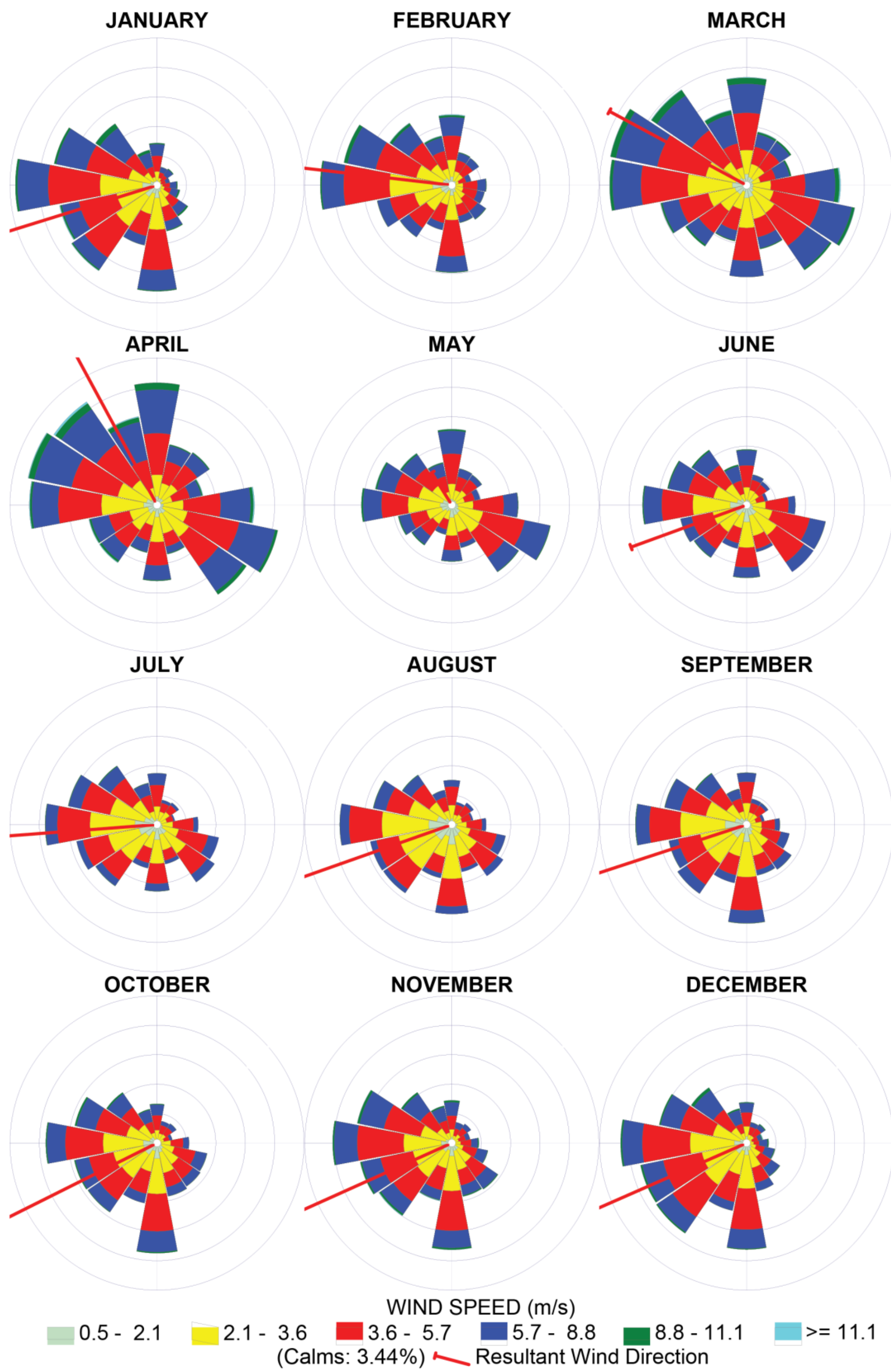



**Figure 3.14: Monthly wind roses for Alpena, MI.**
**Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

The southern site along the east coast of Lower Michigan (Fig. 3.1) is approximately 5.5 km north of Port Sanilac, MI in Sanilac County (Fig. 3.15). In contrast to the other study sites, this locale is noteworthy because it has the most extensive residential development. As a result, a large majority of the properties along this site have some form of erosion mitigation structure erected (Fig. 3.16). Unlike the other three sites, dunes were completely absent at the Sanilac County site. Gravel and large rocks were much more prevalent along the entire stretch than at any of the three other sites (Fig. 3.17).

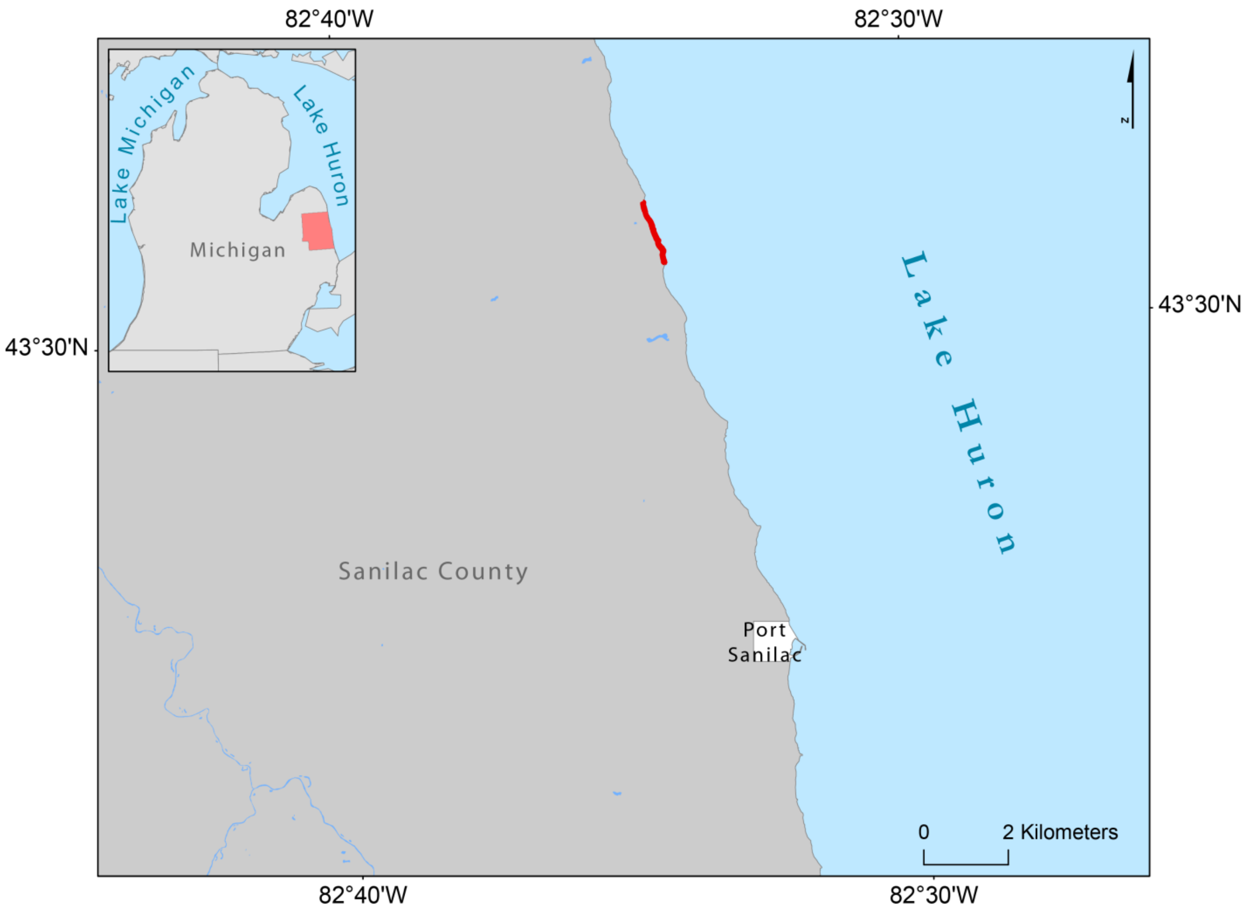



**Figure 3.15: Location of the Sanilac County site (red line) in east-central Lower Michigan (inset).**

Wind data near the Sanilac County site was not available, nor was there a station within 100 km of this site. The closest weather station was located approximately 110 km west in Flint, MI. Prevailing wind direction at this station was westerly (Fig. 3.18) with an average speed of 4.40 m/s. Similar to weather data for the other sites, the Flint weather station data showed monthly variation in wind direction and frequency (Fig. 3.19). Rare wind gusts up to 61.15 kilometers per hour have been recorded at this station (NOAA National Climatic Data Center, 2012).

A) 

B) 

**Figure 3.16: Seawalls and other erosion control structures at Sanilac County site. A) Looking north at the prominent groins along the coast. B) In addition to groins, there are large portions where sea-walls are present. (photos by Phil Wernette)**

**Figure 3.17: View of the rocky beach at the Sanilac County site.**
**(photo by Phil Wernette)**

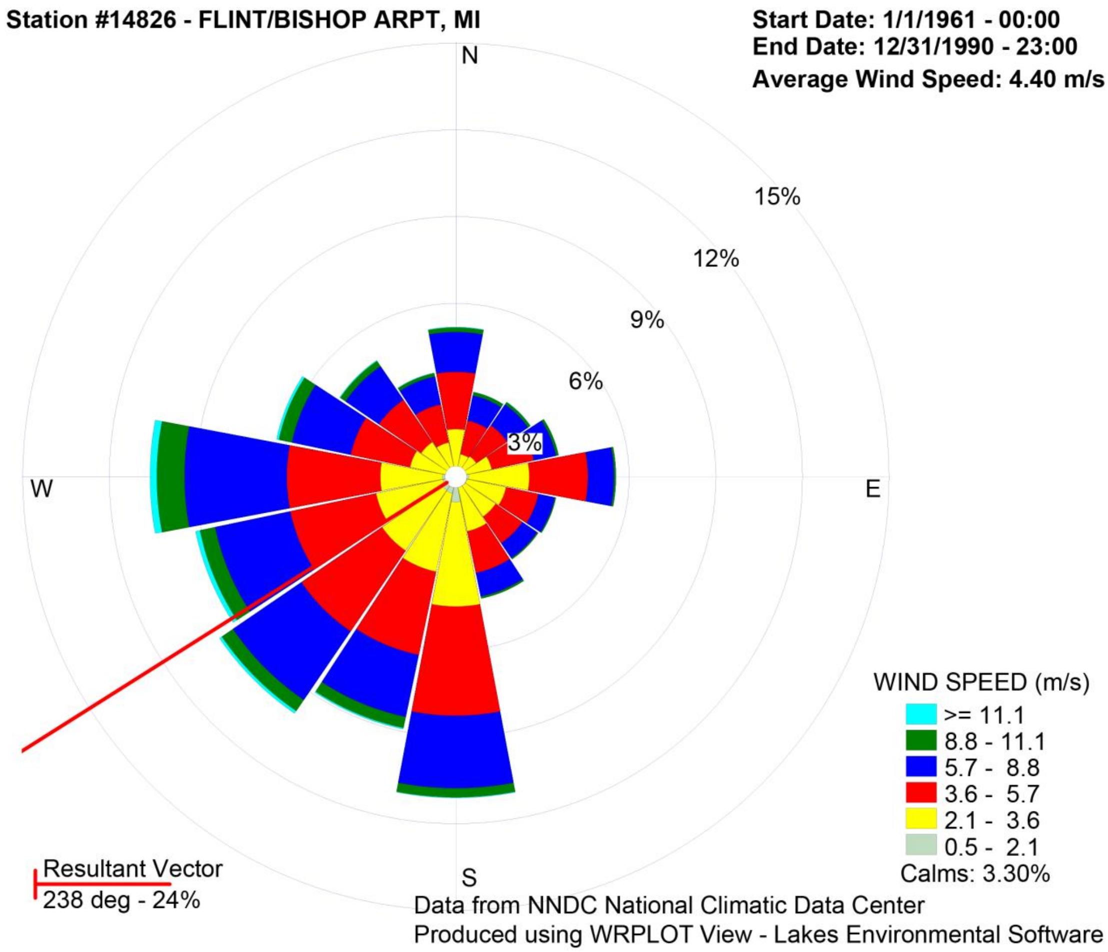



**Figure 3.18: Wind rose for Flint, MI**
**Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

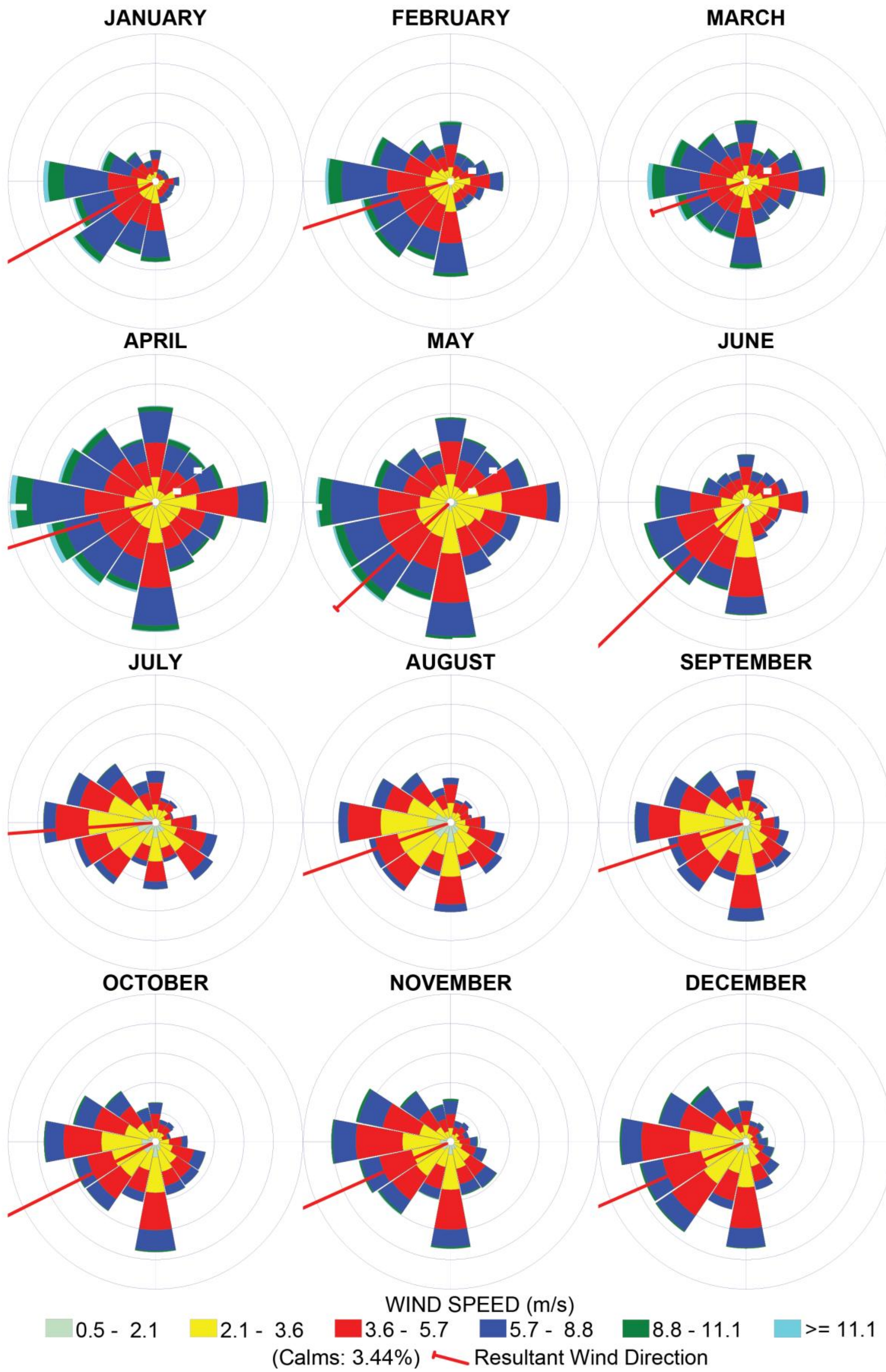



**Figure 3.19: Monthly wind roses for Flint, MI**
**Wind speed is indicated by color. Wind direction and frequency are indicated by the vector of each spoke. The resultant wind direction is indicated by the vector of the solid red line. Data from NOAA National Climatic Data Center, 2012; produced using WRPLOT View Software, 2012.**

In summary, each of the four coastline study segments was selected based on its geologic composition, depth to bedrock, juxtaposition to river outlets and bays, and general coastline orientation. No site was within several kilometers of a prominent erosion control structure such as large groins or jetties that protrude into the lake. Extensive erosion mitigation structures were only present at the Sanilac County site (Fig. 3.16). The area around each of the four sites was classified as ‘dune sand’ by a Quaternary Geology of Michigan map (Farrand and Bell, 1982), although field observations revealed that the Sanilac County site had significantly more gravel, cobbles, boulders (Fig. 3.17). In the vicinity of this site, the depth to the bedrock surface was the shallowest of any of the sites, but still exceeds 18 m (MDEQ, 2005).

# CHAPTER 4: METHODS

In order to assess historical shoreline change at each of the study sites, shoreline position was interpreted at several points in time. The methodology used to accomplish this task was based on the interpretation of shoreline position using aerial imagery. Air photo interpretation is well documented in previous coastal research (Seibel, 1972; Hands, 1979, 1980; Buckler and Winters, 1983, LaMoe and Winters, 1989; Anders and Byrnes, 1991; Pendleton, et al., 2005).

## AERIAL IMAGE SELECTION

Aerial images used in this research were chosen from the earliest available, the onset of air photo acquisition in Michigan in 1938 and at various time intervals until 2010 (Table 4.1). The specific years were selected based on four criteria: availability, image type (i.e., panchromatic/true color versus infrared), photo scale, and image contrast.

This research used images that were taken at all four sites during the same month (July). Imagery acquired in July was preferred because large storms are least likely during July, which means that extreme shifts in wind and wave regime are rare. In an effort to minimize differences in environmental conditions from year to year, I attempted to obtain images for each site that were acquired within 5 years of the images that were selected for the other sites. This was not always possible. Across all four sites, the mean time difference between images was approximately 8 years, with a maximum difference of 24 years. Imagery taken during the same month and year at all four sites was available for four years (1998, 2005, 2009, and 2010).

To qualify for the study, the imagery also had to be panchromatic, either black and white or true color, and have a minimum photo scale of 1:47,000. Limiting the candidate imagery to panchromatic ensured that the image characteristics used for air photo interpretation and shoreline delineation were consistent (see the image exposure discussion below). Images with a scale smaller than 1:47,000 were not used because important small landscape features were not resolvable at these smaller scales.

The final requirement was that the image exposure not be too dark or light. Unvegetated, sandy sediment is highly reflective, often resulting in overexposure of part of the image. Overly bright beach sediments artificially brighten the water. These overly bright images often lack the clear land-water contrast necessary to accurately delineate the shoreline.

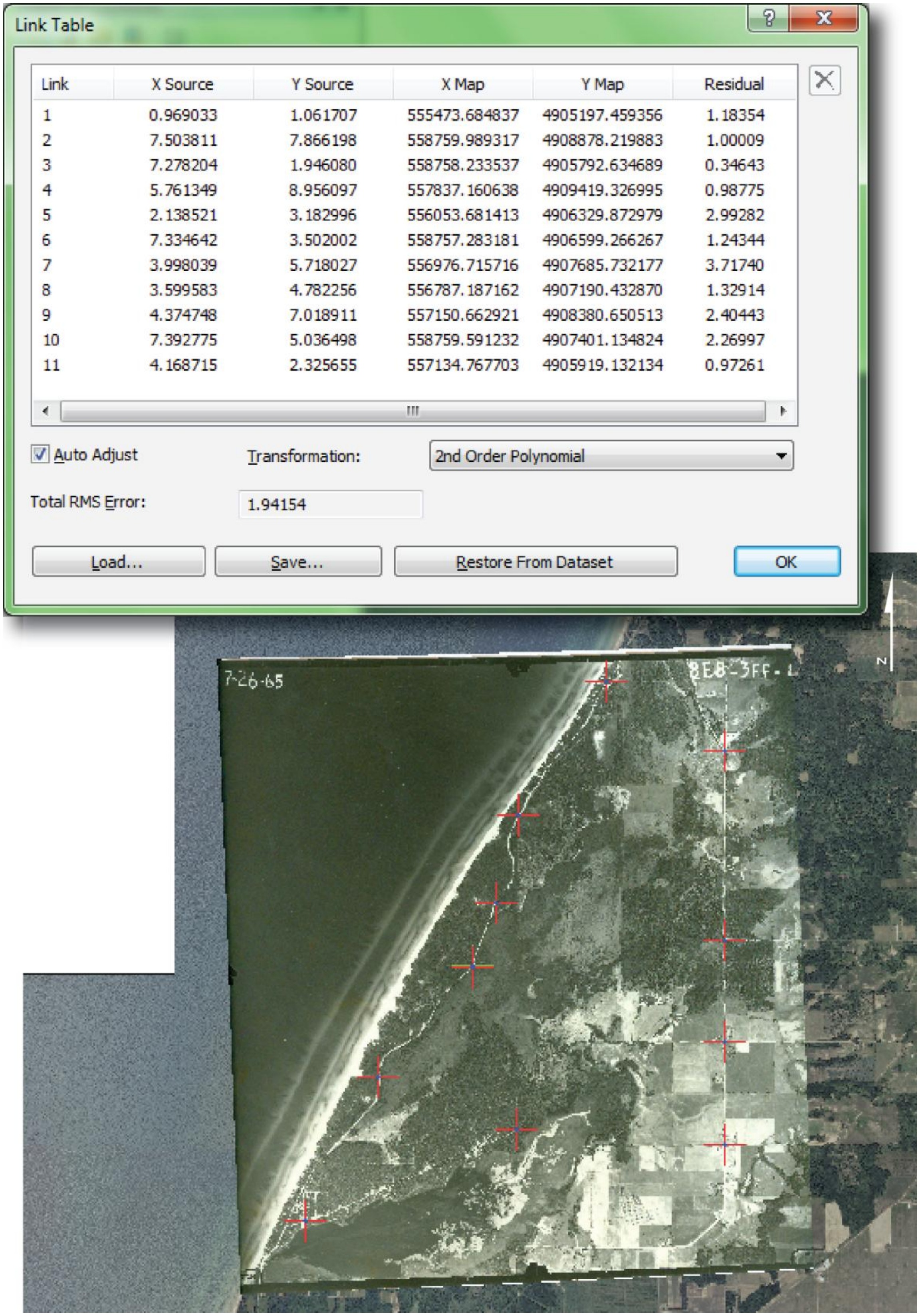
## SHORELINE DELINEATION PROCESS AND UNCERTAINTY

A geographic information system (GIS) was used to assist in the interpretation of the shoreline position from the various aerial images. Images acquired in 1992 were already available in digital format; however, pre-1992 imagery was only available in hard copy form. To convert the analog images into a digital format, they were first scanned at high-resolution (at least 600 dpi) to obtain a digital image with at least a 1-meter resolution. The resulting digital images were then georeferenced to the 2010 NAIP imagery using ArcGIS 10. A minimum of 10 geographically distributed ground control points (GCPs) were used to reference the scanned historical images to the 2010 imagery (Fig. 4.1). GCPs consisted of low-elevation features with minimal radial distortion that appeared stable through time (e.g. persistent road intersections).

The maximum root-mean square error (RMSE) among all the georeferenced images was less than 3 m. The most complex transformation used was a second-order polynomial (Table 4.1). Higher-order transformations typically introduce artificial folds into the georeferenced surface, resulting in a highly distorted image. Since the historical aerial imagery was georeferenced to the 2010 imagery, the 2010 RMSE (6 meters RMSE; USDA, 2011) was added to the georeferencing RMSE of the historical imagery. The sum of both uncertainties represents a worst-case scenario where errors are in the same direction (Zeng and Crowell, 1999; Zhang and Goodchild, 2002).

$$Image\ Accuracy\ (at\ 95\%) = 1.7308 * Image\ RMSE \qquad [4.1]$$

RMSE is the "square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points" (FGDC, 1998). In accordance with the National Standards for Spatial Data Accuracy (NSSDA) specifications, a more appropriate horizontal accuracy standard is calculated by multiplying the raw RMSE by 1.7308 (Equation 4.1; FGDC, 1998). This results in an RMSE with a 95% confidence level (Table 4.1). Equation 4.1 assumes that the errors are normally distributed in both the X and Y directions and are independent of one another (Greenwalt and Schultz, 1968; Congalton and Green, 2009).



| Link | X Source | Y Source | X Map | Y Map | Residual |
|---|---|---|---|---|---|
| 1 | 0.969033 | 1.061707 | 555473.684837 | 4905197.459356 | 1.18354 |
| 2 | 7.503811 | 7.866198 | 558759.989317 | 4908878.219883 | 1.00009 |
| 3 | 7.278204 | 1.946080 | 558758.233537 | 4905792.634689 | 0.34643 |
| 4 | 5.761349 | 8.956097 | 557837.160638 | 4909419.326995 | 0.98775 |
| 5 | 2.138521 | 3.182996 | 556053.681413 | 4906329.872979 | 2.99282 |
| 6 | 7.334642 | 3.502002 | 558757.283181 | 4906599.266267 | 1.24344 |
| 7 | 3.998039 | 5.718027 | 556976.715716 | 4907685.732177 | 3.71740 |
| 8 | 3.599583 | 4.782256 | 556787.187162 | 4907190.432870 | 1.32914 |
| 9 | 4.374748 | 7.018911 | 557150.662921 | 4908380.650513 | 2.40443 |
| 10 | 7.392775 | 5.036498 | 558759.591232 | 4907401.134824 | 2.26997 |
| 11 | 4.168715 | 2.325655 | 557134.767703 | 4905919.132134 | 0.97261 |



**Figure 4.1: Sample distribution of GCPs and RMSE of georeferenced image for Manistee County site.**

The shoreline was delineated from imagery based on tonal contrast at the land-water interface. Water has a low spectral reflectivity relative to dry bare sand. This high moisture decreases the spectral reflectivity of the wetted beachface sands (e.g. Fig. 4.2; Balsam, et al., 1998, Li, et al., 2005). Consequently, the wetted beachface appears darker than the dry beach due to the high water content (low reflectivity) of the lower beachface. This change occurs over a narrow zone that can clearly be delineated by manual photogrammetric interpretation. This line, the HWL, is the best indicator of the shoreline for historical change studies (Crowell, et al., 1991; Boak and Turner, 2005). Shoreline position varies based on the photointerpreter (Edwards, 1999; Zhang and Goodchild, 2002).

**ASSESSING DELINEATION BIAS**

In order that the uncertainty analysis includes the possible bias in my shoreline delineations, two GIS/remote sensing professionals were asked to delineate the shoreline for three images at the Alcona County site. This resulted in 6 professionally-delineated shorelines (3 years selected for delineation for each of the 3 professionals). Using 20 transects at right angles to an on-shore baseline, the professionally-delineated shorelines were then compared to my shorelines for the same years (all delineations were strictly independent). The mean bias of my delineations compared to the 6 professionally-delineated Shorelines was 0.6656 ± 1.4689 m. In order to have the delineation bias match the 95% accuracy of the imagery, 2 standard deviations were added to the mean delineation bias. This 95% accuracy bias of 3.was then added to the image accuracy (Equation 4.2). The uncertainty for each shoreline was calculated by summing the uncertainties of the images and the delineation bias. The resulting shorelines were analyzed using a combination of two methods: dual epsilon bands, and traditional transects.

| Site | Year | # GCPs | Reference Image RMSE (m) | Georeference RMSE (m) | Cumulative RMSE (m) | Horizontal Accuracy 95% (m) | Delineation Bias 95% (m) | Shoreline Accuracy 95% (m) |
|---|---|---|---|---|---|---|---|---|
| Alcona County site | 1938 | 10 | 6.00000 | 0.92152 | 6.92152 | 11.97977 | 3.60250 | 15.58227 |
| | 1952 | 10 | 6.00000 | 1.45291 | 7.45291 | 12.89950 | 3.60250 | 16.50200 |
| | 1963 | 10 | 6.00000 | 2.74427 | 8.74427 | 15.13458 | 3.60250 | 18.73708 |
| | 1979 | 12 | 6.00000 | 2.50530 | 8.50530 | 14.72097 | 3.60250 | 18.32347 |
| | 1992 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 1998 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2005 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2009 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| | 2010 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| Allegan County site | 1938 | 12 | 6.00000 | 1.67249 | 7.67249 | 13.27955 | 3.60250 | 16.88205 |
| | 1950 | 10 | 6.00000 | 1.60018 | 7.60018 | 13.15439 | 3.60250 | 16.75689 |
| | 1960 | 10 | 6.00000 | 2.08686 | 8.08686 | 13.99674 | 3.60250 | 17.59924 |
| | 1967 | 11 | 6.00000 | 1.85843 | 7.85843 | 13.60137 | 3.60250 | 17.20387 |
| | 1974 | 10 | 6.00000 | 2.77565 | 8.77565 | 15.18890 | 3.60250 | 18.79140 |
| | 1998 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2005 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2009 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| | 2010 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| Manistee County site | 1938 | 11 | 6.00000 | 2.46109 | 8.46109 | 14.64445 | 3.60250 | 18.24695 |
| | 1952 | 10 | 6.00000 | 1.74115 | 7.74115 | 13.39838 | 3.60250 | 17.00088 |
| | 1965 | 11 | 6.00000 | 1.94154 | 7.94154 | 13.74522 | 3.60250 | 17.34772 |
| | 1973 | 10 | 6.00000 | 1.89042 | 7.89042 | 13.65674 | 3.60250 | 17.25924 |
| | 1992 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 1998 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2005 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2009 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| | 2010 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| Sanilac County site | 1941 | 10 | 6.00000 | 0.67863 | 6.67863 | 11.55937 | 3.60250 | 15.16187 |
| | 1955 | 12 | 6.00000 | 1.38623 | 7.38623 | 12.78409 | 3.60250 | 16.38659 |
| | 1963 | 10 | 6.00000 | 0.59682 | 6.59682 | 11.41778 | 3.60250 | 15.02028 |
| | 1982 | 12 | 6.00000 | 2.60146 | 8.60146 | 14.88741 | 3.60250 | 18.48991 |
| | 1998 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2005 | - | 10.14984 | - | 10.14984 | 17.56734 | 3.60250 | 21.16984 |
| | 2009 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |
| | 2010 | - | 6.00000 | - | 6.00000 | 10.38480 | 3.60250 | 13.98730 |

**Table 4.1: Calculated accuracy of each aerial image that was used in this research.**

## GEOPROCESSING

The epsilon band, also known as the Perkal band (Perkal, 1966), has been used to represent uncertainty (Blakemore, 1984; Goodchild and Min-hua, 1988; Goodchild, et al., 1995; Bruce, 2005) and assess the accuracy of geographic information (Goodchild and Hunter, 1997) for many years. An epsilon band is a buffer around a feature with radius epsilon (Perkal, 1966; Blakemore, 1984) representing the positional uncertainty of the feature. One advantage of this technique is that it is an effective tool to cartographically display the uncertainty of a feature.

