DETERMINING HUMAN DOMINANCE THRESHOLDS FOR BARRIER ISLANDS ALONG THE NEW JERSEY COAST

By

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and approved by

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Abstract of the Dissertation

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Increased development and subsequent shoreline stabilization practices on barrier islands (i.e. groins, seawalls, bulkheads) suggest thresholds exist at which human dominance supersedes natural geomorphic processes. Geomorphic thresholds are defined by ratios where opposing variables (numerators and denominators) have opposing tendencies. Determining thresholds is important because once a barrier island is human-dominated, physical dynamic processes altering the island are considered undesirable.

The research in this dissertation shows human dominance thresholds were reached for New Jersey's eight (8) developed barrier islands by 1962. This finding is based on human and physical factors of historical landscape evolution. A "Developed Barrier Island Life-Cycle" conceptual model was used to identify stages of development along the barrier islands and define when island-scale human dominance occurs. A Geographic Information System (GIS) was used to delineate human and physical land cover types (i.e. urban polygons, barren land polygons and wetland polygons) and additional human variable datasets (i.e. building points, road polylines, shore protection structure polylines) from aerial photographs for every decade between 1920 and 2012. Island-wide, 100m zonal analysis areas (bins) were used along the entire study area to quantify the land cover types and human variable datasets through time. A ratio calculation was used to determine when a human dominance threshold was reached within a given bin. Thresholds were calculated by dividing the area of urban land cover polygons (human factor) by the area of barren land and wetland polygons (physical factor). Results were analyzed at the bin, island, and study area scales. The distribution of human dominance in the study area was compared across the barriers located in the northern “wave-dominated” and southern “mixed energy” geomorphic regions at the three scales to determine if geomorphic classifications influence where and when human dominance occurs. Island mobility was calculated as the standard deviation of the total land cover area (combined urban, barren land, and wetland polygons) within every bin for each year’s land cover dataset. Results show that (1) developed barriers experience a state-change, when human activities overshadow natural processes, (2) barrier morphology and geomorphic classifications of barrier type do not dictate when and where a given section of the barrier is human dominated. Morphology of the two barrier types plays a significant role in where humans access barrier islands and when they are initially developed, (3) island mobility correlates with human dominance thresholds at various scales and determines that human agency is a more important factor than shoreline change at the local scale and (4) human dominance at the local scale can be attributed to access via railroads, while the construction of vehicular access bridges and roads induce human dominance at the island-scale.

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Chapter 1: Research Background, statement and purpose

1.1 Introduction

Assessments of the significance of human action in landform change have increased over the past few decades (James & Marcus 2006). Most recently, Donchyts (2016) found that at the global scale, coastal areas gained 33,700km^2 of land over the past 30 years. The data documents how humans have created more land along coasts, even as sea level is rising globally (Morelle 2016).

At smaller scales, studies of human-induced changes to processes and morphology are especially numerous in fluvial systems (Brooks & Brierley 1997; Hooke 2006; Wohl 2006) and are increasingly common in studies of slopes (Wilkerson & Schmid 2003; Remondo et al. 2005; Chiverrell et al. 2007), playas (Gill 1996), glaciers (Burger et al. 1999) and coastal systems (Stutz & Pilkey 2005; Nordstrom 2000; Lentz & Hapke 2011; Rogers et al. 2015). Input of human processes to landform change can be evaluated at large temporal and spatial scales (Werner & McNamara 2007; Sabatier et al. 2009; Hapke et al. 2013; Donchyts et al. 2016) or small scales (Nordstrom et al. 2000).

Studies by Morton et al (1995; 2002; 2008) and Moore et al (2007; 2010) focus on modeling and documenting geomorphic responses of barrier islands to extreme coastal storm events and sea-level rise along the Texas, North Carolina, and Virginia coasts. The studies were performed at local and regional scales across varying temporal scales (decades to centuries), but do not account for human alterations to these areas. This is a problem since different scales are often linked:

small-scale human alterations to landforms take on increased regional importance when they are ubiquitous or recurring. Nordstrom and Jackson (1995) and Rogers et al. (2015) address this problem by demonstrating how human development and restoration following major storms along a developed coasts differ from non-developed areas, and determine that human processes are as predictable as natural processes. Even more significant is that Nordstrom and Jackson (1995) found the speed at which humans develop the landscape following storms outpaces natural processes.