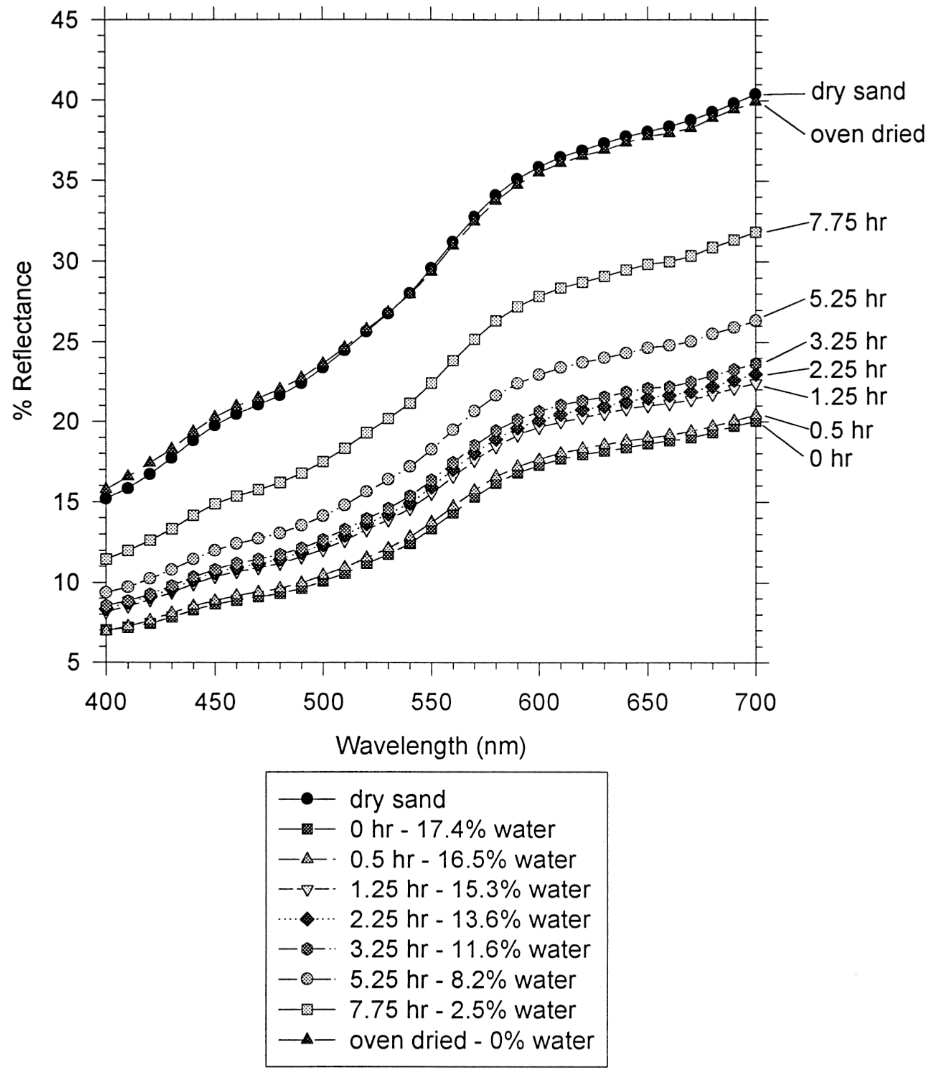



**Figure 4.2: Influence of water content on spectral reflectance of beach sand composed of 150-250 µm sized grains.**
**(from Balsam, et al., 1998, page 186)**

$$Shoreline\ Accuracy = (0.6646\ m + 2 * 1.4689\ m) + Image\ Accuracy \quad [4.\ 2]$$

In this research, epsilon bands and traditional transects were used to analyze shoreline change (Fig. 4.3). An epsilon band was used to represent the positional uncertainty associated with each shoreline delineation. The first step in the epsilon band analysis was to calculate the uncertainty associated with the aerial image (see Shoreline Delineation Process and Uncertainty in Chapter 4). Next, a buffer was generated around shoreline A with radius equal to the uncertainty of the imagery for year A (e.g. blue area in Fig. 4.4). This step is repeated for shoreline B with uncertainty equal to that of the imagery for year B (e.g. red area in Fig. 4.4). These buffers were then merged into a single area and the area of this merged buffer ($AB_{TOTAL}$) was then calculated (e.g., purple area in Fig. 4.5). To determine how much change has occurred from year A to year B, the two buffers were intersected (e.g., bright red area in Fig. 4.5). This overlapping area ($AB_{INTERSECT}$) was divided into the total area of A and B ($AB_{TOTAL}$). The resulting value represents the proportion of the area that is shared by the buffers around shoreline A and shoreline B. A large shared proportion indicates that the two shorelines have a large area in common and that the observed change is more likely to be influenced by uncertainty. This process was repeated for each possible temporal pairwise combination of shorelines at each site (see Appendix A for complete python script).

The epsilon band approach was used to identify the proportion of shoreline change from year A to year B, assuming that positional errors are normally distributed in the X and Y positions. If the proportion of similarity was smaller than the threshold proportion then the observed change is significant. It is important that the researcher appropriately defines this threshold based on their objectives. Conservative measures of change are represented by the lower thresholds such as 0.05 and 0.10. These low thresholds are the most conservative and least likely to indicate significant change has occurred. In contrast, higher thresholds represent more liberal tests of significant change. For this study I explored how the 0.00, 0.05, 0.10, 0.20, 0.30, 0.40, and 0.50 significance thresholds affected which changes were evaluated as significant.

One advantage of using dual epsilon bands to determine the level of significance of shoreline changes is that it examines change along the entire length of shoreline, while still accounting for positional uncertainty of each shoreline. Each shoreline was treated as a single observation, and each observation (e.g. 1938 shoreline, 1952 shoreline, 1974 shoreline, etc.) was considered independent. The second advantage of the epsilon band analysis, as it is used in this research, is that highlights areas where the shoreline is most stable. These are the intersected areas of the buffers around shorelines A and B. These areas indicate areas of the shoreline that have changed the least from year A to year B. The most significant limitation of the dual epsilon bands approach is that it does not provide information about the magnitude or direction of change from year A to year B.

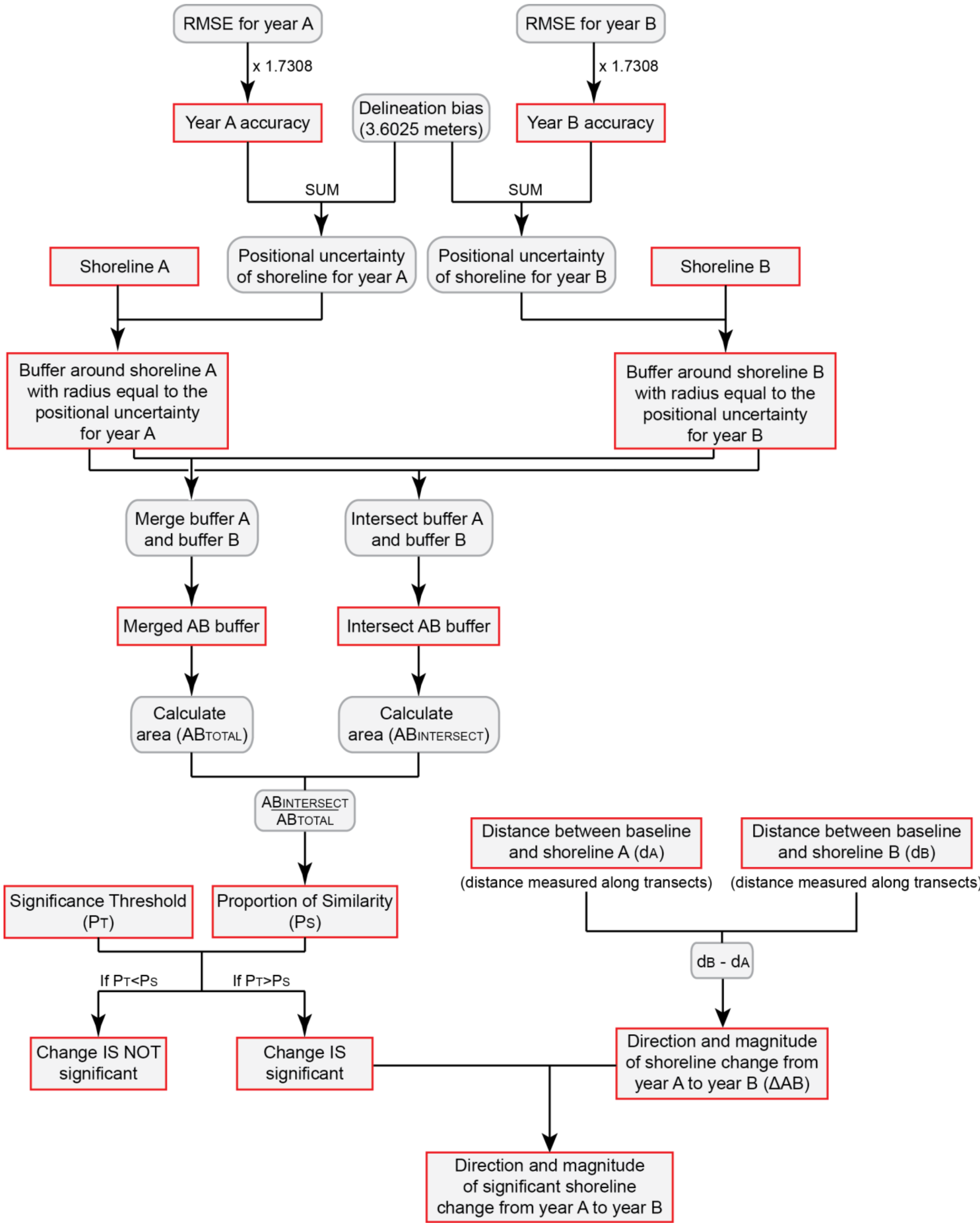



**Figure 4.3: Geoprocessing model used to identify the significance, direction, and magnitude of shoreline change from one year to another.**
**Red bordered boxes indicate GIS objects or key values. Gray bordered boxes represent processes.**

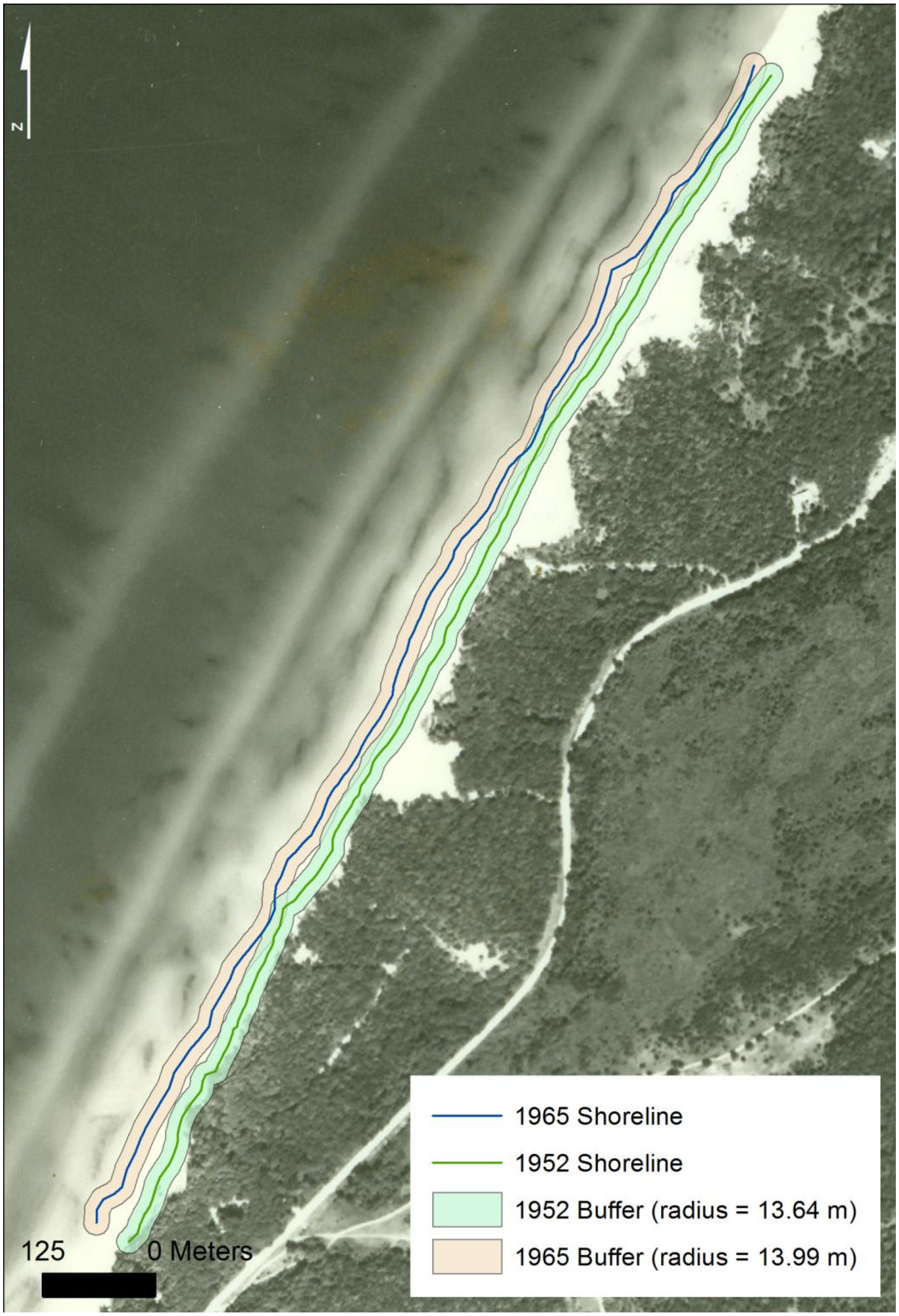



**Figure 4.4: Use of dual epsilon bands to analyze shoreline change (part 1). The first step of the dual epsilon band analysis is to generate a buffer around each shoreline with a radius equal to the uncertainty for that year.**

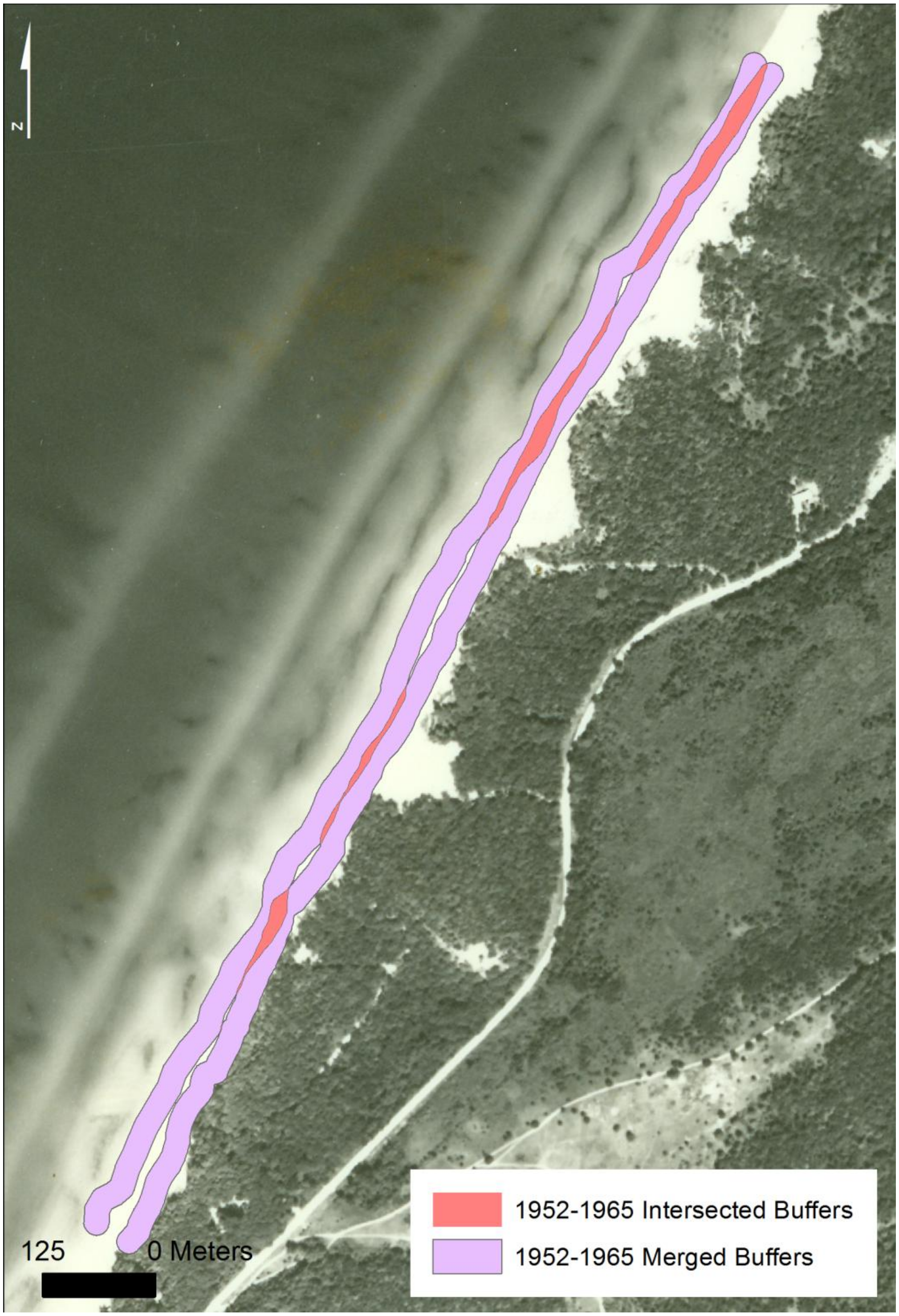



**Figure 4.5: Use of dual epsilon bands to analyze shoreline change (part 2).**
**The second step of the dual epsilon band analysis is to merge the two buffers and calculate the area of this merged area (purple and red area). In this figure, the merged area (purple) continues under the red areas. The third step is to intersect the two buffers and sum the areas of intersect regions (red in this figure).**

To calculate the magnitude and direction of change the traditional transect method was applied (Fig. 4.6). This method has been used in previous coastal change studies (Anders and Byrnes, 1991; Crowell, et al., 1991; Burroughs and Tebbens, 2008; Barnhardt, et al., 2009; Hapke, et al., 2009) and treats each transect-shoreline intersection as an independent observation. The primary issue with this assumption is that longshore drift redistributes sediment from one shoreline reach to an adjacent shoreline reach; as a result, the samples may not be independent. To test for spatial autocorrelation in the transect datum, variograms were produced for each year at each site using the R statistical software (R Development Core Team, 2011). If transect measurements were spatially autocorrelated, the variogram should have a clear form with a nugget, sill, and range. In the proposed shoreline analysis method, the transect method was only used to determine direction and magnitude of change.

In the traditional transect method, a shore-parallel baseline is first constructed immediately onshore at each of the research locations. Individual transects are then constructed at right angles to this baseline (Fig. 4.6). In this research, transects were spaced 75 m apart resulting in a total of 20 transects per site. At each transect, the distance from the baseline to each intersecting shoreline was calculated (see Appendix B for transect analysis script). The direction and magnitude of change were calculated by subtracting the distance from the baseline to shoreline A from the distance from the baseline to shoreline B. Negative values indicated that the shoreline at time B was landward from where it was at time A. In this study, landward refers to a change in which the shoreline at time B is farther inland than where it was at time A. Conversely, a lakeward change in shoreline position is one where the shoreline at time B is more towards the center of the lake than it was at time A.

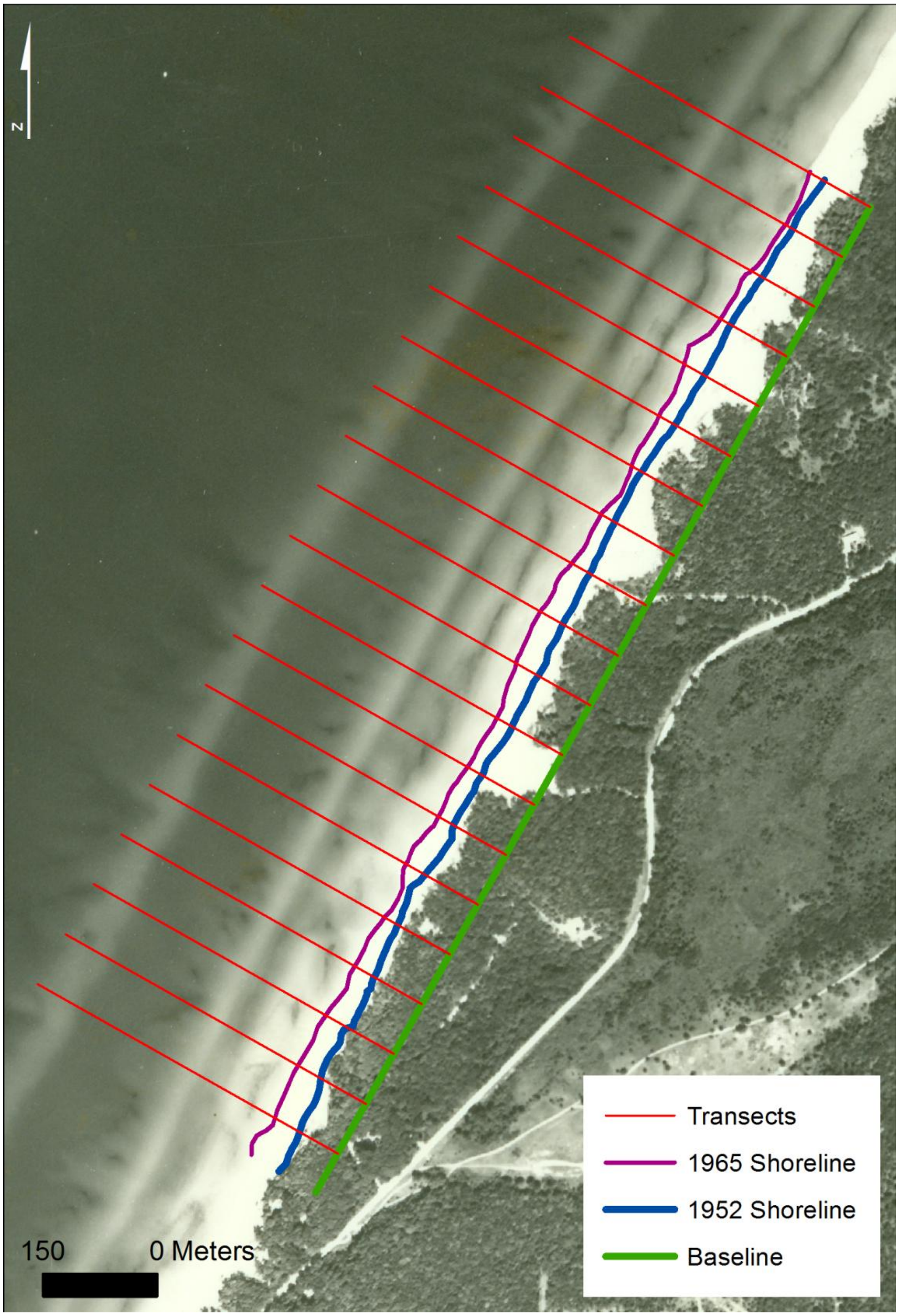



**Figure 4.6: Traditional transect example.**
**This is one example of how traditional transects were used to determine the direction and magnitude of shoreline change at the Manistee County site between 1952 and 1965. Transects are spaced 75 m apart.**

In addition to identifying the significance, direction, and magnitude of change, this study further explored the relationship between lake-level fluctuations and observed shoreline change by using simple linear regression. The shoreline position was regressed against lake level for each pair of years. This regression was run for each site, as well as for a combined dataset with all of the data. The advantage of using linear regression for this analysis is that it is relatively straightforward to implement and the resulting statistics provide insight about the direction and strength of the relationship.

# CHAPTER 5: RESULTS

This chapter presents the results of this research. All values are presented with one standard deviation ranges. Results are organized by site with the west coast sites first, followed by the two east coast sites. Within each site, the results are presented first without any significance test because this is the traditional approach to shoreline change studies. A variogram for each set of shoreline-transect data is presented to test for spatial autocorrelation within shoreline position. The results of the linear regression relating shoreline position and lake level are then presented.

Following the analysis of the raw transect data, six thresholds (0.05, 0.10, 0.20, 0.30, 0.40, and 0.50) were applied to explore which measured changes were significant at each threshold. Additionally, this analysis will help determine the relationship between the significance threshold and the number of significant change pairs. Each of the significance tests compares the proportion of similarity to the significance threshold to determine the level of significance, followed by transect data for the direction and magnitude of that change. It is important to remember that lower threshold proportions (i.e. 0.05, 0.10, and 0.20) are more conservative measures of change and larger thresholds (i.e. 0.30, 0.40, and 0.50) are more liberal significance tests. Following the results of each significance test, the general trends for each site and the results for all sites synthesized together are summarized. This comprehensive synthesis will provide insights about the methods used and trends in the data.

## WEST COAST OF LOWER MICHIGAN

*Manistee County Site*

The shoreline position changed frequently at the Manistee County site (Fig. 5.1). Using only the transect data (without any significance test), the shoreline at the Manistee County site retreated 30 m landward from 1938 to 2010 (Fig. 5.2). Assuming that this change occurred at a steady rate, the average annual change for the Manistee County site was -3.75 m per year. It is important to remember that these values do not account for uncertainty in shoreline position.

For the 1938 and 2010 pair, the uncertainty is greater than the observed change. If we assume that the uncertainty for the 1938 shoreline and the 2010 shoreline were in opposing directions, then subtracting or addind the uncertainty provides a likely minimum and maximum measure of change from 1938 to 2010. Subtracting the uncertainty essentially shifts each shoreline towards each other, which yields a likely minimum change of -2.32 m. Conversely, adding this uncertainty shifts each shoreline away from each other, an equally plausible scenario. This provides a likely maximum change of -62.39 m.

The greatest change for pairs with consecutive years occurred from 1965 to 1973 (-40.95 m; Fig. 5.3). Overall, 20 of the 36 change pairs had negative change values which indicated that the shoreline had moved landward more frequently than it had moved lakeward. The number of negative change pairs and overall shoreline change 1938 to 2010 suggests that the Manistee County site experienced more shoreline retreat than advance, both in frequency and magnitude. There was no clear spatial or temporal pattern in the fine-scale shoreline change segments at any significance level.


**Figure 5.1: Variability in shoreline positions at the Manistee County site.**
**Each gray line represents the shoreline position for one single year. The shoreline position fluctuated over a wide area.**


**Figure 5.2: Shoreline change from 1938 (purple) to 2010 (green) at the Manistee County site.**
**Although the shoreline retreated about 4.88 m (change exceeding uncertainty) landward from 1938 to 2010, the center of the reach changed less than either end. The background imagery is from 2010.**


**Figure 5.3: Shoreline change from 1965 (purple) to 1973 (green) at the Manistee County site.**
**The change was fairly even along the entire 1.5 km reach of coast. The background imagery is from 1973.**

Variograms of each shoreline provided valuable information about the degree of spatial autocorrelation in the longshore direction (Fig. 5.4). A majority of the variograms lacked a clear nugget, sill, and range, but variograms for the 1938 and 1973 shorelines had a clear sill at a range of 300 m (Fig. 5.4). This indicated that shoreline position was spatially autocorrelated at distances of 300 m.

Shoreline position and lake level elevation were weakly negatively correlated (R-squared = 0.44; Fig. 5.5), although this relationship was very weak. This negative correlation suggests that the shoreline was more likely to move lakeward with a decrease in lake level. Conversely, landward change in shoreline position is more likely with an increase in lake level. This relationship is best exemplified by plotting shoreline position for consecutive years against the lake level during the same years (Fig. 5.6).

There was one pairs of years where the proportion of similarity was 0.00: 1938 to 1973. At this significance threshold there is no overlap between the buffers around the shorelines. In other words, the shoreline in 1973 was in a completely different location than it was in 1938. The shoreline appeared to move landward by -53.38 m; however, when uncertainty was accounted for, the actual change may range from -10.55 m to -96.22 m.

When the significance threshold was increased to 0.05, there were 5 pairs of years for which shoreline change was significant. All of these pairs indicated change in the negative direction which indicates that the shoreline moved landward. The average movement for these 5 pairs was -44.16 ± 7.41 m, but when uncertainty was accounted for, this average movement was reduced to -30.38 ± 7.64 m. At the 0.05 significance threshold there were two consecutive year pairs that had significant change: 1938 to 1952 and 1965 to 1973. Of these two pairs, the greatest change was from 1965 to 1973 with -41.00 m of change (i.e., the shoreline retreated landward -41.00 m between 1965 and 1973). When uncertainty is accounted for in the transect data, the actual change may range from -88.14 m to -0.17 m of landward shoreline movement.

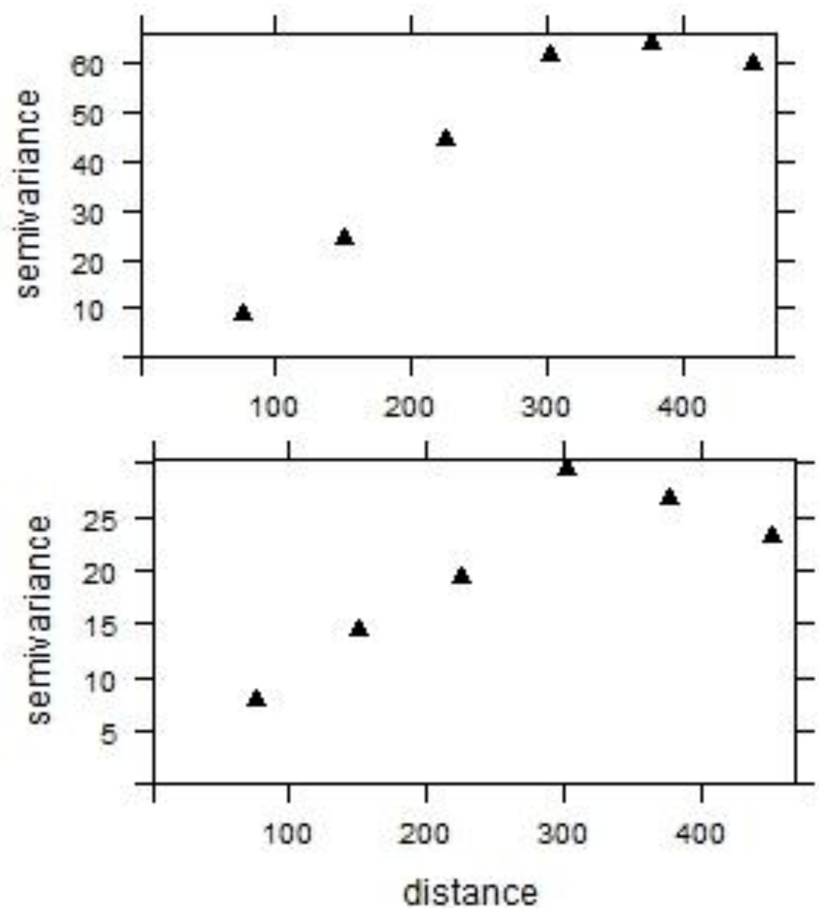



**Figure 5.4: Variograms for the Manistee County site shoreline position. Variograms for A) 1938 and B) 1973.**

At the 0.10 significance threshold, there were 8 pairs of years with significant change in shoreline position. All of these pairs had negative change values, which indicated that the shoreline had moved landward for each pair of years. The average of these 8 pairs was –40.20 ± 8.27 m, although it is important to note that this value does not account for uncertainty. It is important to note that this change value does not account for uncertainty. Accounting for uncertainty, change may range from -82.53 m of landward shoreline movement to 2.12 m of lakeward shoreline movement.

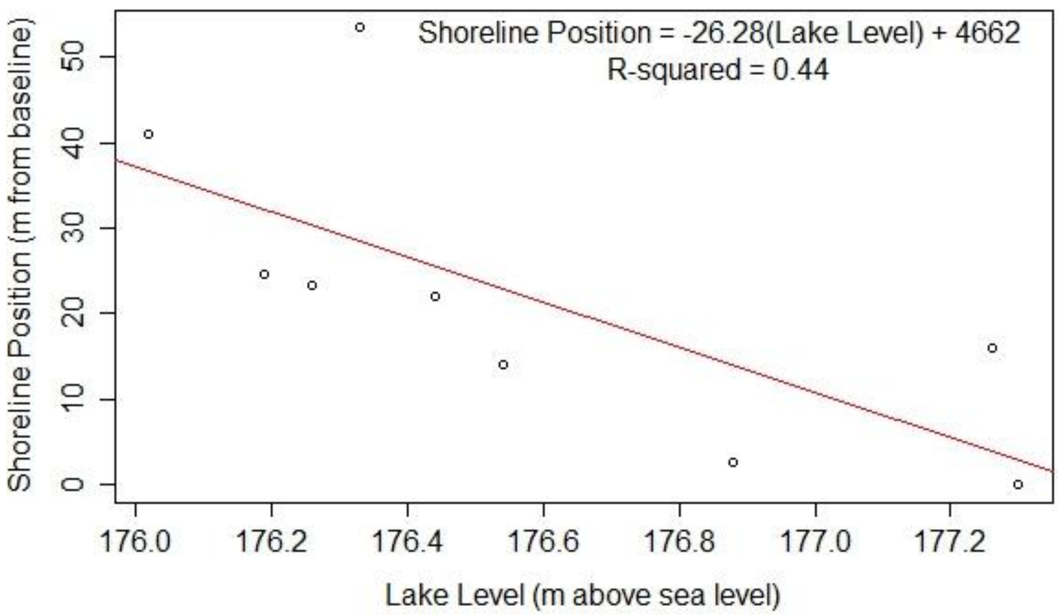



**Figure 5.5: Relationship between the observed shoreline position and lake level for the Manistee County site.**

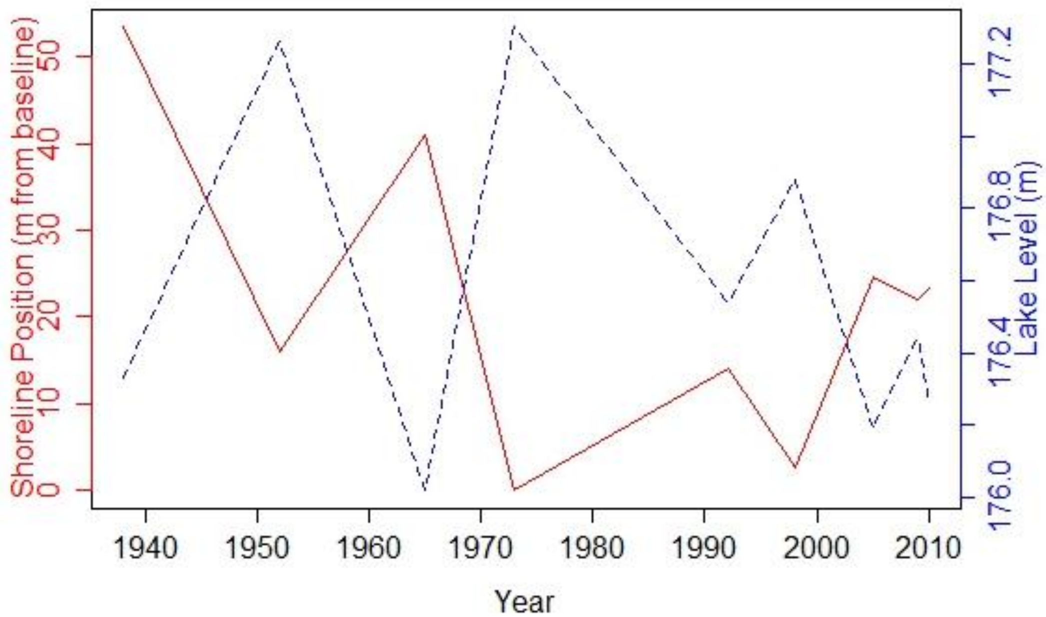



**Figure 5.6: Relationship between lake level (dashed blue line) and shoreline position (solid red line) at the Manistee County site.**
**Note the strong inverse relationship between shoreline position and lake level.**

When the significance threshold was increased to 0.20, there were five additional pairs of years with significant shoreline change for a total of 13 pairs. The majority of the change pairs indicated landward movement in shoreline position, and the mean change was -23.62 ± 27.92 m. However, when uncertainty was accounted for, the average change ranged from -65.38 m of landward shoreline movement to 18.12 m of lakeward shoreline movement.

Increasing the threshold proportion to 0.30 increased the number of pairs with significant change to 18. The mean change for all 18 pairs was -15.50 ± 29.07 m, and the uncertainty adjusted mean ranged from -56.41 m of landward shoreline movement to 25.41 m of lakeward shoreline movement. Among these pairs, landward shoreline movement was dominant, with 12 of the 18 pairs indicating that the shoreline had moved significantly landward from one time to another. The average change for 12 pairs of years with landward shoreline change was -34.50 ± 11.10 m. The six pairs of significant lakeward movement had a mean raw change of 22.48 ± 2.18 m.

The results at the 0.40 and 0.50 significance thresholds are similar to each other. At the 0.40 threshold there were 20 total pairs of significant change and at the 0.50 threshold there were 25 pairs. The mean change for the 0.40 threshold level was -13.65 ± 28.75 m and the median was -22.96 m. At the 0.50 threshold, the mean raw change was -11.76 ± 26.48 m and the median change was -16.36 m. It is important to note that, at both the 0.40 and 0.50 thresholds, the standard deviation was larger than the mean change. This suggests that these data are not unimodal, but might be more appropriately represented by a bimodal distribution with one mode centered on the negative change values and the other centered on the positive change values.

The significance threshold and number of significant change pairs were positively correlated (Fig. 5.7). This relationship was nearly 1:1 with an R-squared value of 0.94. The pair of years with the greatest landward shoreline movement (1938 to 1973) was the only pair of year that was significant at all of the tested thresholds. Shoreline position was strongly inversely related to lake level (Fig. 5.6). When subtracting uncertainty from shoreline position the sign, indicating the direction of change, would occasionally change. This issue was present at the 0.20, 0.30, 0.40, and 0.50 thresholds and was most prolific at higher thresholds.

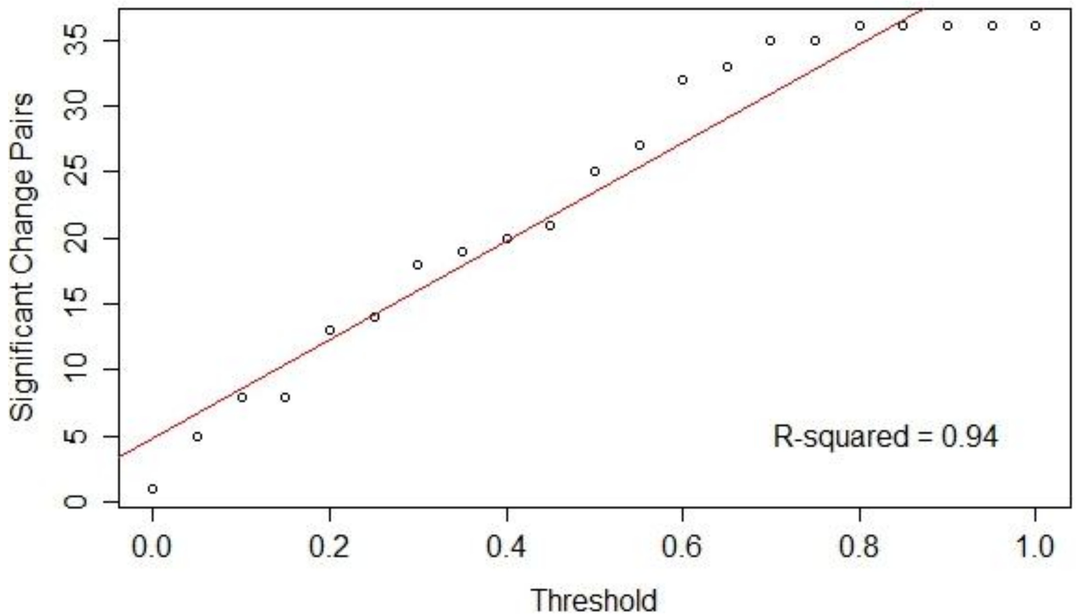



**Figure 5.7: Relationship between the significance threshold level and the number of pairs of years with significant change at the Manistee County site.**

*Allegan County Site*

Between 1938 and 2010, the shoreline at the Allegan County site occupied a wide range of positions (Fig. 5.8). Using only the transect data, the Allegan County site moved a total of -10.94 m from 1938 to 2010 (Fig. 5.9). In other words, the shoreline in 2010 was 10.94 m landward from where it was in 1938. When this change is divided equally into the 72 years that elapsed from 2010 to 1938, the average annual change rate was -1.36 m. However, it is important to remember that the shoreline moved both lakeward and landward between 1938 and 2010. The greatest change for pairs with consecutive years was +16.14 m for 1950 to 1960 (Fig. 5.10). Just over half of the change pairs indicated that the shoreline had moved landward (20 of

36 pairs). Shoreline position and lake level were negatively correlated (Fig. 5.11), although this relationship is very poorly defined (R-squared = 0.24; Fig. 5.12).

The variograms for shoreline position measured at each transect provide important insight about spatial autocorrelation along each year's shoreline. All of the variograms steadily increase with increasing distance (Fig. 5.13). There is no nugget in any of the variograms that would suggest the instantaneous variation away from a point. However, variograms for the 1960, 1974, 1998, and 2005 shorelines have a pronounced sill, which suggests that shoreline position is spatially autocorrelated (Fig. 5.13). Shoreline position appears to be spatially autocorrelated at 200 m for the 1960 and 1974 shorelines, 300 m for the 1998 shoreline, and 350 m for the 2005 shoreline.

At the 0.00 significance threshold there were no significant change pairs. This indicates that there were no pairs of years where the two shorelines did not overlap. Applying 0.05 significance threshold indicated that there were two pairs of years where the shoreline had changed significantly: 1938 to 1978 and 1960 to 1974. Both of these pairs indicated that the shoreline had moved significantly landward, by an average of -40.43 ± 0.01 m. When uncertainty is accounted for in the transect data, then change ranged from -83.79 m of landward shoreline movement to 2.92 m of lakeward shoreline movement.

Increasing the significance threshold to 0.10 resulted in two additional pairs of years exhibiting significant shoreline change. The mean change for these 4 pairs was -37.44 ± 3.45 m and the median was -37.44 m. However, the actual change may range from -80.01 ± 4.38 m of landward shoreline movement to 5.12 ± 2.57 m of lakeward shoreline movement. Each of these pairs had a negative change value, indicating that the shoreline had moved significantly landward. Additionally, one pair of consecutive year pairs had significant change: 1960 to 1967.

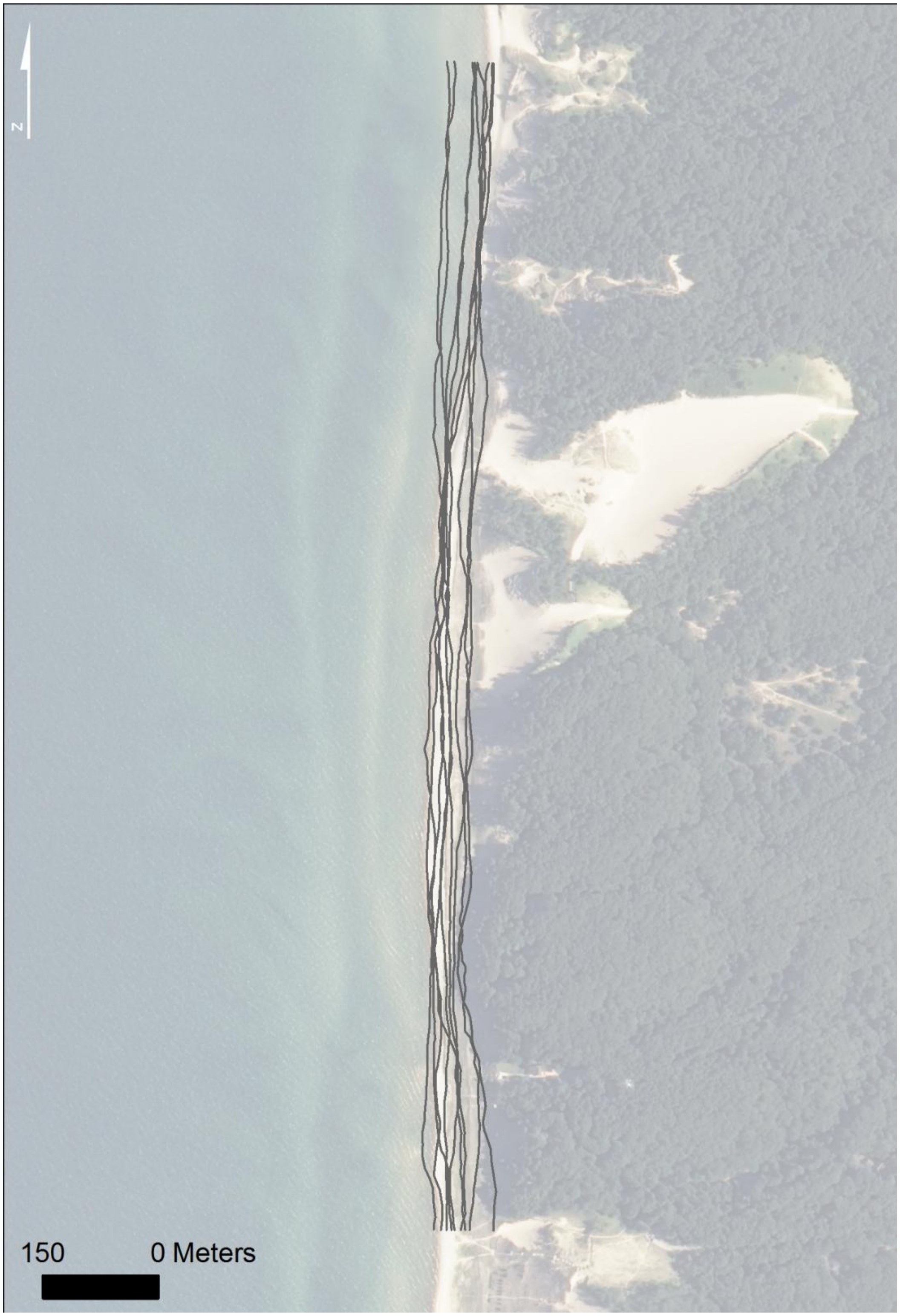



**Figure 5.8: Variability in shoreline position at the Allegan County site.**
**Each gray line represents the shoreline position for one single year. The shoreline position fluctuated over a wide area.**

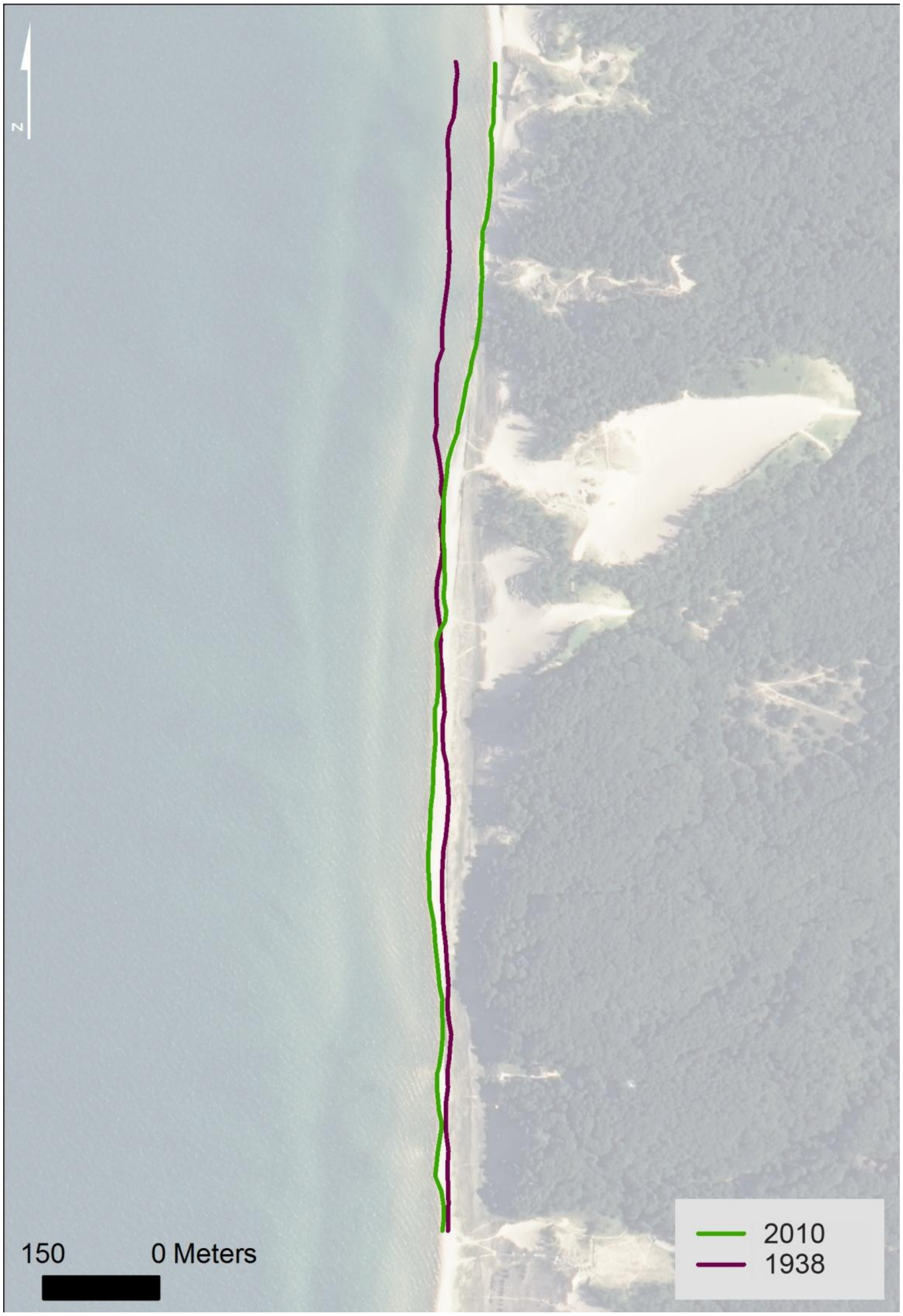



**Figure 5.9: Shoreline change from 1938 (purple) to 2010 (green) at the Allegan County site.**
**The shoreline retreated about 10.94 m landward from 1938 to 2010. However, since the uncertainty was greater than the change, it is possible that this change is only due to uncertainty. Additionally, change was greatest at the northern third of the reach. The background imagery is from 2010.**

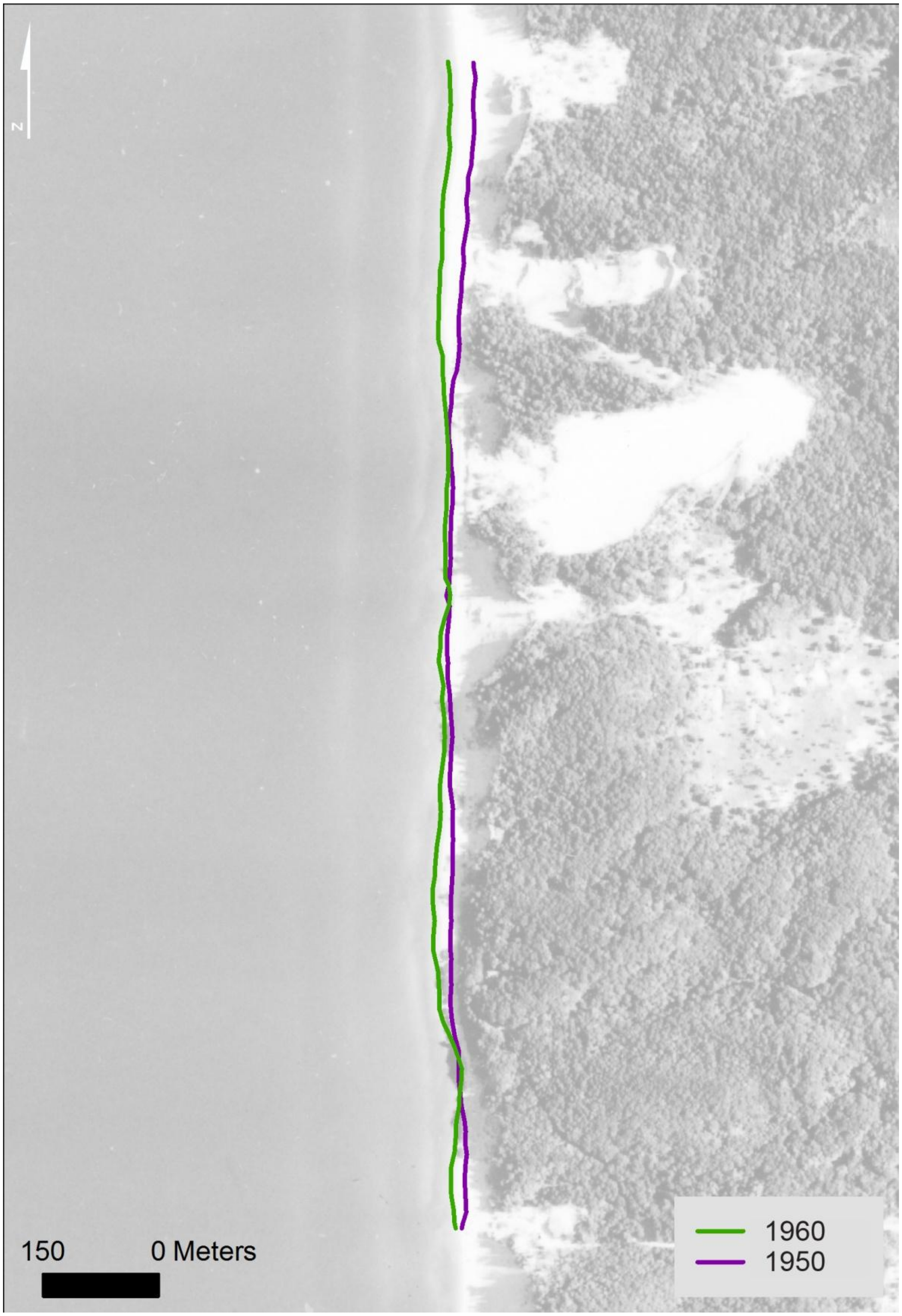



**Figure 5.10: Shoreline change from 1950 (purple) to 1960 (green) at the Allegan County site.**
**The northern third of the shoreline changed more than the rest of the reach. The background imagery is from 1960.**

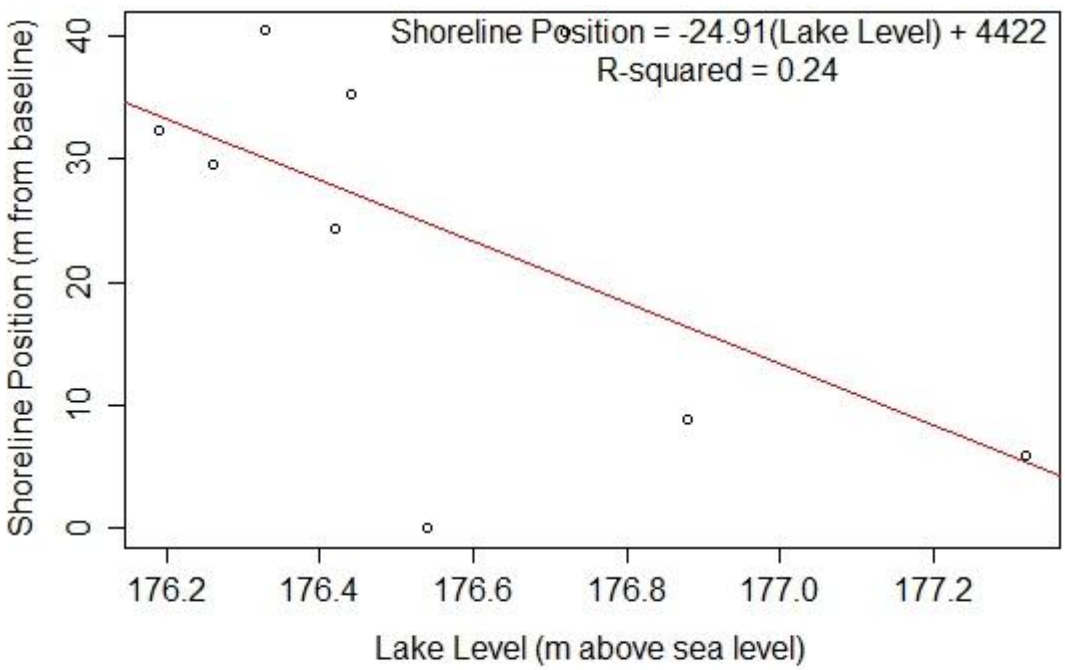



**Figure 5.11: Relationship between shoreline position and lake level at the Allegan County site.**

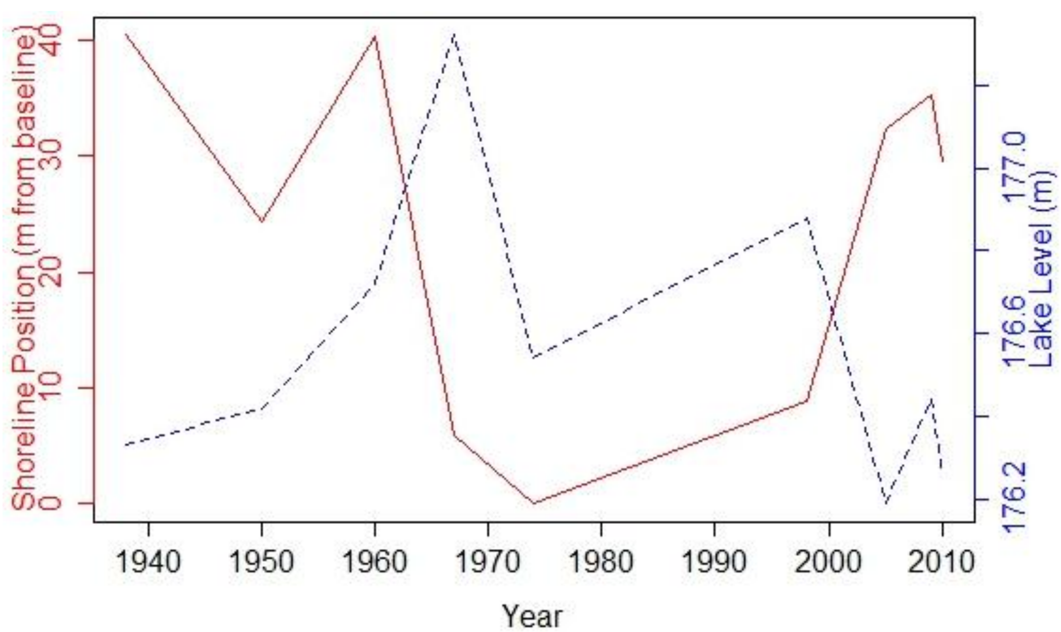
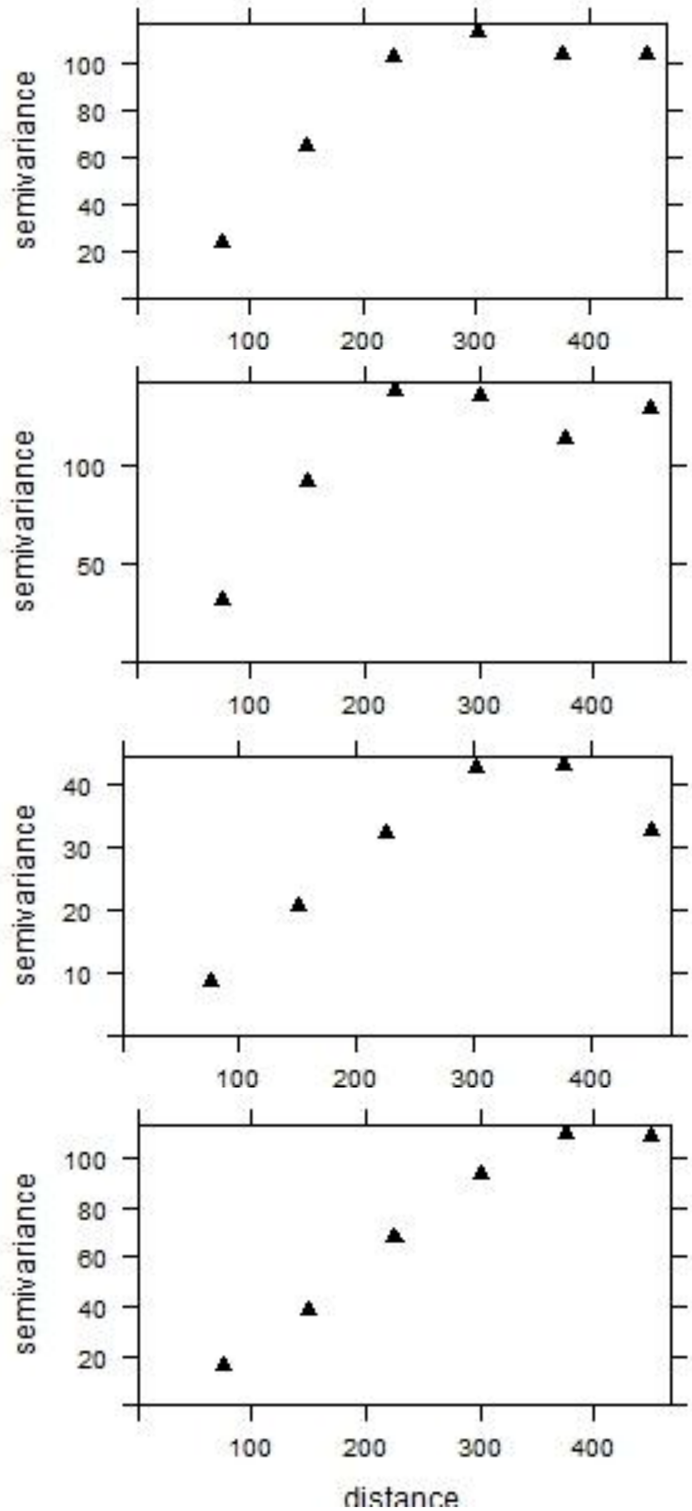



**Figure 5.12: Relationship between lake level (dashed blue line) and shoreline position (solid red line) at the Allegan County site.**
**The inverse relationship between shoreline position and lake level is poorly defined.**

At the 0.20 significance threshold, the number of significant change pairs increases to 15. Half of these pairs indicate that the shoreline moved significantly landward, while the other half indicates that the shoreline had moved significantly lakeward. The mean change for all 15 pairs was -2.33 ± 31.49 m and the median was 5.22 m. The large standard deviation, relative to the mean and median, suggests that the data may be not unimodal. Rather, the data appear to be bimodal, with one mode centered on the positive change values (mean = 25.29 ± 9.33 m) and a second mode centered on the negative change values (mean = -33.91 ± 5.60 m). One of the change pairs was for consecutive years: 1960 to 1967. This change pair indicated that the shoreline in 1967 was landward from where it was in 1960.