Understanding the evolution of human-altered coastlines is important since the coastal counties in the United States contain 53% of the nation's population but only account for 17% of the country's land area (Crossett 2004). This understanding is critical for heavily developed barrier islands because these landforms are dynamic and especially susceptible to shoreline erosion related to accelerated sea-level rise, coastal storms, and changes in longshore current patterns. These events can exacerbate erosion and cause island-wide changes in relative position (i.e. migration). Recent research presented by Hapke et al. (2013) and Rogers et al. (2015) addressed how human alterations to shorelines are correlated to shoreline change rates and found that human development can override the geomorphic signal of a shoreline. Lentz and Hapke (2011) address the difficulty in identifying barrier responses to anthropogenic or natural influences (i.e., coastal storms) and found that human alterations may have intensified differences already inherent in the system. Nordstrom (1994) also suggests natural coastal evolution models may not be relevant once a coastal barrier has passed a critical threshold of human development and that human alterations are incompatible with natural coastal processes shaping coastal barriers.

Determining thresholds for developed barrier islands can be attained by classifying and analyzing land cover types (human and physical) through time (Jackson et al. 2000). Jackson et al. (2000) quantified spatial and temporal land cover change utilizing aerial photography to classify changes along a developed tide-dominated barrier island on 200 m transects (or analysis zones). The study used principal components and factor analysis to explain several variables of human and physical land cover change through time, including number of buildings, number of hard structures, beach width, and dune width. The analysis produced three factors (geomorphic, settlement, and inlet) and showed they change through time. The results of that study and similar studies such as Kochel (1985) and Stutz and Pilkey (2005) suggest shoreline change and human development are significant factors in barrier island evolution, indicating that these factors can be used to determine human dominance thresholds.

Stutz and Pilkey (2005) documented how human actions have modified the natural function of barrier islands along the Texas coast to "terminate" a barrier island's mobility in response to physical processes. Stutz and Pilkey's (2005) concept of a "terminated" barrier island suggests that when an island's "anthropic index", or the qualitative measure of human modifications, surpasses an island's "geomorphic carrying capacity" (i.e. the qualitative measure of an island's response to natural processes), a barrier island becomes human-dominated. Stutz and Pilkey determined anthropic index and geomorphic carrying capacity values by categorizing several measured regional-scale human (i.e. buildings, roads, jetties, and seawalls) and physical factors (i.e. island width, island elevation, shoreline change, and storm frequency). The semi-quantitative model presented by Stutz and Pilkey (2005) comparing anthropic force to geomorphic carrying capacity (Figure 1) provides a preliminary baseline study at the region-scale for understanding the basic processes of how human modifications to barrier islands may ultimately dominate a natural system.

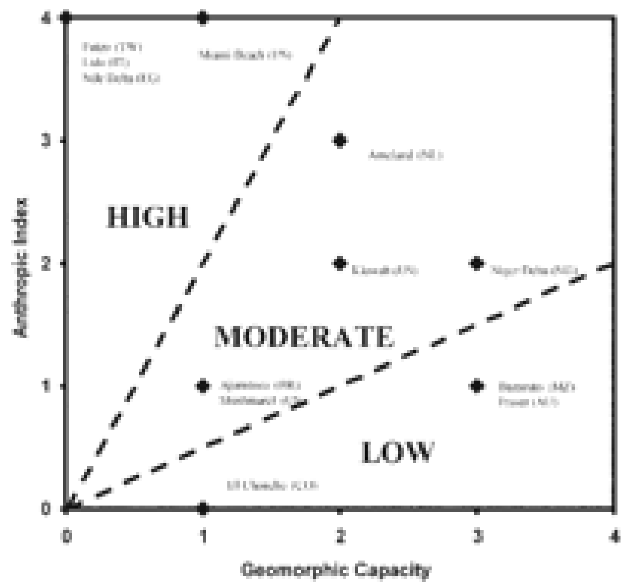


Figure 1. Stutz and Pilkey's (2005) plot of anthropic force versus geomorphic carrying capacity. A high anthropic index value relative to low geomorphic carrying capacity value is indicative of a human-dominated island. A low anthropic index value and high geomorphic carrying capacity value is indicative of a natural process-dominated island. Moderate anthropic index and geomorphic values suggest a balance between human alterations and physical processes shaping a barrier island.

While studies have demonstrated how human alterations to barrier islands can over-ride natural geomorphic processes (Nordstrom & Jackson 1995; Stutz & Pilkey 2005; Lentz & Hapke 2011; Hapke et al. 2013; Rogers et al. 2015), my research introduces a model for quantifying human dominance thresholds for developed barrier islands. The rate at which humans alter barrier islands may vary spatially and temporally due to the geomorphic classification of a given barrier (i.e. wave-dominated, mixed energy), but the methods humans use to modify and maintain a barrier island's landscape through construction of roads, buildings, and shore protection structures (jetties, seawalls, and bulkheads) are consistent. Due to its history of intense development and shore protection practices, New Jersey's *developed* barrier islands were selected for this study. The New Jersey coast has a total of nine (9) barriers. One of the barriers is uninhabited (Little Beach Island) and was not included in the study. The remaining eight (8) developed barriers in the study area are described in Section 1.1.2 and highlighted in Figure 2.

1.1.1 Background

New Jersey has had the longest history of development of any barrier island coast in the United States and is also one of the most heavily engineered (Hapke et al. 2010). Prior to the 1850's, the barrier islands had little human interaction with the exception of Native Americans and European settlers forming small fishing village enclaves. In the 1850's the first railroad from Philadelphia to Atlantic City on Absecon Island was introduced followed by the New York and Long Branch Railroad in the 1870s (Koedel 1979). During the late nineteenth and early twentieth centuries, development along New Jersey's barrier islands grew gradually with the addition of bridges to accommodate automobiles (New Jersey Historical Commission 1980). This development increased significantly between 1950 to 2000 with multi-lane highways replacing railroads as the primary access to the barrier island "resorts" from the major metropolitan areas of New York and Philadelphia (Farrell et al. 2011). A tourism-centric economy emerged with increased access to the barriers. Rapid development increased with the construction of residential and commercial buildings and roads and infrastructure. Hard shore protection structures such as groins, jetties, seawalls, and bulkheads were constructed to stabilize shorelines to protect landward development. Expansion of development along each barrier would have continued if environmental regulations such as the Wetlands Act of 1970 and the creation of state parks, natural areas, and national wildlife refuges were not adopted over time to restrict alterations to tidal wetlands (State of New Jersey 1970). Between 1880 and the adoption of the Wetlands Act in 1970, approximately 40% of the state's wetlands were lost to human alterations such as dredging and infilling for development (Kropilak 2013). In 2015, tourism revenue generated $37.3 billion and provided 318,330 direct jobs for the state of New Jersey (Economics 2015).

1.1.2 Study Area Description

The New Jersey barrier islands are believed to have formed 5,000 to 7,000 years ago (Oertel & Kraft 1994). Belknap and Kraft (1977) produced a generalized sea-level curve for the mid-Atlantic suggesting that sea-level has risen relatively slowly for the past 6,000 to 7,000 years. Oertel and Kraft (1994) suggest that the formation of New Jersey's barrier islands occurred during the last 7,000 years.