Increasing the threshold to 0.30 resulted in 6 additional significant change pairs. Of the 21 significant change pairs, half indicated that the shoreline had moved landward and the other half indicated that the shoreline moved lakeward. There was very little difference between the mean (0.22 ± 27.85 m) and median (5.22 m), but the standard deviation was substantially larger than the mean. Additionally, the minimum likely change (-40.44 m) and maximum likely change (35.24 m) were very different. The large difference in mean and standard deviation, together with the large difference between minimum and maximum values, suggests that the data are bimodal with one mode around the negative changes and a second around the positive changes. Only two of the 21 significant change pairs were for consecutive years: 1960 to 1967 and 1998 to 2005. While the 1960 to 1967 change pair indicated that the shoreline had moved significantly landward, the 1998 to 2005 change pair indicated that the shoreline had moved lakeward.




A) B) C) D)

**Figure 5.13: Variograms for the Allegan County site shoreline position. Variograms for A) 1960, B) 1974, C) 1998, and D) 2005.**

At the 0.40 threshold, there were 26 significant change pairs and at the 0.50 threshold there were 31 significant change pairs. Shoreline recession was only slightly more frequent at both thresholds. The mean (-1.05 ± 25.66 m) and median (-4.02 m) were similar at the 0.40 threshold. The same was true of the mean and median at the 0.50 significance threshold (mean = -1.53 ± 23.72 m; median = -5.17 m). Four consecutive year pairs were significant at the 0.40 threshold, and 6 consecutive year pairs were significant at the 0.50 threshold. A large number of pairs of years were significant at these higher thresholds (Fig. 5.14).

There was a strong relationship between the number of change pairs with significant change and the user-defined threshold (R-squared = 0.85; Fig. 5.14). Of the significant change pairs, shoreline recession was more common before 1998 and shoreline movement lakeward was more common after 1998.

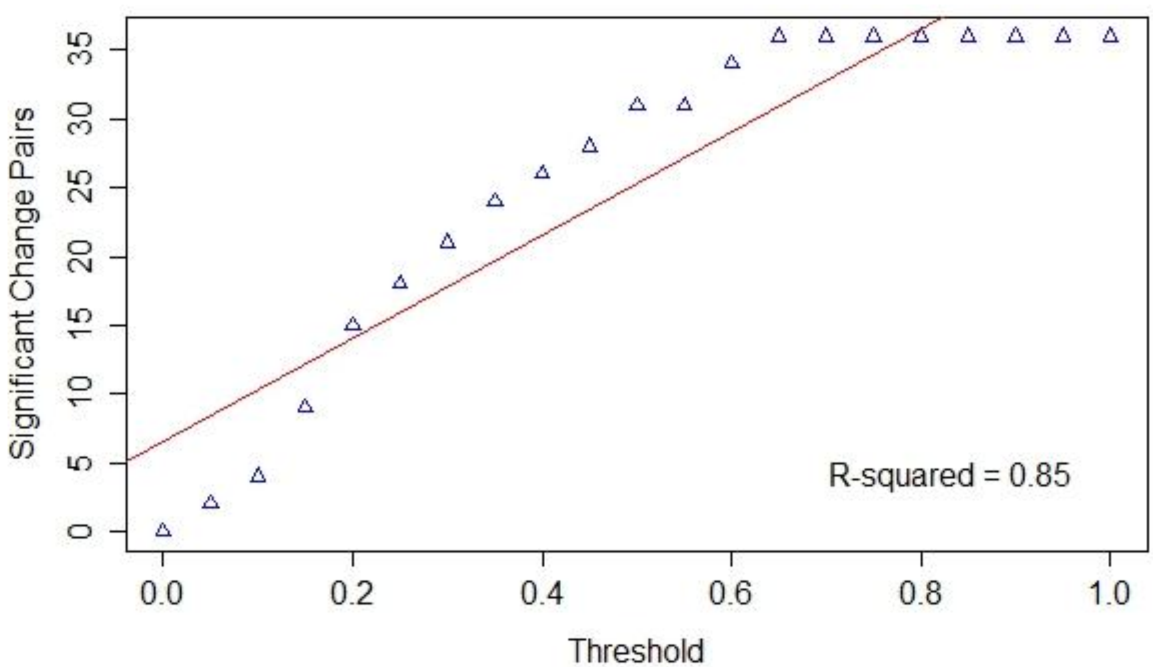



**Figure 5.14: Relationship between the significance threshold level and the number of pairs of years with significant change at the Allegan County site.**

## EAST COAST OF LOWER MICHGIAN

*Alcona County Site*

The Alcona County site shoreline was found to be highly dynamic, with both lakeward and landward changes. The greatest variation in shoreline position was near the center of the reach (Fig. 5.15). Overall the shoreline in 2010 was approximately 15.17 m lakeward from where it was in 1938 (Fig. 5.16). Assuming that this change occurred at a constant rate from 1938 to 2010, the annual rate of change was +1.89 m. The greatest change for a pair of consecutive years was + 40.05m, which occurred between 1952 and 1963 (Fig. 5.17). When the uncertainty for both shorelines is accounted for, the range of actual change is from -2.51 m of landward shoreline movement to 82.62 m of lakeward shoreline movement. Unlike either of the west coast sites, lakeward shoreline movement was much more common at the Alcona County site.

Shoreline position variograms indicated that shoreline position was spatially autocorrelated in 4 of the 9 years sampled: 1938, 2005, 2009, and 2010 (Fig. 5.18). In all 4 cases the shoreline position was spatially autocorrelated at distances greater than 400 m. The remaining 5 variograms had a steadily increasing trend, but lacked a clearly defined nugget, sill, and range.

There was a strong (R-squared = 0.81) negative correlation between shoreline position, measured as the average distance from the baseline, and lake level at this site (Fig. 5.19). This inverse relationship is also visible by plotting the shoreline position and lake level change for the consecutive year pairs (Fig. 5.20).

At the 0.00 significance threshold there were no pairs of significant change. The first significance threshold with a pair of years with significant shoreline change was 0.05. There were three total significant change pairs at this threshold, all of which indicated that the shoreline moved lakeward from one time to another. The mean (47.80 ± 3.29 m) and median (47.53 m) of these change pairs were extremely close with a small standard deviation.

Applying the 0.10 significance threshold resulted in two additional pairs of significant change, for a total of five significant change pairs. Each of the five pairs indicated significant lakeward change. The mean change was 43.90 ± 6.00 m and the median was 44.65 m, although it is likely that the actual change may range from 6.21 m to 81.58 m of lakeward shoreline movement. There was only one pair of consecutive years that was significant at the 0.10 threshold: 1952 to 1963.

When the threshold was increased to 0.20 there were 6 additional pairs of years with significant shoreline change. Ten of the 11 change pairs indicated that the shoreline had moved significantly lakeward. The average change for all 11 pairs was 29.20 ± 23.87 m and the median change was 32.33 m. The large standard deviation is likely a product of the one change pair with a negative value: 1938 to 1952.

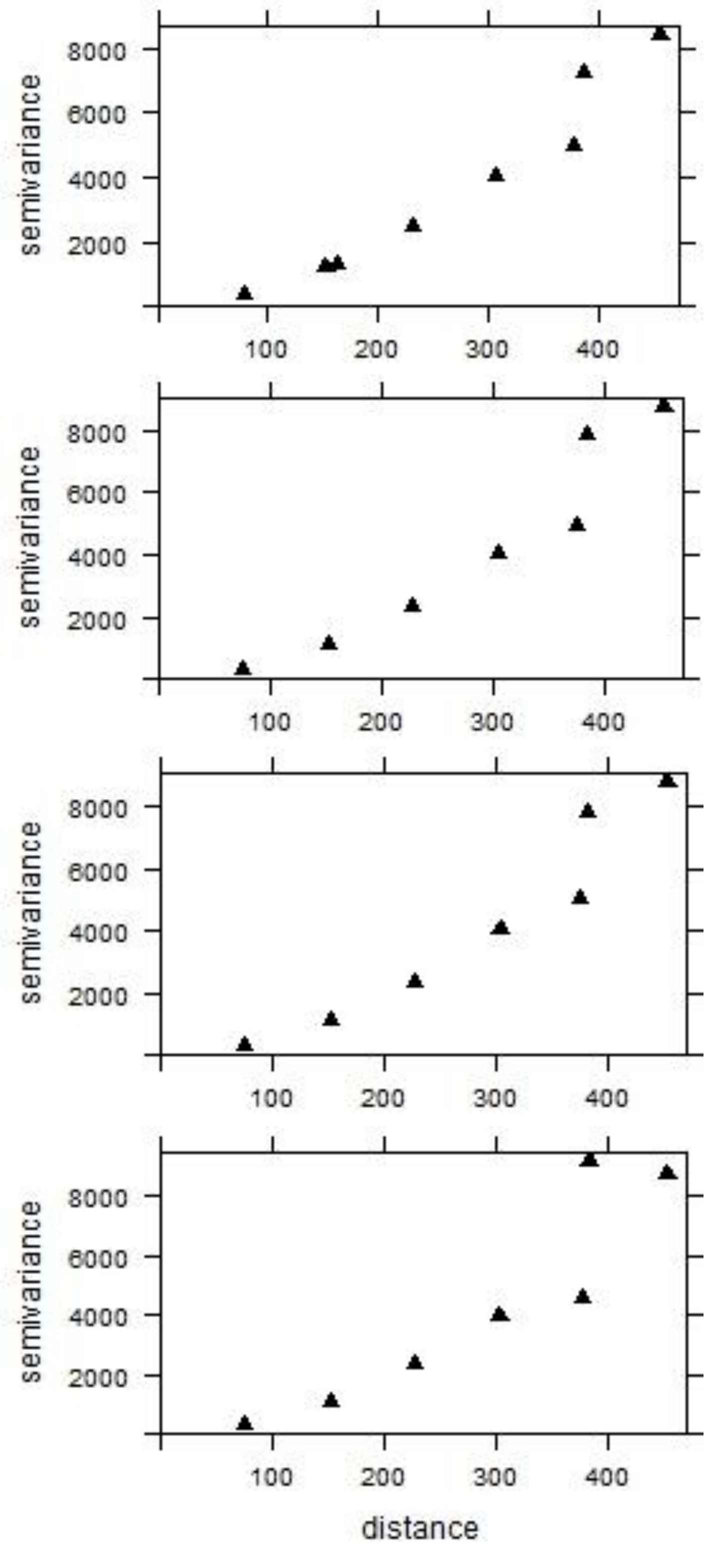
At the 0.30 significance threshold there were 15 pairs of significant change. The mean change was 27.17 ± 20.78 m and the median was 30.84 m. The large standard deviation was likely due to the fact that there was one pair of years (1938 to 1952) that indicated that the shoreline had moved significantly landward. When uncertainty is accounted for, the change is likely to range from -12.07 m of landward shoreline movement to 66.42 m of lakeward shoreline movement. The mean change of the 14 pairs indicating lakeward change was 31.69 ± 11.64 m. Additionally, three pairs of consecutive years had significant change

**Figure 5.15: Variability in shoreline position at the Alcona County site.**
**Each gray line represents the shoreline position for one single year. The shoreline position fluctuated over a wide area.**


**Figure 5.16: Shoreline change from 1938 (purple) to 2010 (green) at the Alcona County site.**

**Although the shoreline moved lakeward about 15.17 m from 1938 to 2010, the uncertainty exceeded this change. This means that the observed change is possibly due to the uncertainty of the position of one or both shorelines. Change was evenly distributed along the entire reach, but the direction of change is reversed in the southernmost quarter of the reach. The background imagery is from 2010.**


**Figure 5.17: Shoreline change from 1952 (purple) to 1963 (green) at the Alcona County site.**
**The center section of the shoreline changed exhibited the greatest change. The background imagery is from 1963.**




A)
B)
C)
D)

**Figure 5.18: Variograms for the Alcona County site shoreline position. Individual variograms were produced for A) 1938, B) 2005, C) 2009, and D) 2010.**

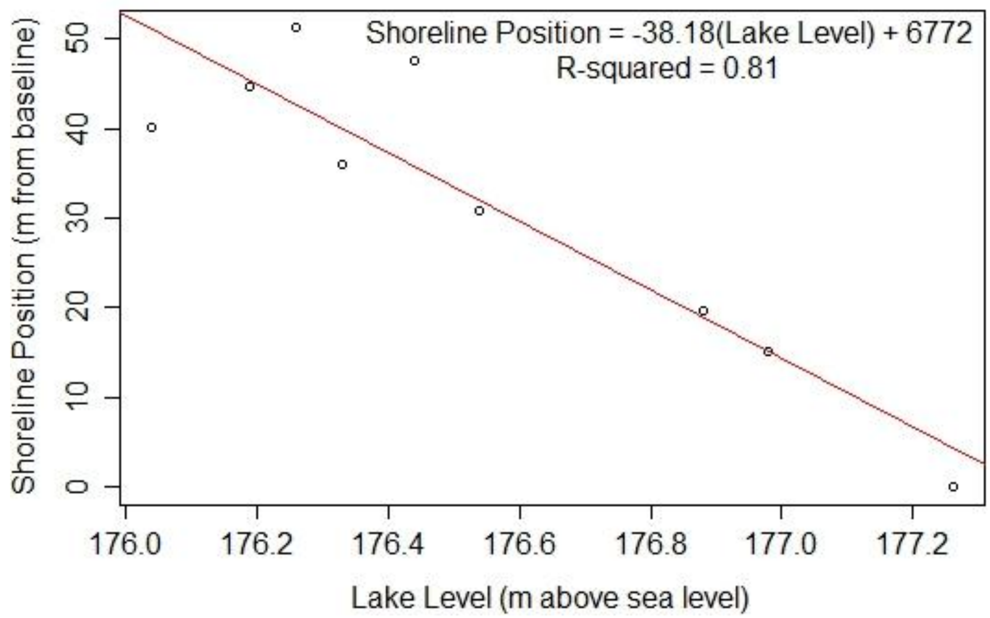



**Figure 5.19: Relationship between the shoreline position and lake level at the Alcona County site.**

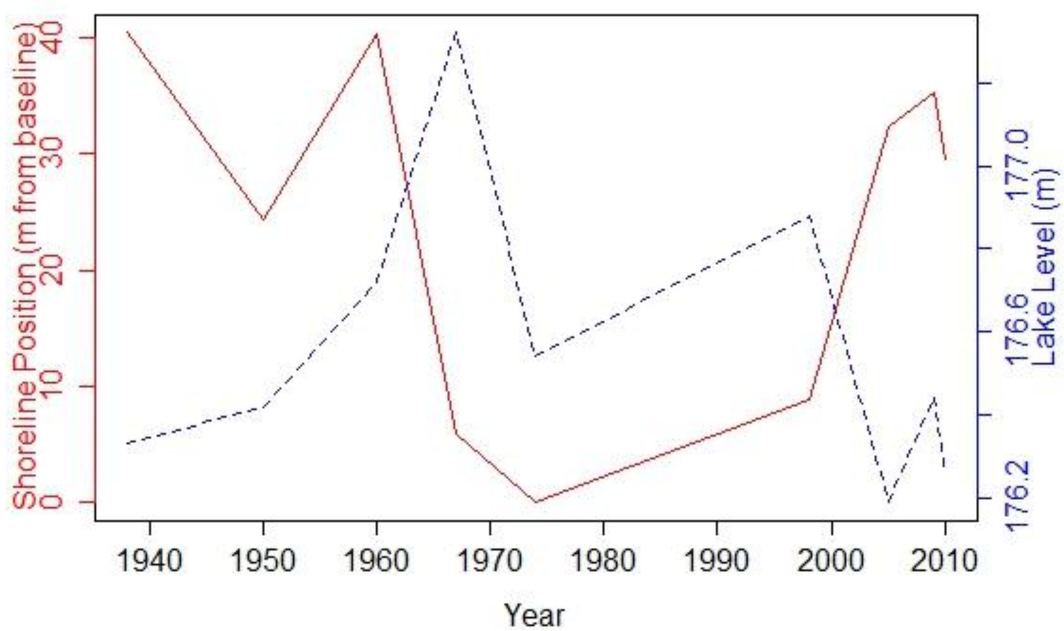



**Figure 5.20: Relationship between lake level (dashed blue line) and shoreline position (solid red line) at the Alcona County site.**
**Note the well-defined inverse relationship between shoreline position and lake level.**

There were 23 pairs of years with significant shoreline change at the 0.40 threshold. Nineteen of these pairs indicated that the shoreline moved significantly lakeward. The mean change was 18.12 ± 23.34 m and the median was 20.38 m. The large standard deviation, relative to the mean change, suggested that the change values were bimodal with one mode centered on the negative change values (mean = 24.55 ± 8.40 m) and the other mode centered on the positive change values (mean = 27.10 ± 12.82 m).

At the 0.50 significance threshold there were 28 pairs of years with significant shoreline change. Similar to lower significance thresholds, the results for this threshold were heavily dominated by pairs or years indicating lakeward shoreline change. The mean change at the 0.50 threshold was 15.61 ± 22.47 m. The arge standard deviation was likely due to the large difference between those pairs indicating lakeward change and those pairs indicating landward change. The mean change for the pairs of years with lakeward shoreline movement was 24.17 ± 13.46 m, and the mean change for the landward shoreline movement pairs was -23.73 ± 7.51 m.

Overall, the significance threshold and number of significant change pairs were positively correlated (R-squared = 0.91; Fig. 5.21). The two pairs with the greatest lakeward shoreline movement (1952 to 2009 and 1952 to 2010) were significant at threshold levels above 0.05. Pairs with lakeward shoreline change were more common than pairs with landward shoreline movement at all threshold levels.

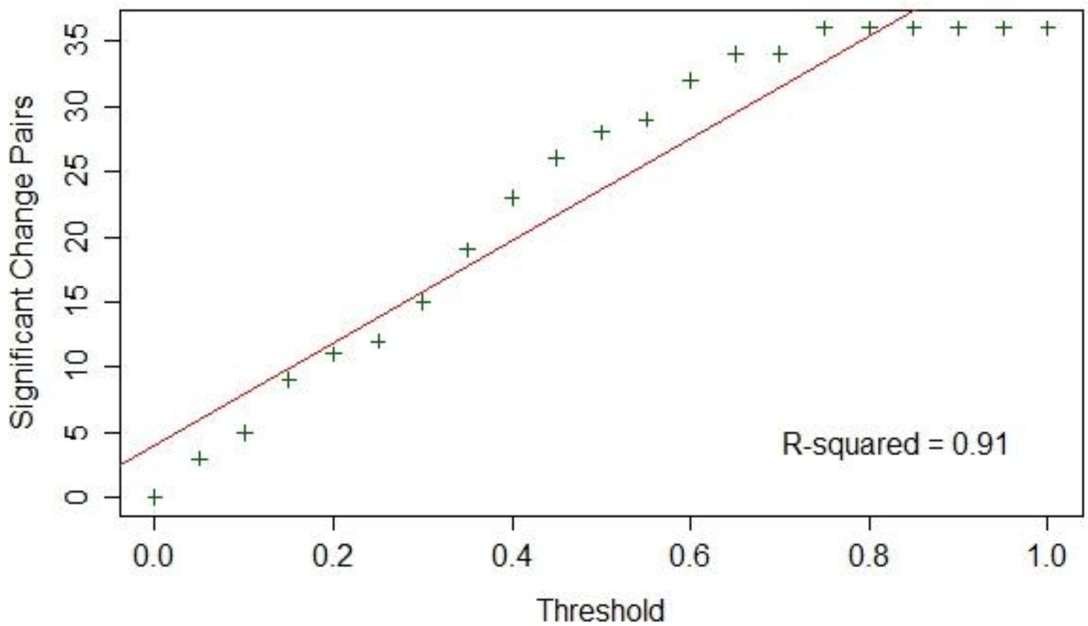



**Figure 5.21: Relationship between the significance threshold level and number of pairs of years with significant change at the Alcona County site.**

*Sanilac County Site*

The Sanilac County site exhibited the least amount of change between 1938 and 2010 (Fig. 5.22). From 1941 to 2010 the shoreline receded approximately -5.28 m (Fig. 5.23). However, it is important to note that the uncertainty associated with either shoreline was greater than the measured shoreline change. When the observed -5.28 m change was divided evenly into the elapsed time (69 years), the average annual change was -0.08 m. However, it is important to note that the actual change is likely between -34.55 m of landward shoreline movement and 23.99 m of lakeward shoreline movement. Pairs of years with landward shoreline movement were slightly more common than pairs exhibiting lakeward shoreline movement; however, the magnitude of change for any given pair of years was less than the other sites.

Variograms of shoreline position for each year exhibit a steadily increasing semivariance with increasing distance (e.g., Fig. 5.24). However, none of these variograms have a clearly defined nugget, sill, or range. This suggests that shoreline position may be spatially autocorrelated, but the exact distance is unknown.

Shoreline position and lake level were strongly correlated (R-squared = 0.83; Fig. 5.25). This strong negative correlation suggested that the shoreline is more likely to appear farther inland when lake level was high. Conversely, shoreline position was farther lakeward when lake level was lower. The inverse relationship between lake level and shoreline position was clearly visible when shoreline position and lake level were plotted against time (Fig. 5.26).

There were no pairs of years with significant change at the 0.00 through 0.40 significance thresholds. The first threshold to have a pair of years with significant change was the 0.50 threshold. At the 0.50 threshold, there were 4pairs of years exhibiting significant change in shoreline position. The average change at the 0.50 threshold was -7.86 ± 12.04 m. Three of these pairs indicated that the shoreline moved significantly landward by an average of -13.83 ± 2.00 m. Two consecutive year pairs exhibited significant change at this threshold: 1955 to 1963 and 1963 to 1982. From 1955 to 1963, the shoreline exhibited approximately 10.03 m of lakeward shoreline movement. The other consecutive year pair (1963 to 1982) exhibited approximately -11.52 m of landward shoreline movement.

Overall, the Sanilac County site had the fewest number of significant change pairs. Of the 6 significance thresholds examined, the first pair of years exhibiting significant shoreline movement was at the 0.50 threshold. This suggests that the Sanilac County site experienced the least amount of change. However, the positive relationship between the number of significant change pairs and significance level was very strong at the Sanilac County site (R-squared = 0.92; Fig. 5.27).


**Figure 5.22: Variability in shoreline position at the Sanilac County site.**


**Figure 5.23: Shoreline change from 1941 (purple) to 2010 (green) at the Sanilac County site.**
**Although the shoreline moved lakeward about 5.28 m from 1941 to 2010, the uncertainty exceeded this change. This means that the observed change is possibly due to the uncertainty of the position of one or both shorelines. Change was evenly distributed along the entire reach. The background imagery is from 2010.**

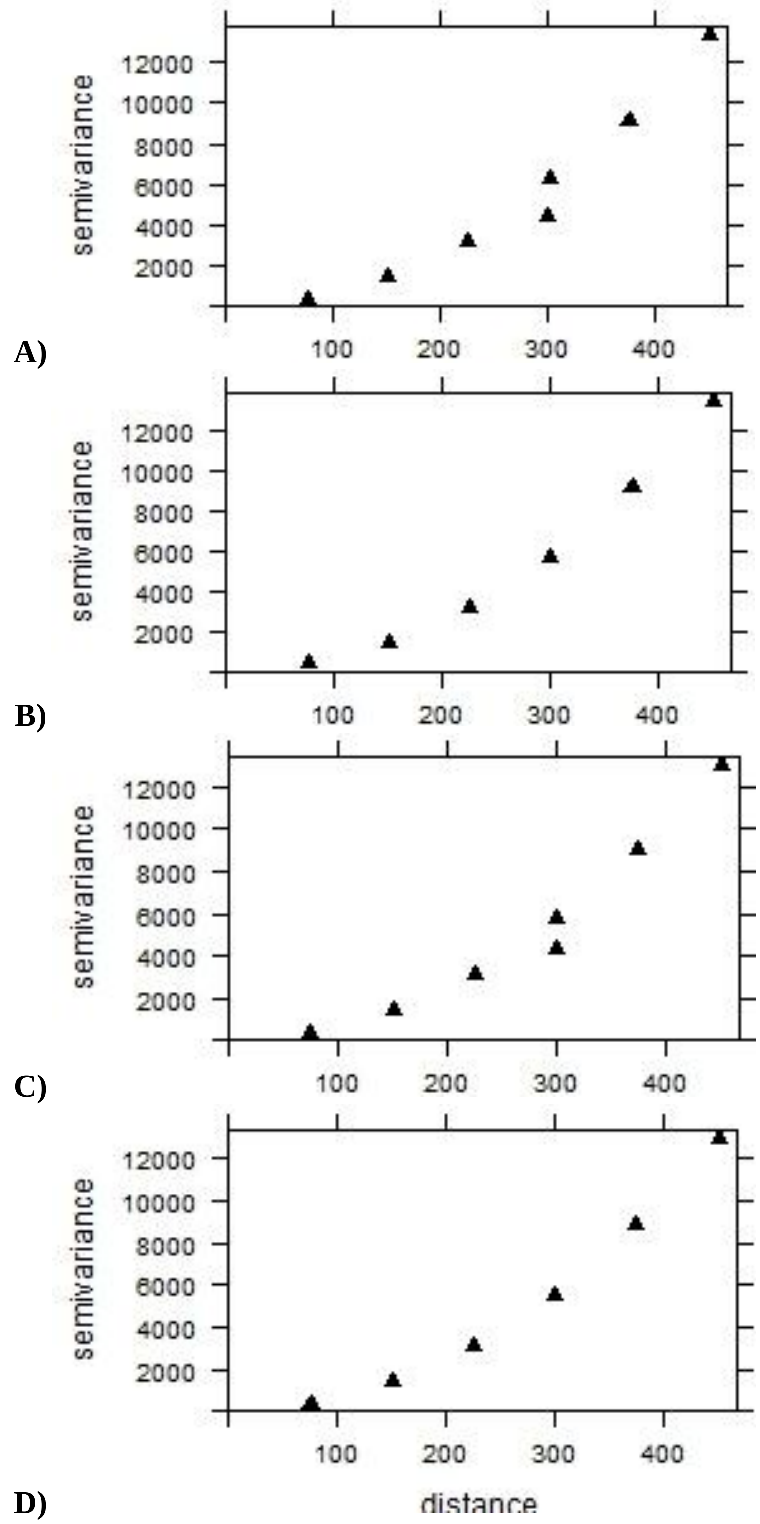



**Figure 5.24: Variograms for the Sanilac County site shoreline position. Variograms for A) 1941, B) 1963, C) 1998, and D) 2010.**

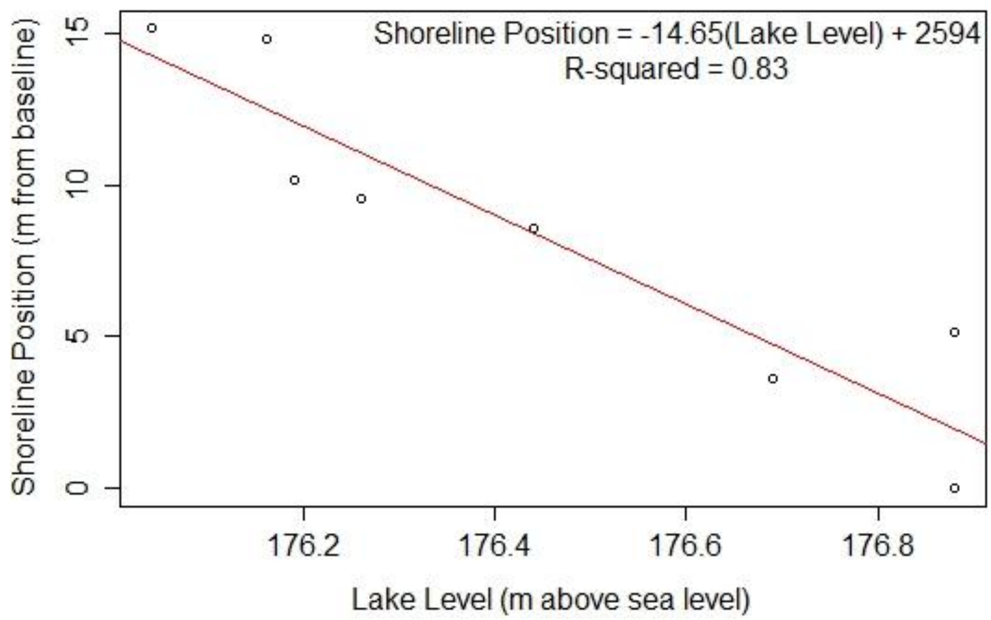



**Figure 5.25: Relationship between the shoreline position and lake level at the Sanilac County site.**

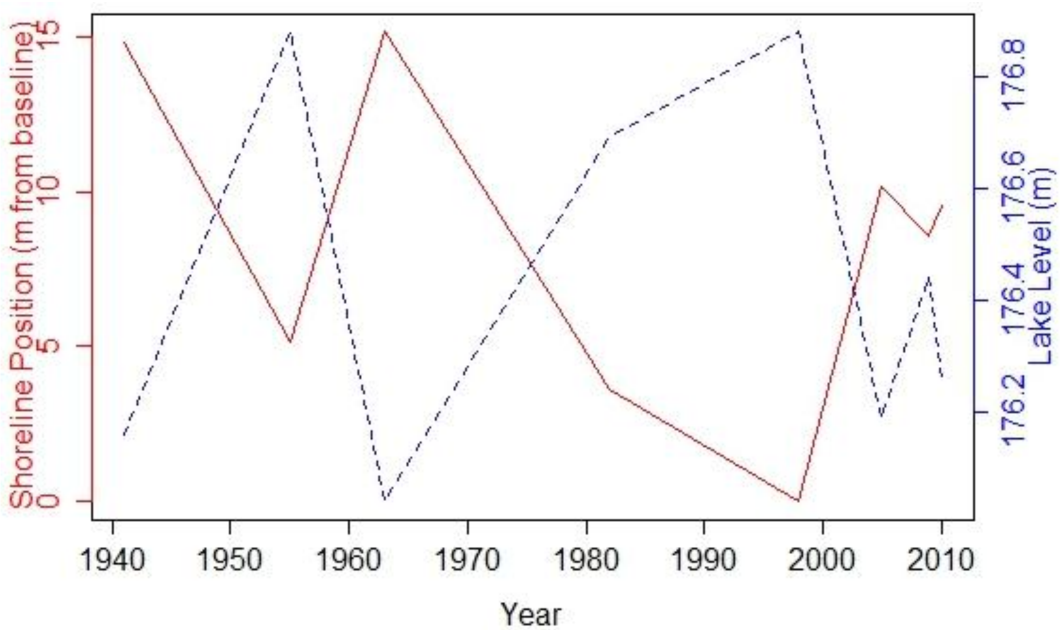



**Figure 5.26: Relationship between lake level (dashed blue line) and shoreline position (solid red line) at the Sanilac County site.**
**Note the well-defined inverse relationship between shoreline position and lake level.**

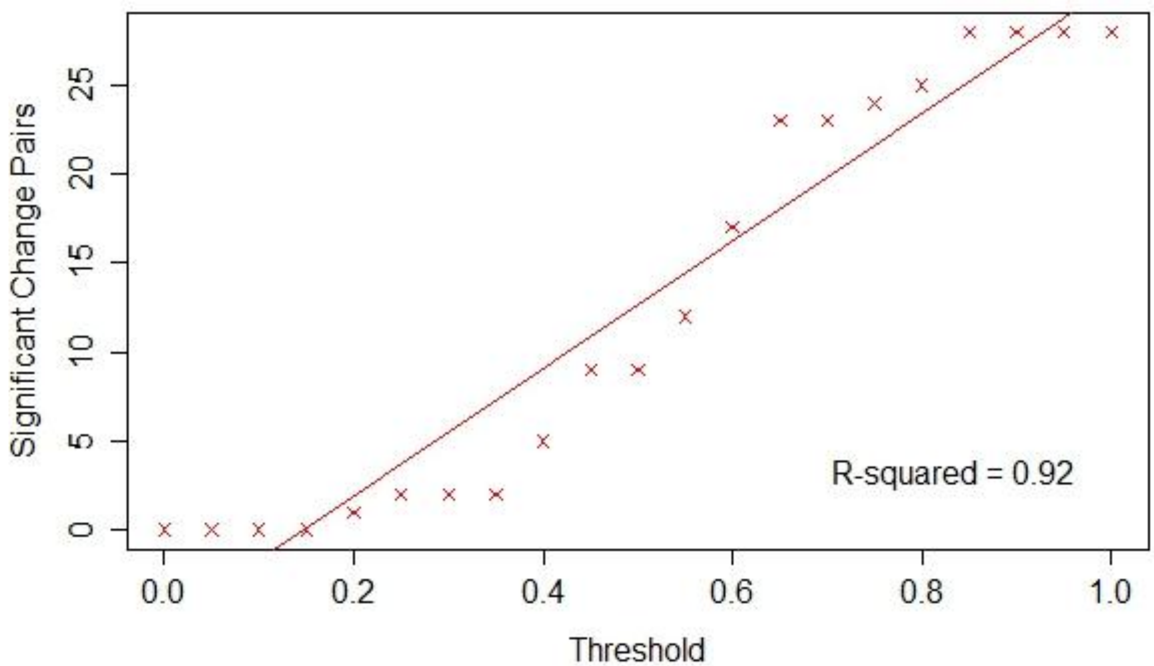



**Figure 5.27: Relationship between the significance threshold level and the number of pairs of years with significant change at the Sanilac County site.**

## SYNTHESIS AND COMPARISON OF ALL SITES

When the raw transect data are compared for all four sites, there are several patterns that emerge. For example, from the earliest image (1938 or 1941) to the most recent image (2010) the two west coast sites exhibit overall shoreline recession. On the other hand, the Alcona County site shows signs of lakeward shoreline movement for this same time period. This pattern is particularly interesting because all four sites share a common water plane and have similar coastal slopes. The fact that the west coast sites wxhibited overall shoreline recession at the same time the Alcona County site shoreline moved lakeward (Table. 5.1) suggests that the change in shoreline position may be due to a change in the volume of coastal sediment.

The number of significant change pairs varied from site to site. The Allegan County site had the greatest number of significant change pairs at larger significance thresholds, although it lags behind the Manistee and Alcona sites at the lower thresholds (Fig. 5.28). The Manistee County site had the most significant change pairs at lower significance thresholds (Table 5.1; Fig. 5.28). Conversely, the Sanilac County site had the fewest pairs of years with significant change (Fig. 5.28; Fig. 5.29). In fact, the first significant change pair at the Sanilac County site occurred at a much higher threshold of 0.45 than any of the three other sites (Table 5.1).

| | Manistee County site | Allegan County site | Alcona County site | Sanilac County site |
|---|---|---|---|---|
| Dominant particle size | Sand | Sand | Sand | Sand, gravel, cobbles |
| Range in shoreline position (m) | 53.38 | 40.44 | 51.23 | 15.15 |
| Endpoint Change (m) | -30 | -10.9 | 15.17 | -5.27 |
| Average annual change (m) | -0.41 | -0.15 | 0.21 | -0.07 |
| Lake level - shoreline position relationship (R-squared) | 0.44 | 0.24 | 0.81 | 0.83 |
| Minimum spatial autocorrelation (m) | >300 | >200 | >400 | ?? |
| Lowest threshold with at least 1 significant change pair | 0.00 | 0.05 | 0.05 | 0.45 |
| Notes | None | Tall bluffs (>5 m) present | None | Groins present |

**Table 5.1: Summary table with key parameters for all four sites.**

Significant recessional pairs were more common before 1998 at all sites and significance thresholds (Fig. 5.30). The shoreline was more likely to move lakeward after 1998. Additionally, the few significant recessional pairs after 1998 had less change than the pre-1998 recessional pairs. This trend was most pronounced at the Alcona County site, where there were no significant recessional pairs after 1998.

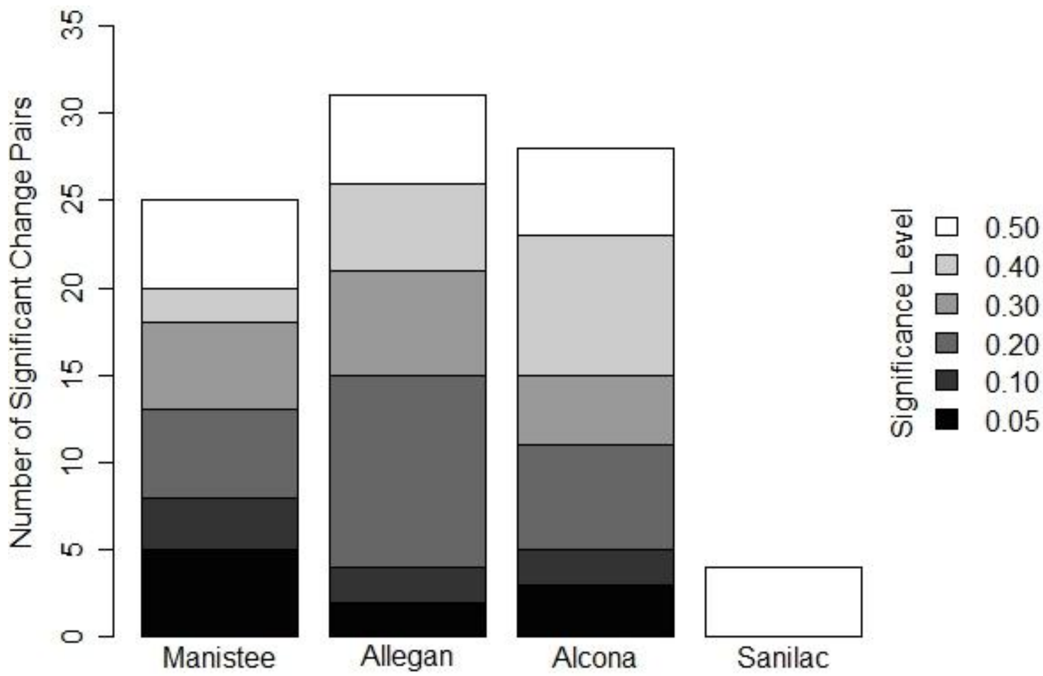



**Figure 5.28: Total number of significant change pairs for each site for each threshold level. Threshold levels are indicated by gray tone. The height of each bar begins at 0 and increases to the number of significant change pairs for the site and thresholds.**

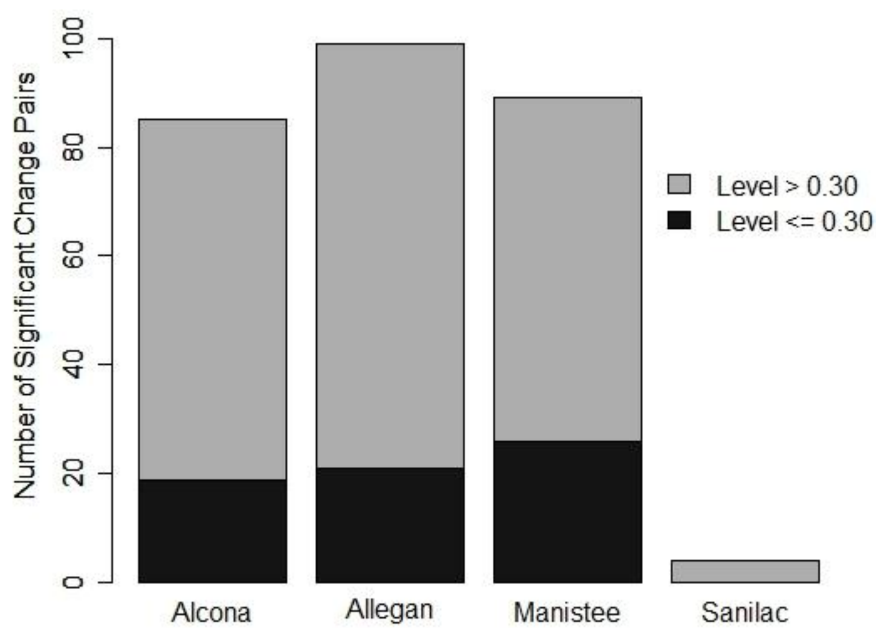



**Figure 5.29: Total number of significant change pairs for each site.**
**The gray bars are the number of significant change pairs at the more liberal change thresholds (i.e. greater than 0.30) and the black bars are the number of significant change pairs at the more conservative change threshold levels (i.e. less than or equal to 0.30). The height of each bar begins at 0 and increases to the number of significant change pairs for the site and thresholds.**

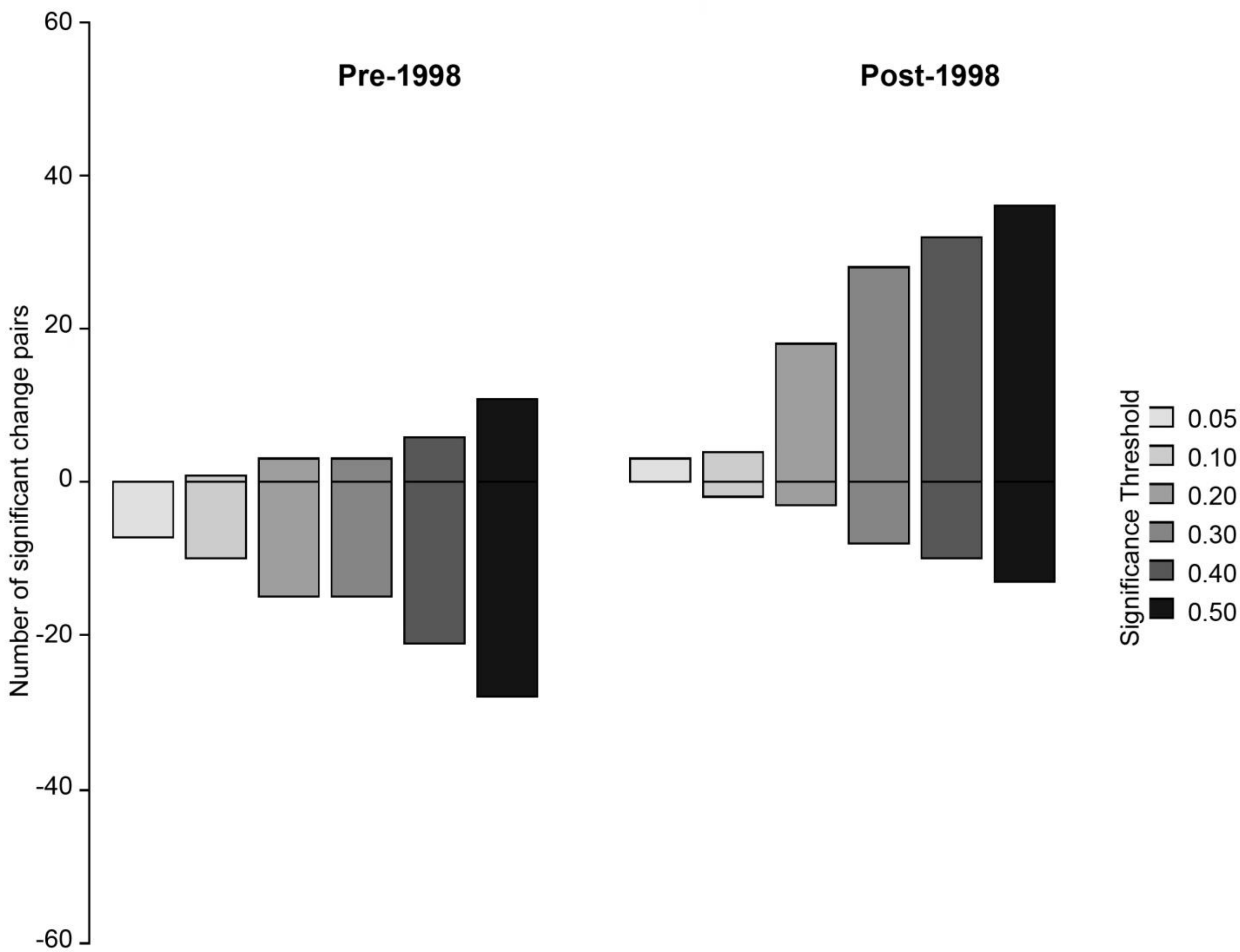



**Figure 5.30: Number of significant change pairs for years before (left) and after (right) 1998.**
**Bars with positive values (increase up from 0) represent the number of significant accretionary pairs at that threshold level, and bars with negative values (increase down from 0) represent the number of significant recessional pairs.**

Regardless of the significance threshold, the two west coast sites exhibited more landward shoreline movement, in both frequency and magnitude, than the east coast sites (Fig. 5.31). In other words, the shoreline retreated landward more at the west coast sites than it did at the east coast sites. The Alcona County site had the most positive significant change pairs (Fig. 5.32), suggesting that lakeward shoreline movement was more common at this site.

Overall, the number of significant change pairs was positively correlated to the significance threshold at each site (Fig. 5.33). This relationship was strongest for the Sanilac County site (red line in Fig. 5.33). The positive correlation between number of significant change pairs and significance threshold remained strong when the data for all sites was averaged and regressed (red line in Fig. 5.34).

In summary, there were more pairs of years with significant change at the two west coast sites than the east coast sites (Fig. 5.31). This suggests that the west coast sites have changed more than the east coast sites. Additionally, shoreline position was at least moderately correlated to lake level at each site (Figs. 5.6, 5.12, 5.20, and 5.26). This inverse relationship was weakest at the Allegan County site (Fig. 5.12) and was strongest at the Alcona and Sanilac County sites (Fig. 5.20; Fig. 5.26). The majority of significant recessional pairs occurred before 1998, whereas the majority of post-1998 significant change pairs were accretionary (Fig. 5.30). The number of significant change pairs was positively correlated with the significance threshold. This relationship was well defined at the all sites, but it was strongest at the Sanilac County site (Fig. 5.33).

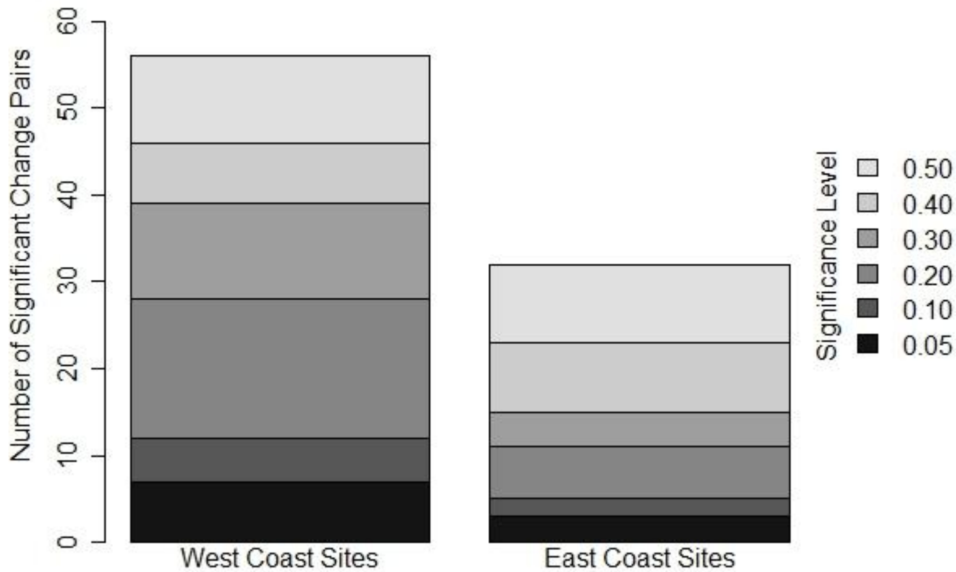



**Figure 5.31: Comparison of the number of significant change pairs for west coast and east coast sites at all significance levels.**
**The height of each bar begins at 0 and increases to the number of significant change pairs for the site and thresholds.**

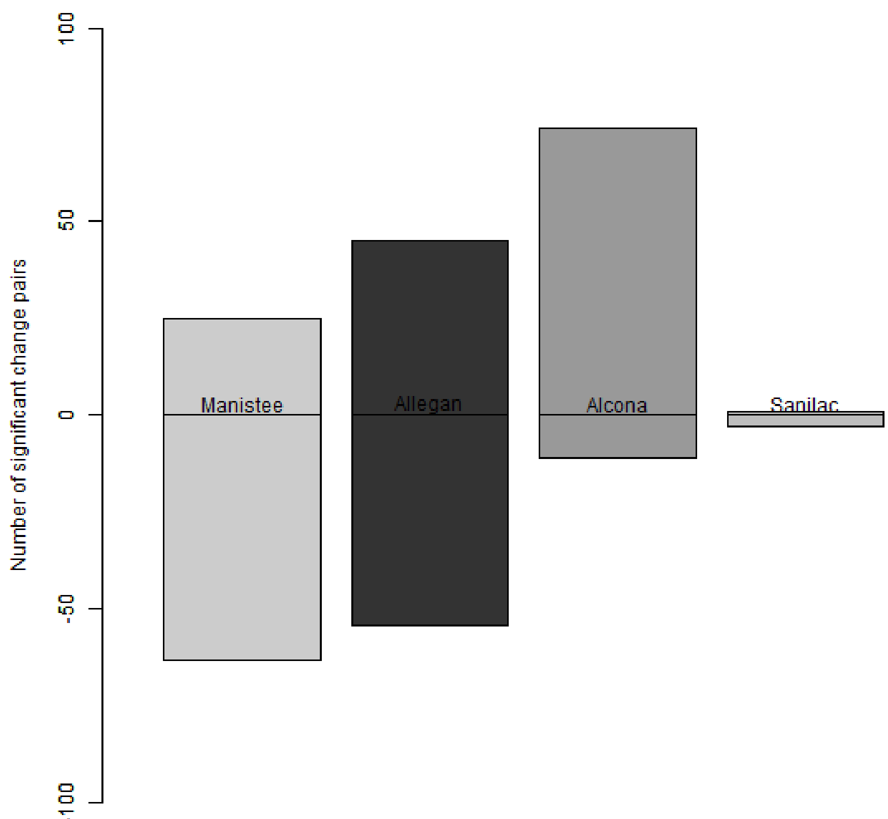



**Figure 5.32: Number of positive and negative significant change pairs at each site across all significance thresholds.**
**Notice that both west coast sites (Manistee and Allegan) exhibited more negative change pairs than either east coast site (Alcona and Sanilac).**

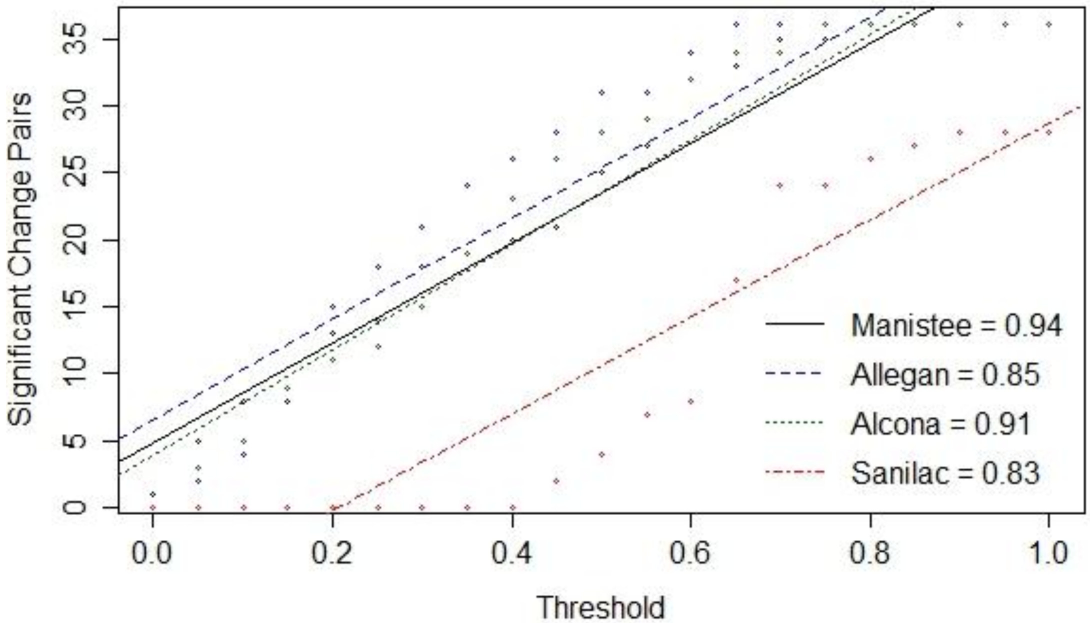



**Figure 5.33: Relationship between the significance threshold and the number of significant change pairs for each site.**
**The values in the legend indicate the R-squared value of the linear regression model. The Sanilac County site had the strongest relationship with an R-squared of 0.92.**

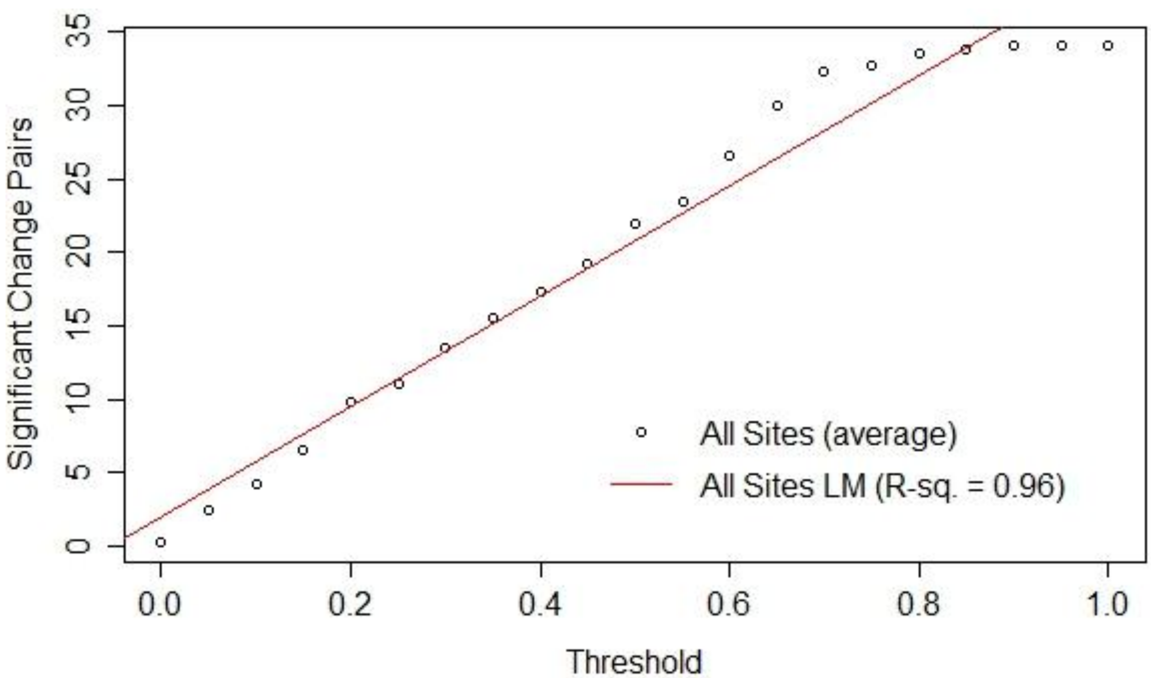



**Figure 5.34: Relationship between the significance threshold and the number of pairs of years with significantly different shoreline positions.**
**The circles represent the average number of significant change pairs across all four sites at a given threshold. The red line is the linear regression model for the averaged data.**

# CHAPTER 6: DISCUSSION

This chapter places the results of this study within the context of previous research (Seibel, 1972; Buckler and Winters, 1983; Jibson, et al., 1994; Pendleton, et al., 2005) and will assess the viability of the method. As a result, the chapter is organized into 3 sections, including 1) the relationship between shoreline position and lake level, 2) spatial patterns of shoreline change, and 3) the proposed method for shoreline analysis. The first section of this chapter will highlight the relationship between lake level and shoreline position across all four sites. The second section will highlight spatial patterns of coastal change and provide some possible explanations for the observed changes. The last section of this chapter will review the assumptions, advantages, and issues of using the proposed method for shoreline change analysis. In addition, I will discuss the applicability of this method to other research.

## RELATIONSHIP BETWEEN SHORELINE POSITION AND LAKE LEVEL

Shoreline position and lake level were inversely related at all four sites. This relationship was strongest at the Manistee, Alcona, and Sanilac County sites and was weakest at the Allegan County site. As expected at all sites, the shoreline generally appeared farther inland during periods of high lake level and farther lakeward during periods of low lake level.

The simplest explanation for this relationship is that shoreline position is caused solely by water level. In this scenario, a change in shoreline position does not reflect any change in beach volume. This concept is best illustrated using basic geometry, where the beach is represented by a right triangle with angle $\theta$ (Fig. 6.1). A change in lake level ($\Delta y$) causes a horizontal change in shoreline position (Δx) based on the slope of the beach (Fig. 6.1). A higher lake level will intersect the beach farther up slope and cause the shoreline to appear further inland (LA in Fig. 6.1). Conversely, a lower lake level will intersect the beach farther down the triangle and cause the shoreline to appear farther lakeward (LB in Fig. 6.1). This geometric model assumes that the slope of the beach is constant through space and time; however, a minor change in beach slope will result in different expected shoreline positions, given the same change in lake level. One example where this geometric model may be present is at the Manistee County site for 1965 and 1973 (Fig. 6.2). In 1965, lake level was 176.02 m asl and by1973, the lake level was 1.28m higher at 177.30 m asl. In 1973, the shoreline appeared approximately 13.42 m landward from its position in 1965 (Fig. 6.2).