Geomorphic classifications presented by Fisher (1967) identify New Jersey's northern geomorphic region (Sandy Hook to Little Egg Inlet) as a "wave-dominated" coast and the southern geomorphic region (Little Egg Inlet to Cape May) as "tide-dominated", or "mixed energy", coast (Figure 2). The southern mixed energy geomorphic region consists of tidal inlets separating barrier islands spaced closer together (approximately 10-15 km) when compared to the northern wave-dominated geomorphic region (approximately 30-40km). The northern wave-dominated geomorphic region has a mean tidal range of 1.31m along the ocean at Seaside Heights (NOAA 2012) and the southern mixed-energy geomorphic region has a mean tidal range of 1.40 m along the ocean at Cape May (NOAA 2012). Within these two regions, there are two wave-dominated barriers separated by three tidal inlets: Manasquan Inlet to Barnegat Inlet (northern Ocean County barrier-spit) and Barnegat Inlet to Little Egg Inlet (Long Beach Island). Since the tidal range difference is minimal, the controlling factors differentiating New Jersey's two geomorphic regions can be attributed to antecedent geology (i.e. stream valleys, offshore topography) and drainage divides (Oertel & Kraft 1994). Oertel and Kraft (Oertel & Kraft 1994) identified that (1) intermediate drainage divides influence the position of shore parallel coastal lagoons located between wave-dominated barriers and the mainland and (2) small drainage divides influence the location of mixed-energy (i.e. tide-dominated) barriers. There are seven mixed energy barrier islands separated by eight inlets: Little Egg Inlet to Brigantine Inlet (Little Beach), Brigantine Inlet to Absecon Inlet (Brigantine), Absecon Inlet to Great Egg Inlet (Absecon Island), Great Egg Inlet to Corsons Inlet (Ocean City), Corsons Inlet to Townsends Inlet (Ludlam Island), Townsends Inlet to Hereford Inlet (7-Mile Island) and Hereford Inlet to Cold Springs Inlet (the Wildwoods). Human alteration to all islands in the study area has been thoroughly documented by Nordstrom (1994) and all of the barrier islands across both geomorphic regions (Figure 2) exhibit similar shore protection features (groins, jetties, seawalls, and bulkheads) as well as dense development and infrastructure (buildings and roads).