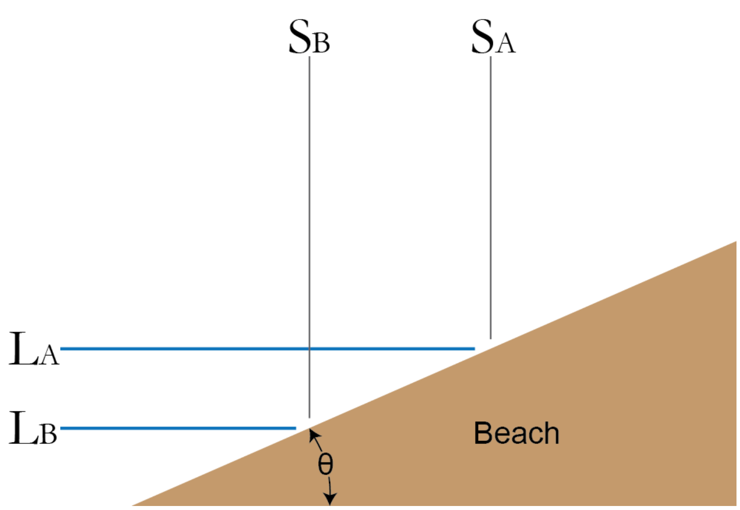



**Figure 6.1: Possible model for the inverse relationship of lake level and shoreline position. This model assumes that the shoreline position is caused only by lake level, that the beach slope is consistent through time, and that there is no change in the volume of coastal sediment.**

**Where: LA is the lake level at TIMEA,**
**LB is the lake level at TIMEB,**
**SA is the shoreline at TIMEA,**
**SB is the shoreline at TIMEB,**
**And θ is the beach slope.**

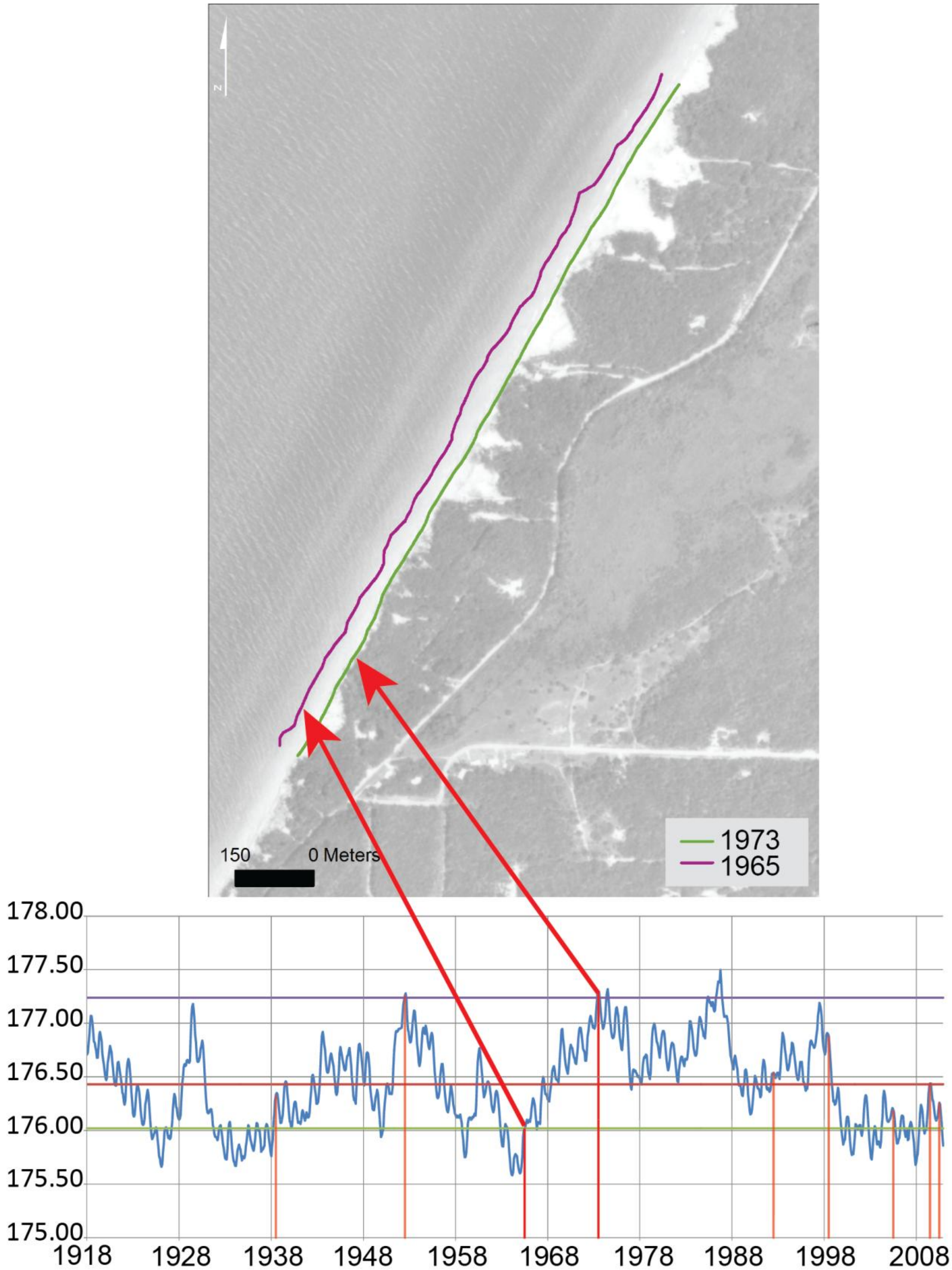



**Figure 6.2: Relationship of lake level and shoreline position at the Manistee County site. Notice how the shoreline appears further lakeward in 1965 (purple line on map) when lake level was low. In 1973 the lake level was higher and the shoreline is farther landward (green line on map).**

Assuming that a change in shoreline position does not reflect a volumetric change in coastal sediment and that lake level is the same for time A and time B, then shoreline A and shoreline B for a site should be at the same position. To test this hypothesis, the 1938 shorelines were compared to the 2010 shorelines at the Manistee (Fig. 6.3), Allegan (Fig. 6.4), and Alcona (Fig. 6.5) County sites. Imagery from 1938 and 2010 is available for all three of these sites, which means that there is an equal amount of time for each site to change. Additionally, all three sites share a common water plane. In 1938, lake level for Lake Michigan-Huron was 176.33 m asl, whereas in 2010 lake level was essentially the same at 176.26 m asl. Since there is only a 7 cm difference in lake level and swells and waves on Lake Michigan-Huron frequently exceed this difference (NOAA National Data Buoy Center, 2012), the difference in lake level from 1938 to 2010 is negligible.

Given that lake level is similar for these two years, the shoreline should appear in the same position for these years if the geometric relationship of Figure 2 is operative. However, the 1938 and 2010 shorelines are not in the same position for the Manistee County (Fig. 6.3), Allegan County (Fig. 6.4), and Alcona County (Fig. 6.5) sites. This suggests that the observed change in shoreline position is due to a volumetric change in beach sediment. At the two west coast sites, the shoreline appears to have moved landward (Fig. 6.3; Fig. 6.4), whereas the shoreline moved lakeward at the Alcona County site (Fig. 6.5). Despite similar lake level elevation in 1938 and 2010, the shorelines are not in the same position for these two years. The apparent shoreline retreat while at the same lake plane suggests that the two west coast sites experienced net coastal erosion between 1938 and 2010. On the other hand, the shoreline at the Alcona County site moved lakeward over the same 72 year span (Fig. 6.5), which suggests that this site accumulated beach sediment during the same time period.

Although it is possible to compare the change rates of this research to those of Seibel (1972) and Buckler and Winters (1983), the focus of my thesis is on the shoreline and the focus of these other two studies is the bluff. It is important to remember that these are two very different geomorphic features that have different mechanisms of change. While the shoreline position will change with a rise or fall in lake level elevation, changes in bluff position are impacted by multiple factors including lithology, groundwater seepage, nearshore bathymetry, bluff height, and fetch (Gray and Wilkinson, 1979; Buckler and Winters, 1983). Therefore, it is my recommendation that the shoreline change rates presented in my thesis should only be compared to bluff recession rates as an exploratory sense.

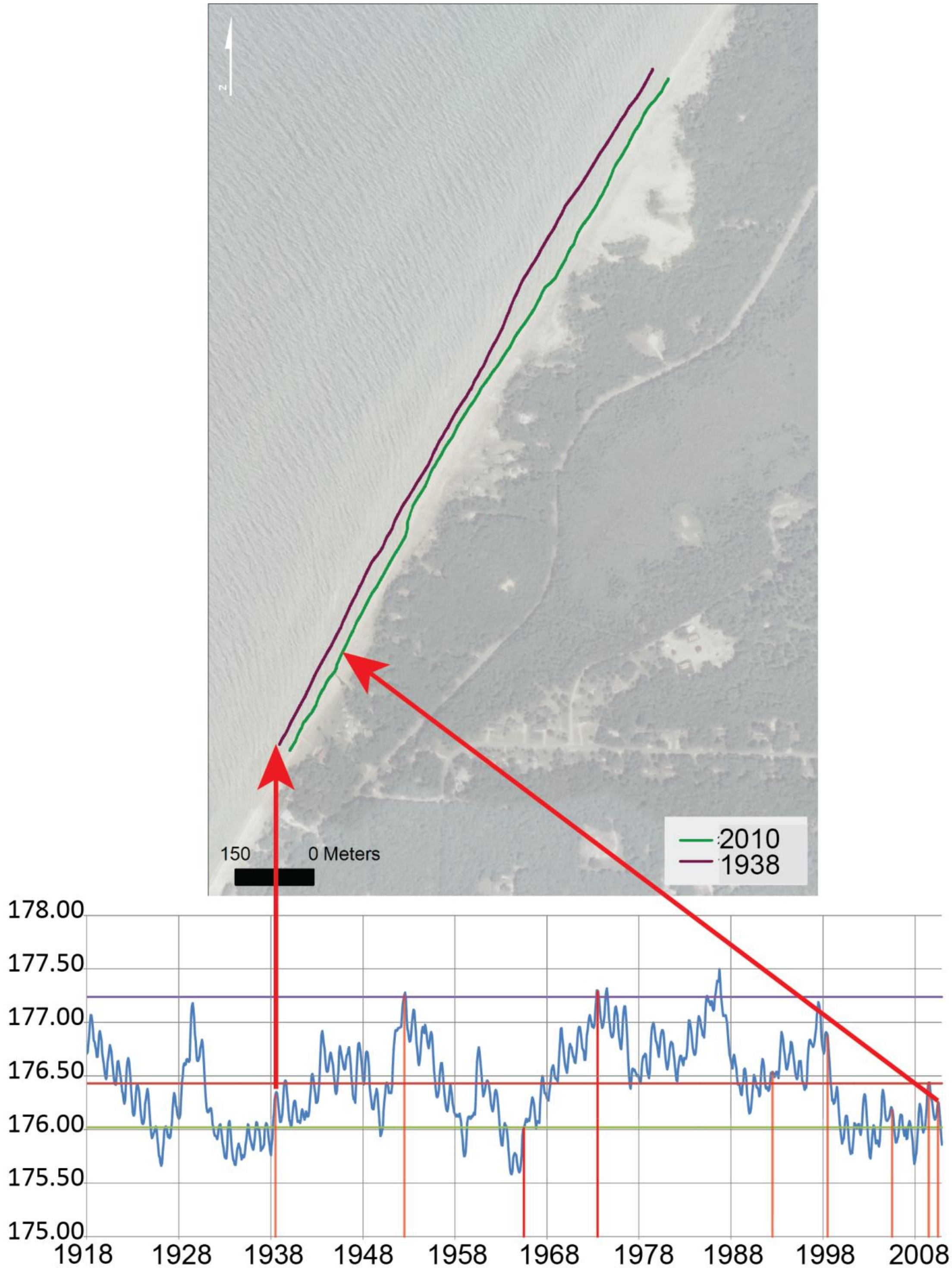



**Figure 6.3: Relationship between lake level and shoreline position at the Manistee County site for 1938 and 2010.**
**Despite a relatively similar lake level, the 1938 shoreline (purple line) is farther lakeward than the 2010 shoreline (green line).**

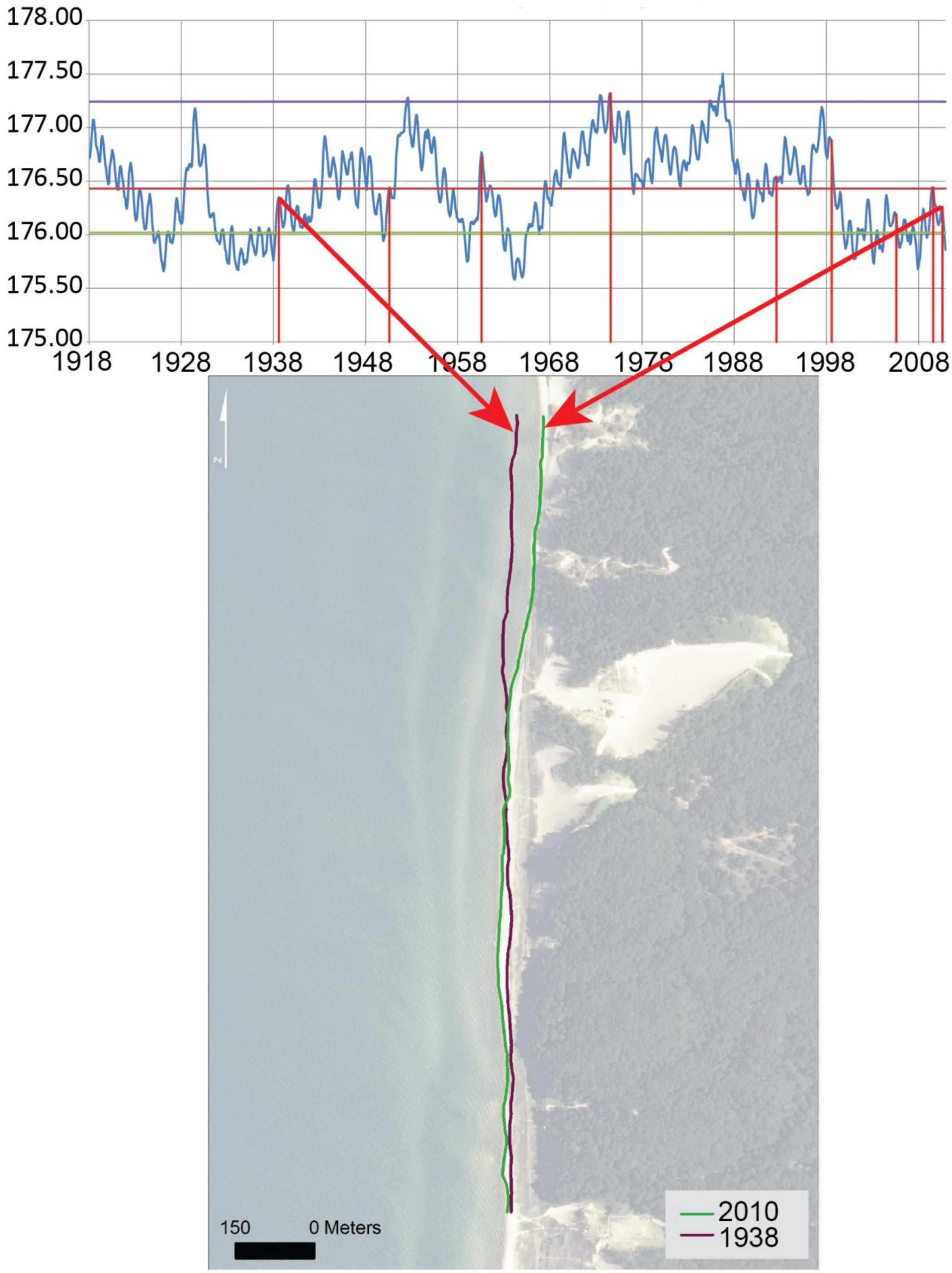



**Figure 6.4: Relationship between lake level and shoreline position at the Allegan County site for 1938 and 2010.**
**Lake level was relatively similar for 1938 and 2010, but the 2010 shoreline (purple line) is landward of where it was in 1938 (green line) in the north half of the reach. In the southern half of the reach, the shoreline in 2010 (purple line) was lakeward of where it was in 1938.**

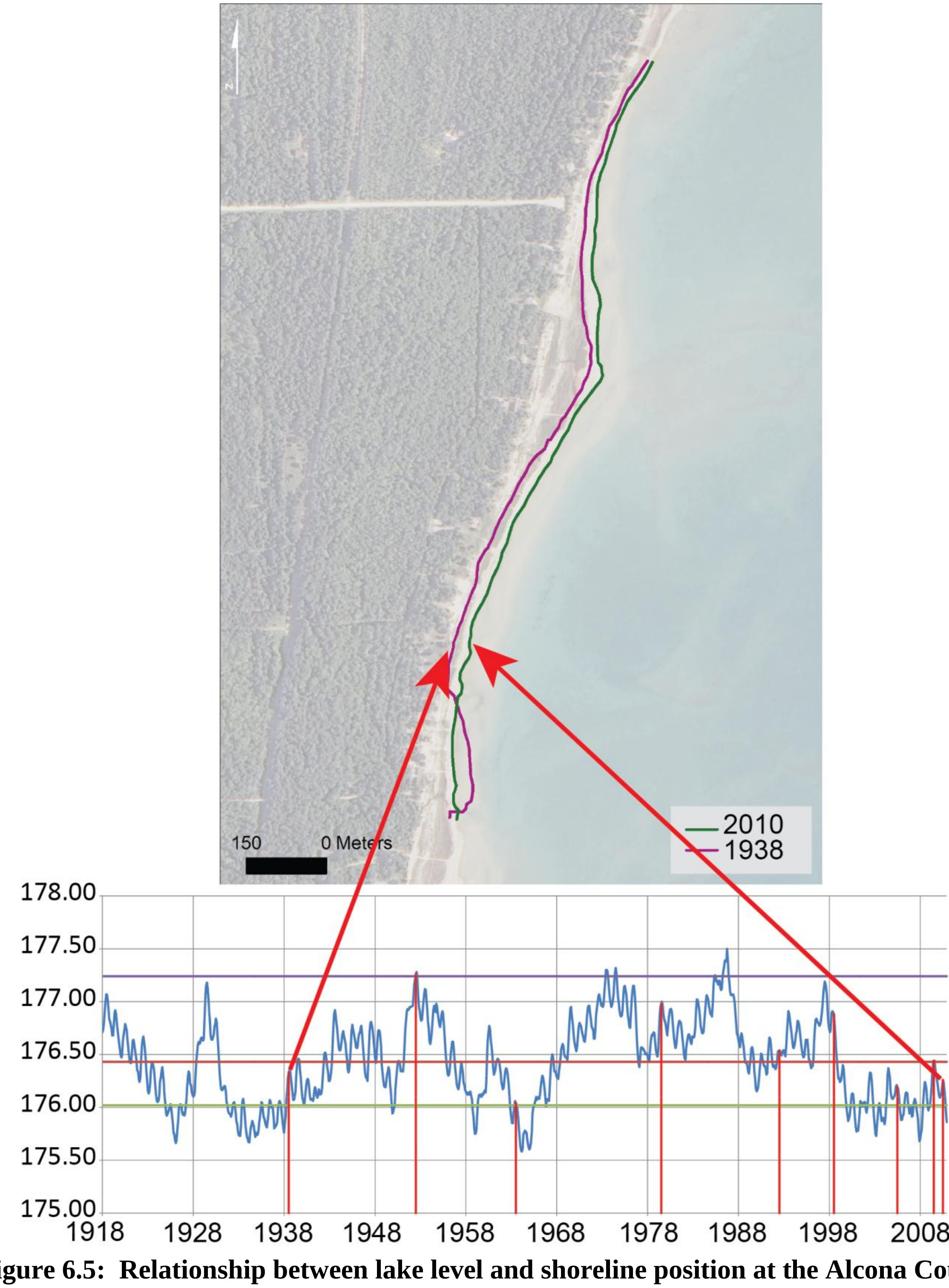



**Figure 6.5: Relationship between lake level and shoreline position at the Alcona County site for 1938 and 2010.**
**Notice that the 1938 shoreline (purple line) is generally landward of the 2010 shoreline (green line) despite the fact that lake level was similar for the two years.**

## SPATIAL PATTERNS OF COASTLINE CHANGE

*Most Change: Manistee County site*

Shoreline position was most variable at the Manistee County site (Fig. 6.6). At the more conservative significance thresholds this site had the most pairs of years with significant shoreline change (Figs. 5.28, 5.29). It is not surprising that this site had the greatest variability in shoreline position, since it is on the west coast of northern Lower Michigan.

Lower Michigan's west coast is open to the full force of dominant westerly winds. Westerly winds drag across the surface of Lake Michigan and produce large westerly waves. These waves are able to grow across the entire fetch of Lake Michigan. When these larger, high-energy waves reach the coast they break and the high energy is released along the coast. This energy mobilizes and redistributes coastal sediment, producing the observed changes in shoreline position.

The Manistee County site had more shoreline change than the Allegan County site, despite more gradual nearshore bathymetry at the Manistee County site. The record wave height for Lake Michigan was 7.01 m and was recorded on September 30, 2011 at a buoy approximately 80 km southwest of Holland, MI (NOAA National Data Buoy Center, 2012). Given that both Manistee County site and Allegan County site are both along the west coast of Lower Michigan and that the bathymetry at the Manistee County site (e.g. Fig. 6.7) is more gently sloping than the Allegan County site nearshore bathymetry (e.g. Fig. 6.8), the Allegan County site should receive more wave energy. The higher energy waves should produce greater shoreline variability at the Allegan County site; however, the Manistee County site had a more variable shoreline position.

A possible explanation for this is that Manistee County site is oriented to the northeast and is located in the northern half of Lake Michigan. This means that the Manistee County site is more likely to be directly impacted by strong northwesterly storms. The waves produced by these large storms have the energy to mobilize large amounts of coastal sediment. The nearly perpendicular angle at which waves impact the coast allows them to dissipate a greater amount of energy at the Manistee County site compared to the Allegan County site. Seibel (1972) and Buckler and Winters (1983) identified northern Lower Michigan coasts with this orientation as the most susceptible to change due to the combination of fetch and coastal orientation. The results of the current study support the findings of Seibel (1972) and Buckler and Winters (1983) by providing evidence that the site with a northeasterly orientation (i.e. the Manistee County site) is the most dynamic of the four sites.

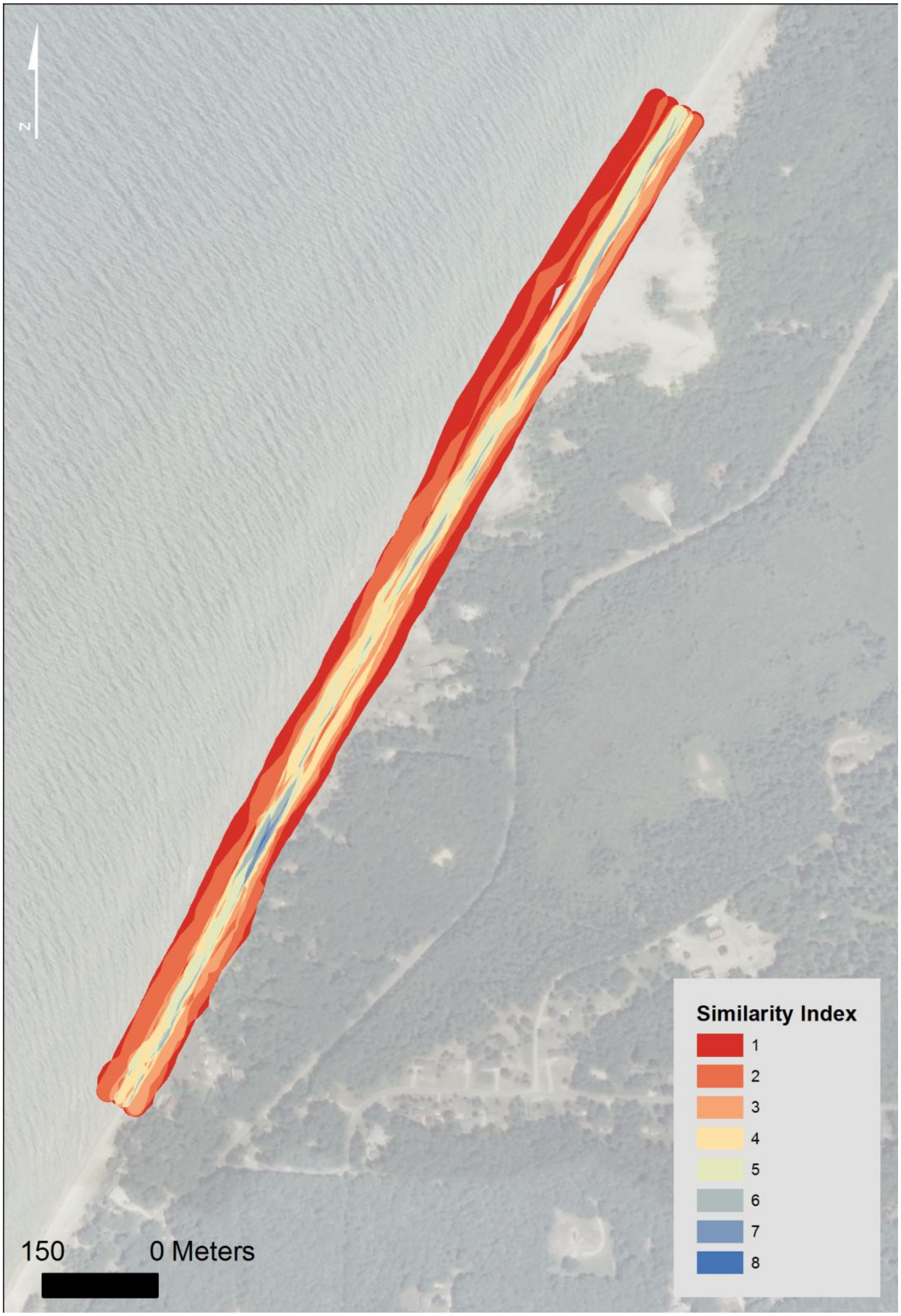



**Figure 6.6: Map of shoreline variability at the Manistee County site.**
**Areas where many shoreline buffers overlap (blue areas) correspond to areas where the shoreline has been more stable. Conversely, more dynamic areas are identified where few shorelines overlap (red areas).**

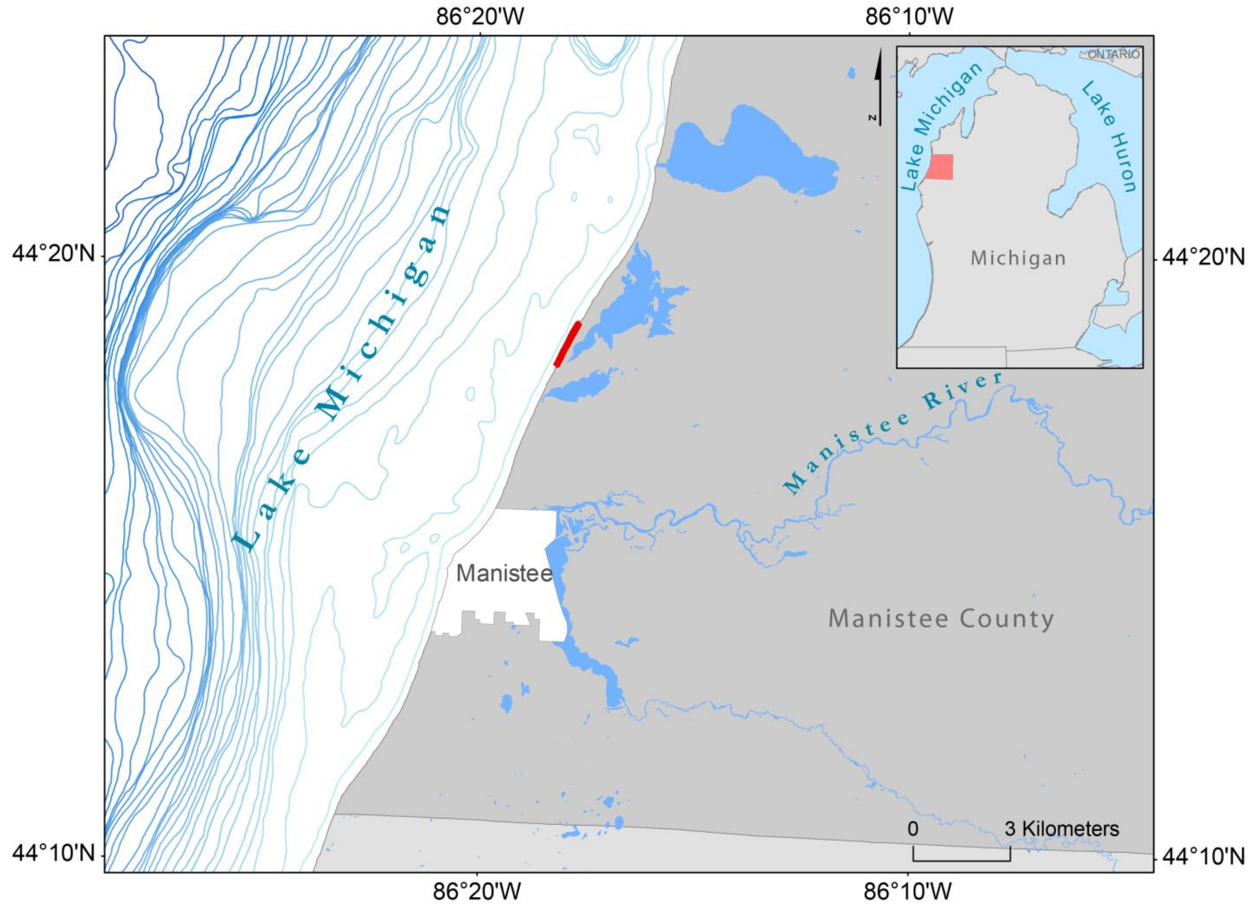



**Figure 6.7: Lake Michigan bathymetry near the Manistee County site. Isobaths represent 5 m contour intervals.**

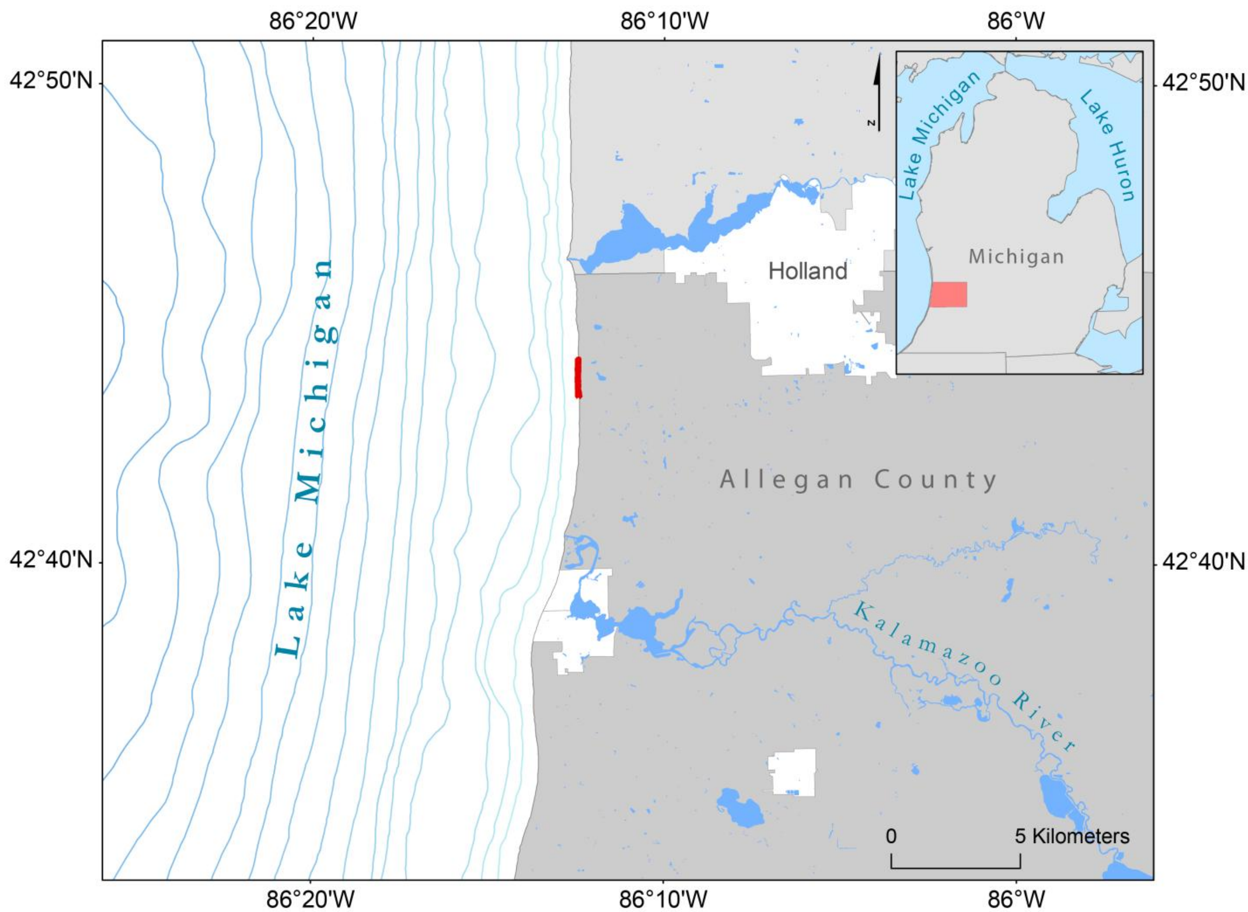



**Figure 6.8 Lake Michigan bathymetry near the Allegan County site. Isobaths represent 5 m contour intervals**

*Least change: Sanilac County site*

In contrast to the Manistee County, Allegan County, and Alcona County sites, the Sanilac County site had the least amount of change at all significance thresholds. Based on simple geometry of Figure 6.1 the Sanilac County site should exhibit shoreline changes similar to the other three sites. However, the Sanilac County site exhibited very little shoreline change (Fig. 6.9). There are several possible reasons for this trend, such as incorrect shoreline delineation, limited fetch, dominant westerly wind and waves, large rocks offshore, the widespread presence of anthropogenic erosion control structures, or a combination of these factors.

One possible explanation for the relatively little change at the Sanilac County site is that shoreline delineation was inconsistent and inaccurate. If this were the case, I would expect there to be little to no relationship between lake level change and shoreline change from one year to the next. However, shoreline position at this site and lake level exhibited a strong inverse relationship (Fig. 5.26). The shoreline was farther inland when lake level was higher and farther lakeward when lake level was lower. This strong inverse relationship suggests that inconsistent or inaccurate shoreline delineation is not the cause of the low-magnitude change observed at the Sanilac County site.

An alternative explanation is that waves reaching the Sanilac County site are limited by the small fetch and dominant westerly winds. Wind data near Flint, MI indicate dominant westerly winds (Figs. 3.18, 3.19). Westerly winds drag across the water surface and transfer energy to the water in the same direction, producing dominant westerly waves. In addition to dominant wind and wave directions, easterly waves impacting this site do not have a large fetch, so there is less distance for easterly winds to transfer energy to the lake. Based on the relatively infrequent and weaker easterly winds, it is likely that easterly waves are smaller and weaker compared to their westerly counterparts. These easterly waves lack the energy necessary to mobilize large amounts of coastal sediment and produce large coastal changes. This hypothesis is supported by Seibel (1972) and Buckler and Winters (1983). Both of these studies concluded that coasts on the west side of Lake Michigan (Buckler and Winters, 1983) and Lake Huron (Seibel, 1972) exhibit less change where fetch is limited and westerly winds are dominant. Similarly, the low change at the Sanilac County site is likely affected by the limited fetch and prevailing westerlies.

A third possible reason that the Sanilac County site exhibited the least amount of shoreline change is that rocks protected the coast from approaching wave energy. The Sanilac County site had a large number of rocks along the coast (Fig. 3.17). It is plausible that these rocks mitigate the amount of wave energy reaching the coast by refracting and reflecting the energy. Waves that are out of phase will interfere with each other, resulting in two weaker waves (Woodroffe, 2002). By the time wave energy reaches the beach face, the energy has been redirected and reduced multiple times. The result is very low-energy waves reaching the beach face. These low-energy waves are less capable of mobilizing large amounts of sandy sediment.

Groins present at the Sanilac County site (Fig. 6.10) likely compound the effects of the naturally occurring rocks. These structures were not visible on the aerial photographs, but likely play a significant role in mitigating shoreline change. Waves approaching the coast at oblique angles are absorbed and redirected by the structures. Overall wave energy is diminished by the interaction of waves, which results in less energy reaching the sandy coastal sediments. In addition to reducing approaching wave energy, these structures interfere with the longshore sediment budget, which may reduce the amount of sediment moving out of the system. This would result in an overall variability of the shoreline position at the Sanilac County site.

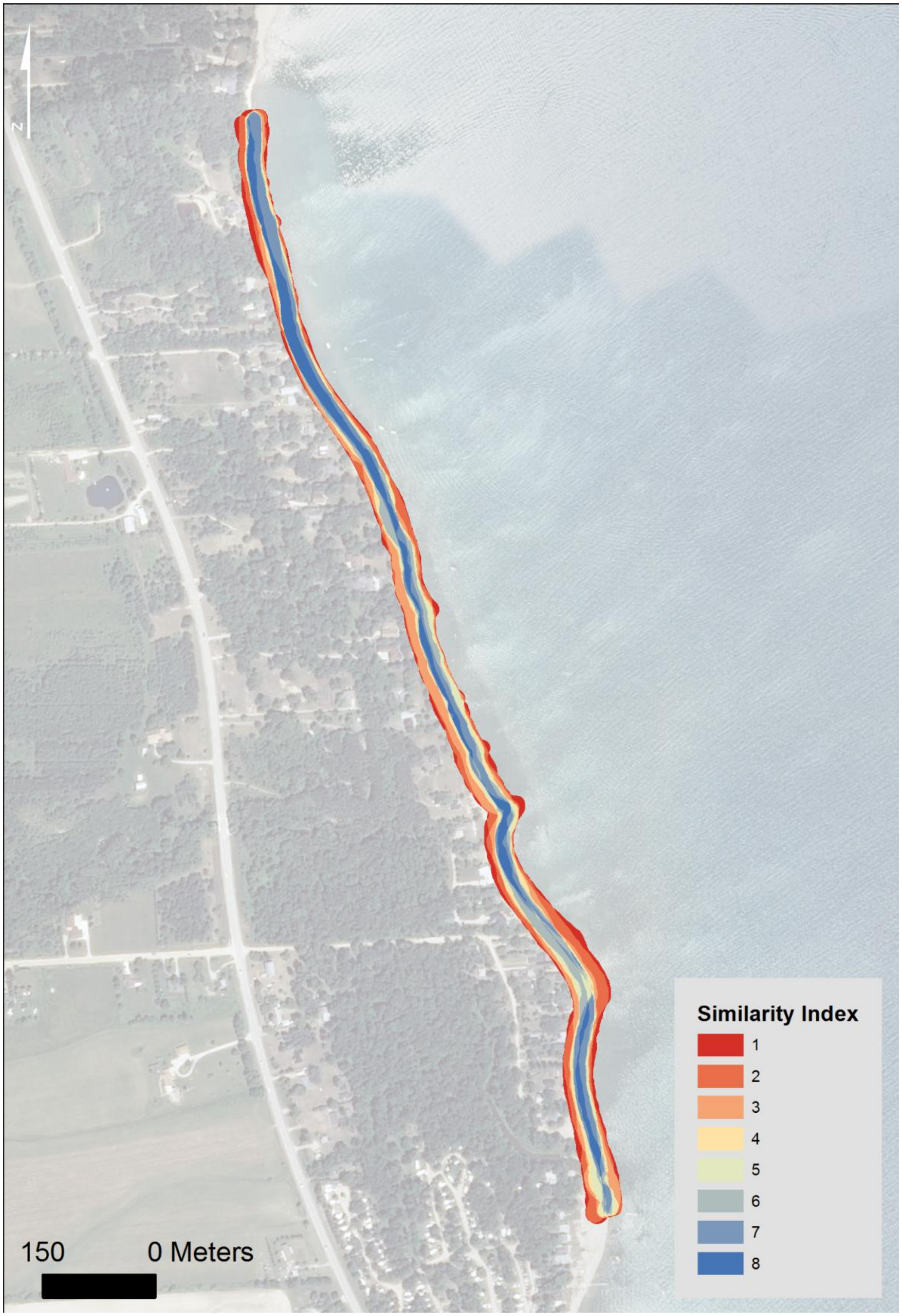



**Figure 6.9: Map of shoreline variability at the Sanilac County site.**
**Areas where many shoreline buffers overlap (blue areas) correspond to areas where the shoreline is more stable. Conversely, more dynamic areas are identified where few shorelines overlap (red areas).**

**Figure 6.10: Looking south at a groin at the Sanilac County site. Note the scale of each of the three control structures present in this photograph. (photo by Phil Wernette)**

Yet another possible explanation for the observed shoreline change at the Sanilac County site is a combination of three previous explanations. Easterly winds are not common but when they do occur they are likely to produce relatively weak easterly waves. These waves are refracted and reflected by naturally-occurring rocks along the coast. This redirection weakens the approaching wave energy. The remaining wave energy is further diminished by the groins, which refract and reflect the remaining wave energy. The combined effect of all three factors is extremely low energy waves reaching the coast. The low energy waves reaching the coast are too weak to mobilize large amounts of coastal sediment. This results in relatively little coastline change at the Sanilac County site.

*West Coast sites versus East Coast sites: Which changed more?*

The primary objective of this research was to compare the spatial variability of coastline change and coastline location on either side of Lower Michigan. In other words, is there more change on Lower Michigan's west coast or east coast? Using the outlined method for shoreline change analysis, the west coast sites appear to be only slightly more dynamic than the east coast sites. The west coast sites had more total pairs of years with significant shoreline change at all significance thresholds (Fig. 5.31). Combined, the Manistee and Allegan sites had 7 significant change pairs at the 0.05 threshold. In contrast, the Alcona and Sanilac sites had a combined total of only 3 significant change pairs at the 0.05 threshold. Both of the western sites were dominated by large landward shoreline movements, while the Sanilac County site exhibited very little shoreline movement (-5.28 m) and no significant change pairs below the 0.45 threshold (Table 5.1).

One possible reason that the east coast had fewer pairs of years with significant change is that the Sanilac County site had different characteristics than the other sites. The Sanilac County site had significantly more gravel, cobbles, and boulders along the coast (Fig. 6.10). Easterly waves that could impact this site would be weak due to the small fetch at this narrow end of Lake Huron. Low-lying groins were also present at this site (Fig. 6.10). Any combination of these factors would likely result in the Sanilac County site being more stable than the other three sites which lacked these characteristics. When combined with the Alcona County site, the relatively stable Sanilac County site would reduce the apparent variability of the combined east coast sites.

A second possible explanation for the west coast having more pairs of years with significant change, mostly landward, is that the coast is influenced more strongly by westerly winds. As a result, there is greater wave run-up along the west coast than on the east coast.

Dominant westerly waves produce small and large westerly waves which impact the west coast of Lower Michigan. Small waves cannot reach as far inland as the larger waves. As a consequence, the shoreline visible on aerial imagery may appear more landward or lakeward depending on the wave conditions at the time the image was acquired. The issue with this explanation is that aerial imagery is typically acquired on days with clear skies and calmer conditions. These calm conditions are less likely to produce a wide range of wave heights that would cause the shoreline to appear in very different positions from one year to the next.

Yet another possible explanation for greater variability at the two west coast sites is that mass wastage processes are more important factors along the west coast. High bluffs were present at both west coast sites. It is plausible that multiple years of shoreline retreat would eventually reach the toe of the bluff and begin to erode toe sediments. This apparent landward change in shoreline position and the associated erosion would cause the bluff to become oversteepened while the shoreline is moving landward. Eroding the toe of the bluff causes the bluff to become oversteepened. Since bluff failure is affected by multiple factors (e.g. Gray and Wilkinson, 1979; LaMoe and Winters, 1989) it is plausible that this failure does not occur immediately, during which time the shoreline appears to be relatively stable. However, when slope failure does occur the bluff sediment is transported downslope. This sediment nourishes the beach and causes the shoreline to appear lakeward from where it was before bluff failure. This process would cause the shoreline to appear to shift lakeward in a single catastrophic event.

## A NEW METHOD FOR COASTLINE CHANGE ANALYSIS

The method used in this study to analyze shoreline change employed a combination of dual epsilon bands and shore-regular transects. This method generates a buffer around shoreline A and shoreline B, based on the uncertainty of each shoreline. A proportion of similarity is then calculated by dividing the overlapping area of buffer A and buffer B by the total area of buffer A and B. This proportion of similarity is then compared to a user-defined significance threshold to determine whether the observed change is significant. If the proportion of similarity is less than the user-defined significance threshold then the change is significant and the traditional transect method can then used to determine the direction and magnitude of change. By combining these two types of analysis, this new method treats the entire shoreline as a single observation while still providing a measure of the direction and magnitude of change. Three assumptions must be met before this method can be applied.

One assumption of this method is that it is possible to determine the positional uncertainty of a shoreline. The historical shorelines used in this research are determined by visual interpretation of georeferenced aerial photographs. During the georeferencing process the $RMSE_{95}$ is calculated for each individual photograph. This georeferencing RMSE is added to the RMSE of the reference image to get the overall RMSE of the georeferenced image. This cumulative RMSE represents a worst case scenario whereby errors from the reference image are compounded by the georeferencing errors. In other words, both errors have the same vector. Since the shorelines are interpreted from these images, the shorelines have the same positional uncertainties as the images. However, the uncertainty of the interpreted shoreline also may include delineation bias. Adding the delineation bias to the georeferenced image RMSE provides a measure of the uncertainty of the interpreted shoreline. In order to use this new method for shoreline change analysis, it is necessary that the uncertainty of a data source can be calculated.

The second assumption of this method of shoreline analysis is that the calculated uncertainty represents a worst case scenario and is constant for the entire length of the shoreline. Since RMSE is a global measure of accuracy within the frame of imagery, it does not allow for spatial variation in accuracy throughout the image (Zhang and Goodchild, 2002). Local variation in the accuracy of the data source will produce variations in the shoreline accuracy. For example, imagery that was georeferenced using a poor network of ground control points will likely contain large errors in parts of the image with sparse control points and smaller errors in areas with many control points (Congalton and Green, 2009). This variability would cause the shoreline to be more accurate in low error areas and less accurate in higher error areas. One way to minimize local variation in accuracy for historical charts and aerial imagery is to use a large number of well-distributed ground control points (Anders and Byrnes, 1991). Yet another way to minimize this variation is to use a set of persistent linear features to georeference the images (Papakosta, et al., 2012). If done appropriately, either one of these georeferencing methods will minimize spatial variation in the accuracy of the data source and the interpreted shoreline.

The third assumption of this method is that shoreline observations are independently delineated. This assumption has been frequently made in previous coastal change studies (Theiler and Danforth, 1994; Pendleton, et al., 2005). To ensure that a shoreline is independent, it is important that no other shorelines are visible during the delineation process. This minimizes the likelihood that the position of the shoreline from one time frame influences the interpreted shoreline position from another date. If these assumptions are met, this new method, which has several advantages, can be applied to analyze shoreline change.

One advantage of the new method is that it propagates uncertainty through to the results. In other words, uncertainty associated with data collection is carried through the entire study to determine the significance of the results. Previous studies acknowledge uncertainty in historical charts (Crowell, et al., 1991; Dolan, et al., 1991), ground surveys (Buckler and Winters, 1983; LaMoe and Winters, 1989), and aerial photographs (Gray and Wilkinson, 1979; LaMoe and Winters, 1989; Jibson, et al., 1994), but no earlier study has quantified and propagated the uncertainty through to the results. By propagating the error and incorporating it into a significance test, this new method maximizes all available information into an unbiased assessment of shoreline change.

The second advantage of this new method is that it can be used across a wide variety of data sources. This study only used aerial imagery to determine shoreline position, but it is possible to apply the method to shorelines derived from other data sources such as ground surveys, GPS measurements, historical charts, lidar, or radar. For example, it is possible to calculate the positional uncertainty of lidar data (Ruggiero and List, 2009) and GPS locations have a positional uncertainty associated with them, as well. The uncertainty associated with the lidar data or GPS observations can be applied to the extracted shoreline and this new method can be used to analyze shoreline change. To apply the new method, it is only necessary to be able to quantify the uncertainty of the data source, which can then be applied to the appropriate shoreline.

A third advantage of the new method is that it treats each entire shoreline as one single independent observation. Previous studies employing the traditional transect method (Crowell, et al., 1991; Pendleton, et al., 2005; Burroughs and Tebbens, 2008; Barnhardt, et al., 2009; Hapke, et al., 2009) treat each intersection of a shoreline in a transect as a single independent observation. The issue with the traditional method is that a large amount of spatial information in the interval between each intersection is completely neglected. The proposed new method addresses this issue by analyzing change along the entire length of a coastal reach. Although the traditional transect method can be used to provide a measure of the magnitude and direction of change, these are only estimates based on a limited sample which will vary depending on the number of transects and space between transects. No information is lost with the new method since the entire length of coast is analyzed to test for the significance of change.

The fourth advantage of using epsilon bands is that they can be applied across multiple spatial and temporal scales. More general spatial changes are identified by comparing the proportion of similarity to the significance threshold. Changes where this proportion is less than the threshold value are more significant than years where the threshold exceeds the proportion. Finer-scale changes are identified by the areas where the two buffers do not overlap (purple areas in Fig. 4.5). These areas are where the shorelines are most dissimilar and change has been most pronounced from one time to another. Another way to identify areas that have more historical variability in shoreline position is to perform a spatial union of all buffers around each shoreline (Fig. 6.11). Areas with pronounced change will have less overlap (e.g. red areas in Fig. 6.11).

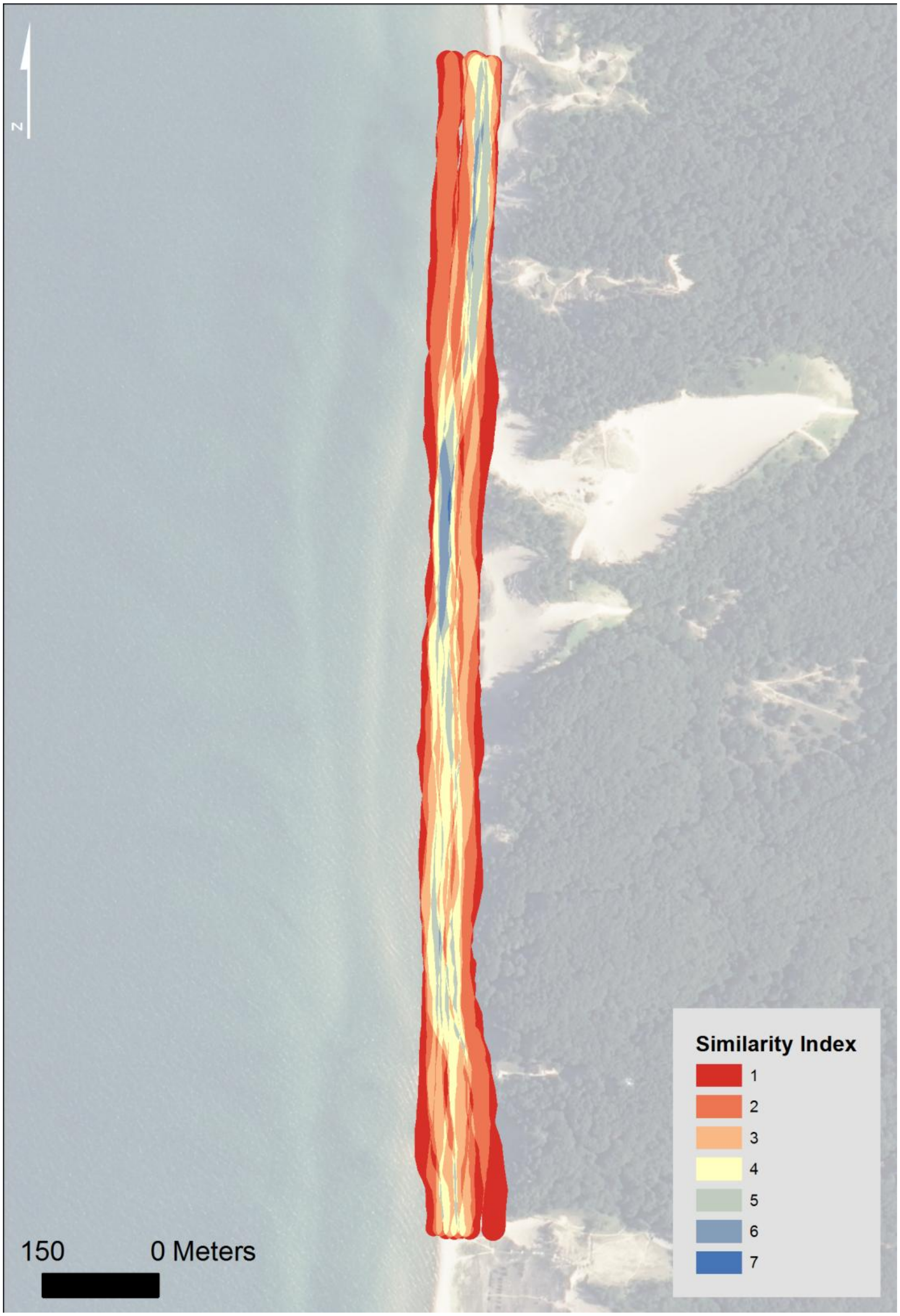



**Figure 6.11: Map of shoreline variability at the Allegan County site.**
**Areas where many shoreline buffers overlap (blue areas) correspond to areas where the shoreline is more stable. Conversely, more dynamic areas are identified where few shorelines overlap (red areas).**

Yet another significant advantage of accounting for uncertainty with the dual epsilon band method is that the uncertainty is applied along the entire reach of shoreline. In the traditional transect method it is theoretically possible to account for uncertainty by simply subtracting or adding the uncertainty to the observed shoreline position. However, mathematically adjusting the shoreline position along a transect suffers from a major issue with transect analysis. That is, there is still a large amount of spatial information that is neglected between each set of transects. Setting the epsilon band radius equal to the uncertainty does not neglect any information along the entire reach of shoreline.

Although there are several advantages to this new method, there are also some potential pitfalls. First, since this method analyzes shoreline change along the entire reach, it is important to determine the appropriate length of coast to analyze. This length will naturally vary depending on the objectives of the researcher. Analyzing longer reaches of shoreline may produce different results than if the same reach was divided into multiple smaller segments. Analyzing longer shoreline segments will assess more general changes, whereas analysis with shorter shoreline segments will permit more detailed information. One way to mitigate this issue is to map the areas that are more stable or more dynamic (Fig. 6.12)

Another potential pitfall with this new method is that the user must set the appropriate significance threshold. The smallest thresholds are the most conservative and result in the fewest pairs of years with significant change. Conversely, larger thresholds are more liberal and result in more pairs of years with significant change (Fig. 6.13). The appropriate threshold depends on the objectives of the researcher.

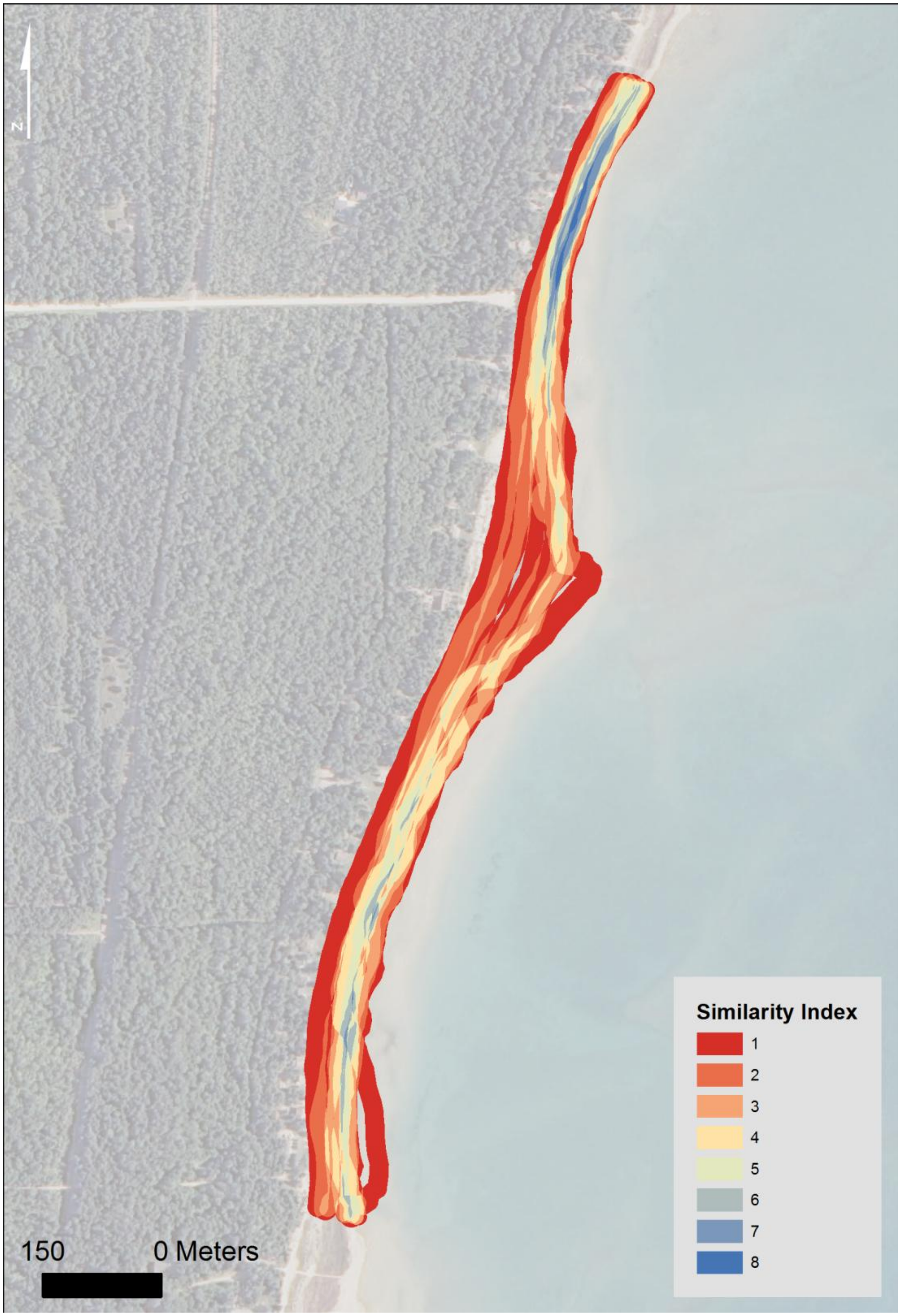



**Figure 6.12: Map of shoreline variability at the Alcona County site.**
**Areas where many shoreline buffers overlap (blue areas) correspond to areas where the shoreline is more stable. Conversely, more dynamic areas are identified where few shorelines overlap (red areas).**

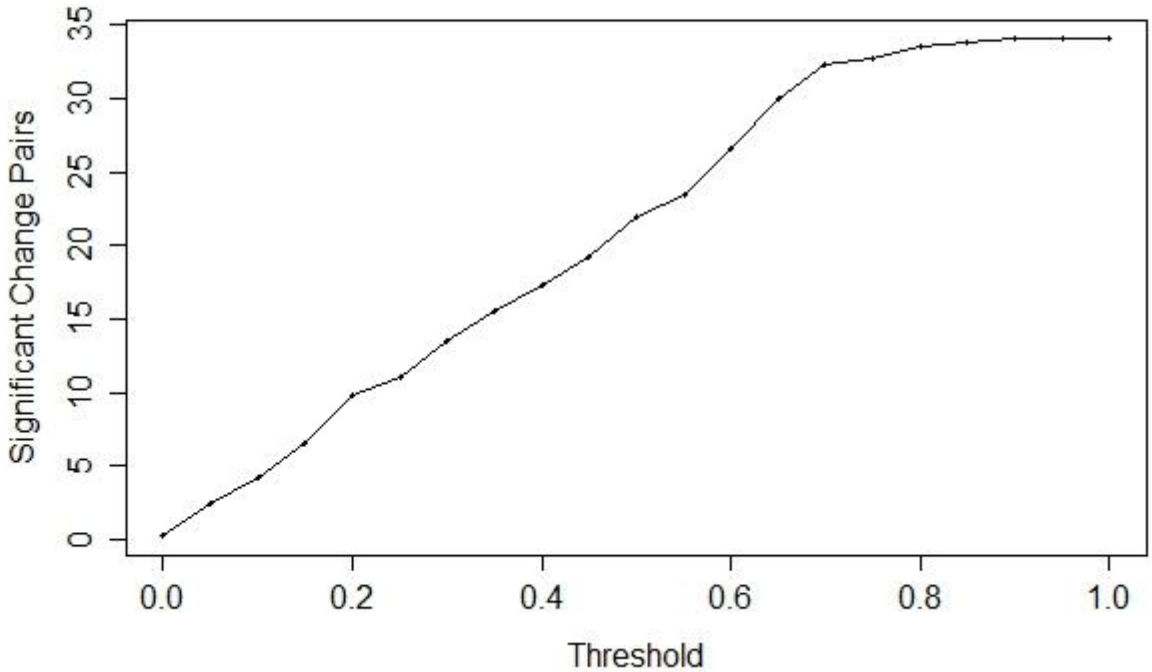



**Figure 6.13: Relationship between the significance threshold and the number of pairs of years with significant change.**

## CONTRIBUTIONS OF THIS RESEARCH

The most significant contributions of this research are directly related to the new method for shoreline change analysis that was devloped. The first is that this new method quantitatively accounts for the positional uncertainty associated with shoreline delineation. Previously documented methods such as the traditional transect method do not account for the uncertainty in shoreline position (e.g. Hands, 1979, 1980; Weishar and Wood, 1983; Anders and Byrnes, 1991; Theiler and Danforth, 1994; Pendleton, et al., 2005; Barnhardt, et al., 2009; Hapke, et al., 2009). Using dual epsilon bands to characterize the uncertainty of the shoreline acknowledges that the shorelines delineated from aerial photos may not be in the correct location compared tothe real world. In addition to quantifying the uncertainty, this study demonstrates that the uncertainty due to image processing is typically greater than the uncertainty due to interpretation errors. The average uncertainty in shoreline position due to image accuracy was typically greater than 10 m. This is much larger than the uncertainty in shoreline position due to delineation bias was only 3.6025 m. The second contribution is that the new method propagates uncertainty through the study into the final results. By propagating the uncertainty through the analysis model and using the epsilon bands to test how significant the observed change is, this new method provides a more accurate representation of how the shoreline has changed from one time to another.

The third major contribution of this study is that the new method analyzes change along the entire length of shoreline. In the traditional transect method change is only measured along evenly spaced transects, which results in a large amount of lost spatial information in the gaps between each of the transect lines. The dual epsilon band method analyzes the change along the entire shoreline, which is important to shoreline change research because there are potentially important morphological changes occurring along the entire coast. The characteristics (e.g., slope, sediment composition, stratigraphy) of one area are likely to influence the forces (e.g., wave run-up, wave energy) acting on adjacent sections of the coast.