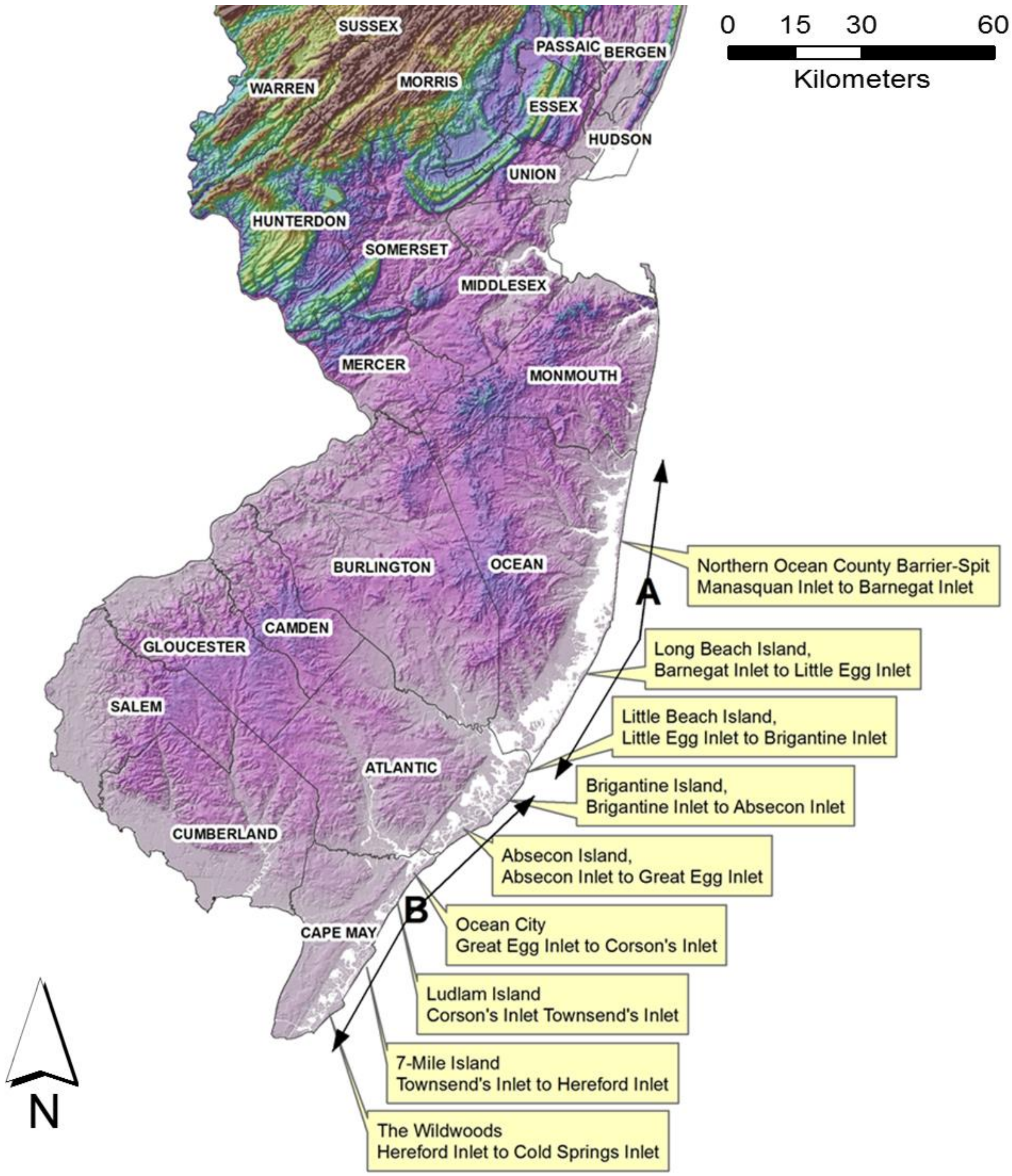


Figure 2. Map of New Jersey identifying barrier island locations and the two geomorphic regions (black) presented by Fisher (1967). From north to south: Region "A" is the wave-dominated geomorphic region and includes the northern Ocean County Barrier-Spit and Long Beach Island. Region "B" is the mixed energy geomorphic region and includes Little Beach Island (uninhabited), Brigantine Island, Absecon Island, Ocean City, Ludlam Island, 7-Mile Island, and The Wildwoods.

In addition to installing hardened structures such as groins, jetties, seawalls, and bulkheads, development has also resulted in land clearing for buildings and dredging and infilling of back-barrier marsh areas to create artificial lagoons adjacent to newly buildable land. Recently (late 1970s-present), most shore protection projects in New Jersey have been beach replenishments (Nordstrom 1994; Psuty & Ofiara 2002; ASBPA 2007).

1.1.3 Geomorphic Regions

Wave-dominated and mixed-energy barrier islands have different morphologies due to the different dominant physical processes shaping them (Hayes 1979). Wave-dominated barrier islands such as Long Beach Island (LBI) are linear landforms that are typically longer, thinner, and associated with large linear tidal lagoons between the barrier and mainland. Mixed-energy barrier islands have well developed ebb-tidal deltas within their inlets, are typically shorter, wider, and associated with large tidal channel/marsh complexes between the island and mainland. Physical processes within tidal inlets bordering both tide- and wave-dominated barrier islands can affect the shape and size of an island. Sediment bypassing inlets to adjacent island shorelines and changes in channel location within an inlet throat between barrier islands can increase or decrease beach width along the ocean front or along the inlet throat (FitzGerald et al. 1984; Nordstrom 1987; FitzGerald 1996; Fitzgerald & Van Heteren 1999). Due to these processes, mixed-energy barrier islands tend to have a “drumstick” shape and are shorter when compared to the longer and more linear wave-dominated type (Davis Jr & Hayes 1984). My research addresses how these distinct geomorphic characteristics may have caused differences in where and when initial human development occurred, but will reveal that all of the developed barrier islands in the study area reached human dominance thresholds through similar human alterations suggesting classifications may require a re-evaluation to account for human dominance.