The fourth contribution of this study is that it is the first study since Seibel (1972) to compare shoreline change on the west and east coasts of Lower Michigan. Despite Lake Michigan and Lake Huron having the same water plane, many studies have focused only on the Lake Michigan coasts (Lee, 1973; Hands, 1979, 1980; Buckler and Winters, 1983; Weishar and Wood, 1983; LaMoe and Winters, 1989; Jibson, et al., 1994). Understanding how the shoreline has historically changed along both coasts of Lower Michigan can provide information that can be used for coastal management. For example, if a certain area of the coast is found to be highly dynamic, then it should be managed differently than an area that is relatively more stable.

## FUTURE RESEARCH

The methods and results of this study provide ample opportunities for future research. The new method that has been outlined in this study only utilized four locations in Lower Michigan. To verify that these sites were not anomalies, with abnormally high or low change rates, the number of sites should be increased. The additional sites should have a wider range of characteristics such as geologic composition and erosion control structures. Expanding the number and diversity of sites will test how robust this method is when applied to sites with a diverse range of characteristics.

In addition to increasing the number and diversity of sites, further research should focus on how the length of shoreline analyzed affects the results. All four sites in this study were 1.5 km long; however, it is possible that the results would be different if the same method was applied to shorter or longer reaches of shoreline. Applying this method to a wide variety of shoreline lengths would provide valuable information about the relationship between scale and results.

Another avenue for future research is to test this method at locations outside of the Great Lakes. This study focused entirely on shoreline change at four sites in Lower Michigan. The largest tides in the Great Lakes are less than 5 cm in height (NOAA National Ocean Service, 2011). As a result, the Great Lakes are essentially tideless. Although this method is viable in a tideless setting, it is unclear how results would differ if the same method was applied to shoreline change along a tidal coast.

# APPENDICES

## APPENDIX A: DUAL EPSILON BAND GEOPROCESSING SCRIPT

This script was designed to analyze shoreline change using dual epsilon bands. It should be executed in a standalone python editor, and it uses the geoprocessing utilities available with ArcGIS 10.

```
'''
Created on May 23, 2012

Copyright 2012: Phil Wernette

This script is designed to do a comprehensive epsilon bands analysis for each research site. It
loops through all of the specified
locations and years at each site. The steps are:
1) Draw buffer A around shoreline A (radius is based on the uncertainty for shoreline A)
2) Draw buffer B around shoreline B (radius is based on the uncertainty for shoreline B)
3) Intersect buffer A and buffer B
4) Calculate area of buffer A, buffer B, intersection of AB
5) Calculate the intersecting proportion by: (area of AB)/((area of A)+(area of B))

The uncertainty for a shoreline is stored as the "UNCERTAINTY" attribute within the feature
class.

NOTES:
   1: Shorelines for all four sites must be stored in the same geodatabase
   2: Shoreline feature classes must follow the naming convention:
      name = (location)_shoreline_(year)    example: 'alcona_shoreline_1938'
   3: Before running script be sure that the locations array is accurate.
'''
T = True
F = False

import time
import arcpy
from arcpy import env
env.overwriteOutput = T

def create_out_table(outpath, tblname):
   # This function creates a new output table in ArcGIS.
   # The new table will be populated later in the process.
```

```
    outtbl = outpath + tblname
    arcpy.CreateTable_management(outpath, str(tblname))
    arcpy.AddField_management(outtbl, "SITE", "TEXT", "#", "#", "20")
    arcpy.AddField_management(outtbl, "YEAR_A", "SHORT")
    arcpy.AddField_management(outtbl, "YEAR_B", "SHORT")
    arcpy.AddField_management(outtbl, "AREA_A", "FLOAT", "10","10","20")
    arcpy.AddField_management(outtbl, "AREA_B", "FLOAT", "10","10","20")
    arcpy.AddField_management(outtbl, "AREA_AB_OVERLAP", "FLOAT", "10","10","20")
    arcpy.AddField_management(outtbl, "PROP_AB_OVERLAP", "FLOAT", "10", "10", "20")
    arcpy.AddField_management(outtbl, "AREA_AB_TOTAL", "FLOAT", "10", "10", "20")
    del outpath, tblname, outtbl

# DATA TO COLLECT:    site | year_A | year_B | area_A | area_B | area_AB_overlap |
prop_AB_overlap | area_AB_total

def insert_out_row(insert_cursor):
    # This function is designed to insert a new row of data into the output table in ArcGIS
    row = insert_cursor.newRow()
    row.SITE = str(l)
    row.YEAR_A = a
    row.YEAR_B = b
    row.AREA_A = area_a
    row.AREA_B = area_b
    row.AREA_AB_OVERLAP = area_ab
    row.PROP_AB_OVERLAP = prop_ab
    row.AREA_AB_TOTAL = a_and_b_area
    insert_cursor.insertRow(row)
    del row

def elapsed_time_out(loc, loc_elapsed):
    if loc_elapsed < 60:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed) + ' seconds'
    elif loc_elapsed >= 60 and loc_elapsed < 3600:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed/60) + ' minutes'
    elif loc_elapsed >= 3600:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed/3600) + ' hours'
    del loc, loc_elapsed

def clean_up(items):
    # This function is designed to search for and delete any feature class in the specified array
    for clean in items:
        if arcpy.Exists(clean):
            arcpy.Delete_management(clean)

# Paths where data is stored and saved throughout processing
path = 'C:/Users/Phil/Documents/ArcGIS/Default.gdb/' # Geodatabase pathname
```

```
outlog_path = 'C:/Users/Phil/Documents/Geography MS/analysis/epsilon_band_95horizontal/' #
Output log file location
overlap_gdb = 'C:/Users/Phil/Documents/ArcGIS/Epsilon_analysis_95horizontal.gdb/' #
Geodatabase with overlapping segments
# diff_gdb = 'C:/Users/Phil/Documents/ArcGIS/Epsilon_analysis_NONoverlap.gdb/'

# List of temporary feature classes that will be used in the processing
buffer_a = path + 'shorelinebuffera'
buffer_b = path + 'shorelinebufferb'
a_and_b = path + 'shorelinebuffersab'
ab_intersect = path + 'shorelinebuffer_AB'

# List of the four location to be assessed
locations = ['alcona','allegan','manistee','sanilac']

# Corresponding list of years to be analyzed for each site
start_year = 1938
end_year = 2010
year_increment = 1
years_a = range(start_year,end_year + 1,year_increment)
years_b = range(start_year + 1,end_year + 1,year_increment)

''' Toggle option to export the intersected areas to individual feature classes
  T = export the overlapping area    F = do NOT export the overlapping area'''
export_intersect = T

delineation_bias = 3.6025

# List of files to delete at the conclusion of the script
clean_list = [buffer_a, buffer_b, ab_intersect, a_and_b]

start_time = time.time() #Start the timer for the overall processing

for l in locations:
    location_start = time.time()

    out_table = overlap_gdb + l + 'OverlappingBufferTable'

    log = open(outlog_path + 'OVERLAPPING_BANDS_' + str(l) + '.txt','w')
    log.write('Site: ' + str(l) + '\n')
    log.write('site | year_A | year_B | area_A | area_B | area_AB_overlap | prop_AB_overlap |
area_AB_total | delineation_bias\n')

    #Check to see if the output table already exists (delete it, if it does)
    if arcpy.Exists(out_table):
        arcpy.Delete_management(out_table)
```

```
create_out_table(overlap_gdb, str(l) + 'OverlappingBufferTable')

# Create search cursor to insert new data into the table
ins_cur = arcpy.InsertCursor(out_table)

# Loop through all the years for any given site
for a in years_a:
   # Define name of shoreline A
   shoreline_a = path + l + '_shoreline_' + str(a)

   if arcpy.Exists(shoreline_a):

      # Create search cursor to extract the shoreline uncertainty
      a_cur = arcpy.SearchCursor(shoreline_a)
      for c in a_cur:
         a_buf_rad = c.UNCERTAINTY + delineation_bias
      '''
      shoreline_buffer = diff_gdb + l + '_shoreline_buffer_' + str(a)
      if arcpy.Exists(shoreline_buffer):
         arcpy.Delete_management(shoreline_buffer)
      arcpy.Buffer_analysis(shoreline_a, shoreline_buffer, a_buf_rad, dissolve_option="ALL")
      '''
      if arcpy.Exists(buffer_a):
         arcpy.Delete_management(buffer_a)
      arcpy.Buffer_analysis(shoreline_a, buffer_a, a_buf_rad, dissolve_option="ALL")

      # Calculate the area of buffer around shoreline A
      t = arcpy.Geometry()
      tgeometryList = arcpy.CopyFeatures_management(buffer_a, t)
      tarea = 0 #Sets default area to 0 before calculating the area
      for tgeometry in tgeometryList:
         tarea += tgeometry.area
      area_a = tarea

      for b in years_b:
         if b>a:
            # Define name of shoreline B
            shoreline_b = path + l + '_shoreline_' + str(b)

            if arcpy.Exists(shoreline_b):
               print ('Processing ' + str(l) + ' for years ' + str(a) + ' and ' + str(b))

               # Create search cursor to extract the shoreline uncertainty
               b_cur = arcpy.SearchCursor(shoreline_b)
               for d in b_cur:
                  b_buf_rad = d.UNCERTAINTY + delineation_bias
```

```
        if arcpy.Exists(buffer_b):
            arcpy.Delete_management(buffer_b)
        arcpy.Buffer_analysis(shoreline_b, buffer_b, b_buf_rad, dissolve_option='ALL')

        # Calculate the area of buffer around shoreline B
        s = arcpy.Geometry()
        sgeometryList = arcpy.CopyFeatures_management(buffer_b, s)
        sarea = 0 #Sets default area to 0 before calculating the area
        for sgeometry in sgeometryList:
            sarea += sgeometry.area
        area_b = sarea

        # Intersect the two shoreline buffers
        if arcpy.Exists(ab_intersect):
            arcpy.Delete_management(ab_intersect)
        arcpy.Intersect_analysis([buffer_a, buffer_b], ab_intersect, "ONLY_FID")

        # Calculate the intersected AB area
        r = arcpy.Geometry()
        rgeometryList = arcpy.CopyFeatures_management(ab_intersect, r)
        rarea = 0 #Sets default area to 0 before calculating the combined area
        for rgeometry in rgeometryList:
            rarea += rgeometry.area
        area_ab = rarea

        # Union areas A and B and calculte the combined area of A and B
        arcpy.Union_analysis([buffer_a, buffer_b], a_and_b) # Join areas A and B

        u = arcpy.Geometry()
        ugeometryList = arcpy.CopyFeatures_management(a_and_b, u)
        uarea = 0 #Sets default area to 0 before calculating the combined area
        for ugeometry in ugeometryList:
            uarea += ugeometry.area
        a_and_b_area = uarea

        prop_ab = area_ab/a_and_b_area

        insert_out_row(ins_cur)

        # Write results to pipe-delimited .csv file
        log.write(str(l) + '|' + str(a) + '|' + str(b) + '|' + str(area_a) + '|' + str(area_b) + '|' +
str(area_ab) + '|' + str(prop_ab) + '|' + str(a_and_b_area) + '|' + str(delineation_bias) + '\n')

        if export_intersect:
```

```
                        arcpy.FeatureClassToFeatureClass_conversion(ab_intersect, overlap_gdb, str(l)
+ '_overlap_' + str(a) + '_' + str(b) + '_intersected')
                        arcpy.FeatureClassToFeatureClass_conversion(a_and_b, overlap_gdb, str(l) +
'_overlap_' + str(a) + '_' + str(b) + '_merged')

    # Calculate elapsed time for the given location
    location_elapsed = time.time() - location_start

    # Print and Export Elapsed Time
    elapsed_time_out(l, location_elapsed)

    # Close oujtput files
    log.close()

    # Clean up temp files
    clean_up(clean_list)

    del a, b, area_a, area_b, area_ab, prop_ab, l, r, s, t, u, a_cur, b_cur, ins_cur, shoreline_a,
shoreline_b

elapsed_time = time.time() - start_time

if elapsed_time < 60:
    print "Elapsed time: " + str(elapsed_time) + ' seconds'
elif elapsed_time >= 60 and elapsed_time < 3600:
    print "Elapsed time: " + str(elapsed_time/60) + ' minutes'
elif elapsed_time >= 3600:
    print "Elapsed time: " + str(elapsed_time/3600) + ' hours'
```

**APPENDIX B: TRANSECT GEOPROCESSING SCRIPT**

This script was designed to analyze change along pre-defined transects using geoprocessing utilities available in ArcGIS 10. The script is designed to be executed in a standalone python editor.

```
'''
Created on 02 February 2012

Copyright 2012: Phil Wernette

Updated: 12 March, 2012

This script is designed to do a comprehensive epsilon bands analysis for each research site. It
loops through all of the specified
locations and years at each of the specified confidence levels. Each year's shoreline at a given
site is analyzed from and to all other
shorelines at the same site. The results of these analyses are output into the same geodatabase as
the shorelines themselves.

CFOR MORE INFORMATION ABOUT MEASURING THE DISTANCE BETWEEN TWO
LINEAR FEATURES:
http://forums.arcgis.com/threads/47780-Distance-between-two-linear-features

NOTES:
   1: Shorelines and transects for all four sites must be stored in a common geodatabase
   2: Shoreline feature classes must follow the naming convention:
      name = (location)_shoreline_(year)    example: 'alcona_shoreline_1938'
   3. Transect feature classes must follow the naming convention:
      name = (location)_transects          example: 'alcona_transects'
   3: Before running script be sure that the locations and years arrays are complete and
consistent with the feature classes present.
'''

import time
import arcpy
from arcpy import env
env.overwriteOutput = True

# Defines function to generate the output table in the specified geodatabase
```

```
def create_out_table(outpath, loc):
    outtbl = path + loc + '_transect_analysis'
    arcpy.CreateTable_management(outpath, str(loc) + '_transect_analysis')
    arcpy.AddField_management(outtbl, "TRANSECT_ID", "TEXT", "#", "#", "20")
    arcpy.AddField_management(outtbl, "YEAR", "SHORT")
    arcpy.AddField_management(outtbl, "DISTANCE", "FLOAT", "10", "10", "20")
    del outpath, loc, outtbl

def create_out_table_prof(outpath, loc):
    outtbl = outpath + loc + '_transect_analysis_professional'
    arcpy.CreateTable_management(outpath, str(loc) + '_transect_analysis_professional')
    arcpy.AddField_management(outtbl, "SITE", "TEXT", "#", "#", "20")
    arcpy.AddField_management(outtbl, "YEAR", "SHORT")
    arcpy.AddField_management(outtbl, "TRANSECT_ID", "TEXT", "#", "#", "20")
    arcpy.AddField_management(outtbl, "PROFESSIONAL", "TEXT", "#", "#", "20")
    arcpy.AddField_management(outtbl, "DISTANCE", "FLOAT", "10", "10", "20")
    del outpath, loc, outtbl

# Defines the function to calculate, print, and export the elapsed time for a site
def elapsed_time_out(loc, loc_elapsed):
    if loc_elapsed < 60:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed) + ' seconds'
        f.write('Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed) + ' seconds\n')
    elif loc_elapsed >= 60 and loc_elapsed < 3600:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed/60) + ' minutes'
        f.write('Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed) + ' seconds\n')
    elif loc_elapsed >= 3600:
        print 'Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed/3600) + ' hours'
        f.write('Elapsed time for ' + str(loc) + ' - ' + str(loc_elapsed/3600) + ' hours\n')
    del loc, loc_elapsed

# Cleans up all temp feature classes that were generated
def clean_up():
    if arcpy.Exists(tempvert):
        arcpy.Delete_management(tempvert)
    if arcpy.Exists(temptable):
        arcpy.Delete_management(temptable)
    if arcpy.Exists(temproute):
        arcpy.Delete_management(temproute)

path = 'C:/Users/Phil/Documents/ArcGIS/Default.gdb/' # Geodatabase pathname
outlog_path = 'C:/Users/Phil/Documents/Geography MS/analysis/' # Output log file location

shorelinebuffer = path + 'shorelinebuffer'
tempvert = path + 'tempshorelineverticies'
temproute = path + 'temptransectroute'
```

```
temptable = path + 'temptable'

# List of professional shoreline delineations to analyze
professionals = ['acmoody','goodwin','lusch']

# List of the four location to be assessed
locations = ['alcona','allegan','manistee','sanilac']

# Corresponding list of years to be analyzed for each site
start_year = 1938
end_year = 2010
year_increment = 1
years = range(start_year,end_year + 1,year_increment)

alcona_skip = True
allegan_skip = True
manistee_skip = True
sanilac_skip = True
profes_skip = False

# Defines the beginning end of the transects
alcona_dir = "UPPER_LEFT"
allegan_dir = "UPPER_RIGHT"
manistee_dir = "UPPER_RIGHT"
sanilac_dir = "UPPER_LEFT"
profes_dir = "UPPER_LEFT"

start_time = time.time()

for location in locations:
  '''
  ######################## ALCONA COUNTY ########################
  '''
  if location == 'alcona':
    if not alcona_skip:
      print "Beginning " + str(location) + ' analysis'
      location_start = time.time() # Start timer

      out_table = path + location + '_transect_analysis'

      # Generate output log .txt file
      f = open(outlog_path + str(location) + '_transect_analysis_log.txt','w')
      f.write('Site: ' + str(location) + '\n')
      f.write('site | year | transect | distance\n')

      #Check to see if the output table already exists (delete it, if it does)
```

```
        if arcpy.Exists(out_table):
            arcpy.Delete_management(out_table)
        create_out_table(path, location)

        # Transects for each individual research site
        transects = path + str(location) + '_transects'

        # Convert starting points of transects to point feature class
        if arcpy.Exists(temproute):
            arcpy.Delete_management(temproute)
        arcpy.CreateRoutes_lr(transects, "TRANSECT_ID", temproute, "LENGTH",
coordinate_priority=alcona_dir)

        # List of years in site to analyze from
        #years = alcona_years

        # Loop through all the years for any given site
        for year in years:
            toshore = path + location + '_shoreline_' + str(year)

            if arcpy.Exists(toshore):
                print str(location) + ' - ' + str(year)

                # Create search cursor to insert new data into the table
                ins_cur = arcpy.InsertCursor(out_table)

                # Convert shoreline verticies to points to calculate minimum and mean distances
                arcpy.Intersect_analysis([toshore, transects], tempvert, "ONLY_FID",
output_type="POINT")

                # Calculate the distance of the shoreling along each transect
                arcpy.LocateFeaturesAlongRoutes_lr(tempvert, temproute, "TRANSECT_ID", "100
Meters", temptable, "RID POINT MEAS", "FIRST", "DISTANCE", "ZERO", "FIELDS",
"M_DIRECTON")

                # Initiate Search Cursor to cycle through the linear referencing output table
                search_cur = arcpy.SearchCursor(temptable)

                for s in search_cur:
                    tran_id = s.RID
                    dist = s.MEAS

                    r = ins_cur.newRow()
                    r.TRANSECT_ID = str(tran_id)
                    r.YEAR = str(year)
                    r.DISTANCE = dist
```

```
            ins_cur.insertRow(r)

            f.write(str(location) + '|' + str(year) + '|' + str(tran_id) + '|' + str(dist) + '\n')

        # Calculate exapsed time for the site analysis
        location_elapsed = time.time() - location_start

        # Output duration information to output log file and print it on screen
        elapsed_time_out(location, location_elapsed)

        # Close output log text file
        f.close()

        # Clean up temp files
        clean_up()

        del ins_cur, search_cur, toshore, f, transects, location_start, location_elapsed, out_table


    if not profes_skip:
        print "Beginning " + str(location) + ' PROFESSIONAL analysis'
        location_start = time.time() # Start timer

        out_table = path + location + '_transect_analysis_professional'

        # Generate output log .txt file
        f = open(outlog_path + str(location) + '_transect_analysis_log_professional.txt','w')
        f.write('Site: ' + str(location) + '\n')
        f.write('site | year | transect | professional | distance\n')

        #Check to see if the output table already exists (delete it, if it does)
        if arcpy.Exists(out_table):
            arcpy.Delete_management(out_table)
        create_out_table_prof(path, location)

        # Transects for each individual research site
        transects = path + str(location) + '_transects'

        # Convert starting points of transects to point feature class
        if arcpy.Exists(temproute):
            arcpy.Delete_management(temproute)
        arcpy.CreateRoutes_lr(transects, "TRANSECT_ID", temproute, "LENGTH",
coordinate_priority=profes_dir)

        # List of years in site to analyze from
        #years = alcona_years
```

```
        # Loop through all the years for any given site
        for year in years:
            for professional in professionals:
                toshore = path + str(location) + '_shoreline_' + str(year) + '_' + str(professional)

                if arcpy.Exists(toshore):
                    print str(location) + ' - ' + str(year)

                    # Create search cursor to insert new data into the table
                    ins_cur = arcpy.InsertCursor(out_table)

                    # Convert shoreline verticies to points to calculate minimum and mean distances
                    arcpy.Intersect_analysis([toshore, transects], tempvert, "ONLY_FID",
output_type="POINT")

                    # Calculate the distance of the shoreling along each transect
                    arcpy.LocateFeaturesAlongRoutes_lr(tempvert, temproute, "TRANSECT_ID",
"100 Meters", temptable, "RID POINT MEAS", "FIRST", "DISTANCE", "ZERO", "FIELDS",
"M_DIRECTON")

                    # Initiate Search Cursor to cycle through the linear referencing output table
                    search_cur = arcpy.SearchCursor(temptable)

                    for s in search_cur:
                        tran_id = s.RID
                        dist = s.MEAS

                        r = ins_cur.newRow()
                        r.SITE = str(location)
                        r.YEAR = str(year)
                        r.TRANSECT_ID = str(tran_id)
                        r.PROFESSIONAL = str(professional)
                        r.DISTANCE = dist
                        ins_cur.insertRow(r)

                        f.write(str(location) + '|' + str(year) + '|' + str(tran_id) + '|' + str(professional) +
'|' + str(dist) + '\n')

        # Calculate exapsed time for the site analysis
        location_elapsed = time.time() - location_start

        # Output duration information to output log file and print it on screen
        elapsed_time_out(location, location_elapsed)

        # Close output log text file
```

```
        f.close()

        # Clean up temp files
        clean_up()

        del ins_cur, search_cur, toshore, f, transects, location_start, location_elapsed, out_table

    '''
    ######################### ALLEGAN COUNTY #########################
    '''
    if location == 'allegan':
      if not allegan_skip:
        print "Beginning " + str(location) + ' analysis'
        location_start = time.time() # Start timer

        out_table = path + location + '_transect_analysis'

        # Generate output log .txt file
        f = open(outlog_path + str(location) + '_transect_analysis_log.txt','w')
        f.write('Site: ' + str(location) + '\n')
        f.write('site | year | transect | distance\n')

        #Check to see if the output table already exists (delete it, if it does)
        if arcpy.Exists(out_table):
          arcpy.Delete_management(out_table)
        create_out_table(path, location)

        # Transects for each individual research site
        transects = path + str(location) + '_transects'

        # Convert starting points of transects to point feature class
        if arcpy.Exists(temproute):
          arcpy.Delete_management(temproute)
        arcpy.CreateRoutes_lr(transects, "TRANSECT_ID", temproute, "LENGTH",
coordinate_priority=allegan_dir)

        # List of years in site to analyze from
        #years = allegan_years

        # Loop through all the years for any given site
        for year in years:
          toshore = path + location + '_shoreline_' + str(year)

          if arcpy.Exists(toshore):
            print str(location) + ' - ' + str(year)
```

```
            # Create search cursor to insert new data into the table
            ins_cur = arcpy.InsertCursor(out_table)

            # Convert shoreline verticies to points to calculate minimum and mean distances
            arcpy.Intersect_analysis([toshore, transects], tempvert, "ONLY_FID",
output_type="POINT")

            # Calculate the distance of the shoreling along each transect
            arcpy.LocateFeaturesAlongRoutes_lr(tempvert, temproute, "TRANSECT_ID", "100
Meters", temptable, "RID POINT MEAS", "FIRST", "DISTANCE", "ZERO", "FIELDS",
"M_DIRECTON")

            # Initiate Search Cursor to cycle through the linear referencing output table
            search_cur = arcpy.SearchCursor(temptable)

            for s in search_cur:
                tran_id = s.RID
                dist = s.MEAS

                r = ins_cur.newRow()
                r.TRANSECT_ID = str(tran_id)
                r.YEAR = str(year)
                r.DISTANCE = dist
                ins_cur.insertRow(r)

                f.write(str(location) + '|' + str(year) + '|' + str(tran_id) + '|' + str(dist) + '\n')

        # Calculate exapsed time for the site analysis
        location_elapsed = time.time() - location_start

        # Output duration information to output log file and print it on screen
        elapsed_time_out(location, location_elapsed)

        # Close output log text file
        f.close()

        # Clean up temp files
        clean_up()

        del ins_cur, search_cur, toshore, f, transects, location_start, location_elapsed, out_table

    '''
    ######################### MANISTEE COUNTY #########################
    '''
    if location == 'manistee':
        if not manistee_skip:
```

```
        print "Beginning " + str(location) + ' analysis'
        location_start = time.time() # Start timer

        out_table = path + location + '_transect_analysis'

        # Generate output log .txt file
        f = open(outlog_path + str(location) + '_transect_analysis_log.txt','w')
        f.write('Site: ' + str(location) + '\n')
        f.write('site | year | transect | distance\n')

        #Check to see if the output table already exists (delete it, if it does)
        if arcpy.Exists(out_table):
            arcpy.Delete_management(out_table)
        create_out_table(path, location)

        # Transects for each individual research site
        transects = path + str(location) + '_transects'

        # Convert starting points of transects to point feature class
        if arcpy.Exists(temproute):
            arcpy.Delete_management(temproute)
        arcpy.CreateRoutes_lr(transects, "TRANSECT_ID", temproute, "LENGTH",
coordinate_priority=manistee_dir)

        # List of years in site to analyze from
        #years = manistee_years

        # Loop through all the years for any given site
        for year in years:
            toshore = path + location + '_shoreline_' + str(year)

            if arcpy.Exists(toshore):
                print str(location) + ' - ' + str(year)

                # Create search cursor to insert new data into the table
                ins_cur = arcpy.InsertCursor(out_table)

                # Convert shoreline verticies to points to calculate minimum and mean distances
                arcpy.Intersect_analysis([toshore, transects], tempvert, "ONLY_FID",
output_type="POINT")

                # Calculate the distance of the shoreling along each transect
                arcpy.LocateFeaturesAlongRoutes_lr(tempvert, temproute, "TRANSECT_ID", "100
Meters", temptable, "RID POINT MEAS", "FIRST", "DISTANCE", "ZERO", "FIELDS",
"M_DIRECTON")
```

```
        # Initiate Search Cursor to cycle through the linear referencing output table
        search_cur = arcpy.SearchCursor(temptable)

        for s in search_cur:
            tran_id = s.RID
            dist = s.MEAS

            r = ins_cur.newRow()
            r.TRANSECT_ID = str(tran_id)
            r.YEAR = str(year)
            r.DISTANCE = dist
            ins_cur.insertRow(r)

            f.write(str(location) + '|' + str(year) + '|' + str(tran_id) + '|' + str(dist) + '\n')

    # Calculate exapsed time for the site analysis
    location_elapsed = time.time() - location_start

    # Output duration information to output log file and print it on screen
    elapsed_time_out(location, location_elapsed)

    # Close output log text file
    f.close()

    # Clean up temp files
    clean_up()

    del ins_cur, search_cur, toshore, f, transects, location_start, location_elapsed, out_table

'''
######################## SANILAC COUNTY ########################
'''
if location == 'sanilac':
  if not sanilac_skip:
    print "Beginning " + str(location) + ' analysis'
    location_start = time.time() # Start timer

    out_table = path + location + '_transect_analysis'

    # Generate output log .txt file
    f = open(outlog_path + str(location) + '_transect_analysis_log.txt','w')
    f.write('Site: ' + str(location) + '\n')
    f.write('site | year | transect | distance\n')

    #Check to see if the output table already exists (delete it, if it does)
    if arcpy.Exists(out_table):
```

```
        arcpy.Delete_management(out_table)
    create_out_table(path, location)

    # Transects for each individual research site
    transects = path + str(location) + '_transects'

    # Convert starting points of transects to point feature class
    if arcpy.Exists(temproute):
        arcpy.Delete_management(temproute)
    arcpy.CreateRoutes_lr(transects, "TRANSECT_ID", temproute, "LENGTH",
coordinate_priority=sanilac_dir)

    # List of years in site to analyze from
    #years = sanilac_years

    # Loop through all the years for any given site
    for year in years:
        toshore = path + location + '_shoreline_' + str(year)

        if arcpy.Exists(toshore):
            print str(location) + ' - ' + str(year)

            # Create search cursor to insert new data into the table
            ins_cur = arcpy.InsertCursor(out_table)

            # Convert shoreline verticies to points to calculate minimum and mean distances
            arcpy.Intersect_analysis([toshore, transects], tempvert, "ONLY_FID",
output_type="POINT")

            # Calculate the distance of the shoreling along each transect
            arcpy.LocateFeaturesAlongRoutes_lr(tempvert, temproute, "TRANSECT_ID", "100
Meters", temptable, "RID POINT MEAS", "FIRST", "DISTANCE", "ZERO", "FIELDS",
"M_DIRECTON")

            # Initiate Search Cursor to cycle through the linear referencing output table
            search_cur = arcpy.SearchCursor(temptable)

            for s in search_cur:
                tran_id = s.RID
                dist = s.MEAS

                r = ins_cur.newRow()
                r.TRANSECT_ID = str(tran_id)
                r.YEAR = str(year)
                r.DISTANCE = dist
                ins_cur.insertRow(r)
```

```
            f.write(str(location) + '|' + str(year) + '|' + str(tran_id) + '|' + str(dist) + '\n')

        # Calculate exapsed time for the site analysis
        location_elapsed = time.time() - location_start

        # Output duration information to output log file and print it on screen
        elapsed_time_out(location, location_elapsed)

        # Close output log text file
        f.close()

        # Clean up temp files
        clean_up()

        del ins_cur, search_cur, toshore, f, transects, location_start, location_elapsed, out_table

elapsed_time = time.time() - start_time

if elapsed_time < 60:
   print "Elapsed time: " + str(elapsed_time) + ' seconds'
elif elapsed_time >= 60 and elapsed_time < 3600:
   print "Elapsed time: " + str(elapsed_time/60) + ' minutes'
elif elapsed_time >= 3600:
   print "Elapsed time: " + str(elapsed_time/3600) + ' hours'
```

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## BIBLIOGRAPHY


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