1.1.4 Geomorphic Thresholds (Bull, 1980)

A geomorphic threshold is defined by Schumm (1979) as a condition at which there is a significant landform change. Geomorphic thresholds allow for detailed descriptions of landform evolution, highlighting changes over small time-scales, where analyses over larger time-scales may not account for natural complexity of landform evolution (Brunet 1968; Schumm 1979; Bull 1980; Church 2002; Chin et al. 2014). Schumm adds that geomorphic thresholds gain increasing importance when humans attempt to manage and control various landscapes (i.e. rivers, slopes, flood plains). Chin et al. (2014) suggests that feedbacks are critical for understanding human-altered geomorphic systems, but notes gaps exist in understanding geomorphic systems with significant human alterations. Initially, geomorphic thresholds were considered intrinsic, in that a threshold represented an abrupt change in a landform without a change in an external variable such as climate or land use. However, external variables such as extreme coastal storms causing abrupt physical changes to barrier islands are accepted as extrinsic thresholds (Schumm 1979). Phillips (2006) notes that changes within geomorphic systems are non-linear, since they are largely threshold-dominated. Human influence on geomorphic thresholds was specifically addressed by Church (2002) in riverine landscapes. Church (2002) found human actions dictate the character of riverine landscapes and can precipitate a threshold being reached, causing a change in state (extrinsic). Church (2002) also found that changes occur systematically along a drainage system, identifying a sequence of change. While Church's study views humans as a contributing factor for determining overall threshold values, my research concludes humans are the determining factor in identifying a change in barrier island state. Stutz and Pilkey (2005) present a regional-scale, semi-qualitative study for determining human-dominated systems by comparing human activities to natural processes. However, the method used to determine the relative influence human activities have on barrier islands does not present a means to model human alteration processes at varying spatial (local to regional) and temporal (decades to centuries) scales nor does it identify when and where human dominance occurs at these scales.

The importance of spatial and temporal scale in geomorphology (and geomorphic thresholds) cannot be overstated. Schumm and Lichty's (1965) research of drainage basin geomorphology brought scale into the forefront of geomorphologic research, demonstrating that relationships between geomorphic variables within a given system may be interdependent at one scale and independent at another scale. Schumm and Lichty's work on this concept related primarily to the temporal scale. However, as Phillips (1988) demonstrated by researching geomorphic controls of desert stream channels, the concept that processes act upon systems over different, independent scales can be applied to spatial scale as well.

My research quantitatively determines human dominance thresholds at varying spatial scales. By treating the human dominance threshold as a ratio between human and physical factors at the 100m scale for roughly each decade over a 92-year time-period, results were aggregated to island and study area scales and analyzed to compare the rate and location of human dominance across the various scales.

Bull (1980) presented geomorphic threshold ratio as a means to simplify complex geomorphic systems into numerators and denominators where the factors that reduce the likelihood of a threshold being crossed are represented as a denominator value and the factors contributing to the threshold being crossed are represented as the numerator. When the ratio represents a value equal to or greater than one, the threshold has been crossed. Bull (1980) presented several examples of where this concept is applicable, one of which describes the hillslope runoff threshold (Equation 1).

Equation 1. Hillslope runoff geomorphic threshold equation presented by Bull (1980):

$$Geomorphic\ Threshold\ = \frac{Factors\ that\ Promote\ Runoff}{Factors\ that\ Promote\ Infiltration} = 1$$

When applied to the factors quantified for this study (Table 2), Bull's geomorphic threshold equation (Equation 1) can be modified to determine human dominance thresholds for developed barrier islands at the 100m zonal analysis bin scale (Equation 2).

Equation 2. Human dominance threshold equation modified from Bull (1980):

$$Human\ Dominance\ Threshold\ = \frac{Total\ Area\ of\ Urban\ Polygons}{Total\ Area\ of\ Barren\ Land\ and\ Wetlands\ Polygons} = 1$$

Where,

$Total\ Area\ of\ Urban\ Polygons$ is the "human factor" delineation encompassing human altered land variables including roads, buildings, cleared land, and "hard" shore protection features (e.g. bulkheads, groins, jetties, and seawalls) and;

Total Area of Barren Land and Wetlands Polygons is the "physical factor" encompassing delineations of variables including beaches, dunes, tidal marshes, maritime forests, and any other lands where physical processes continue to alter them without human alteration.

Chapter 2, section 2.2 provides a detailed description of measured factors used for determining human dominance thresholds at the island and study area scales.

1.1.5 Human Dominance Thresholds

Butler (1980) developed a "Tourism Area Life-Cycle" model (TALC) to understand change relative to the amount of tourists in coastal areas relative to time (Figure 3).

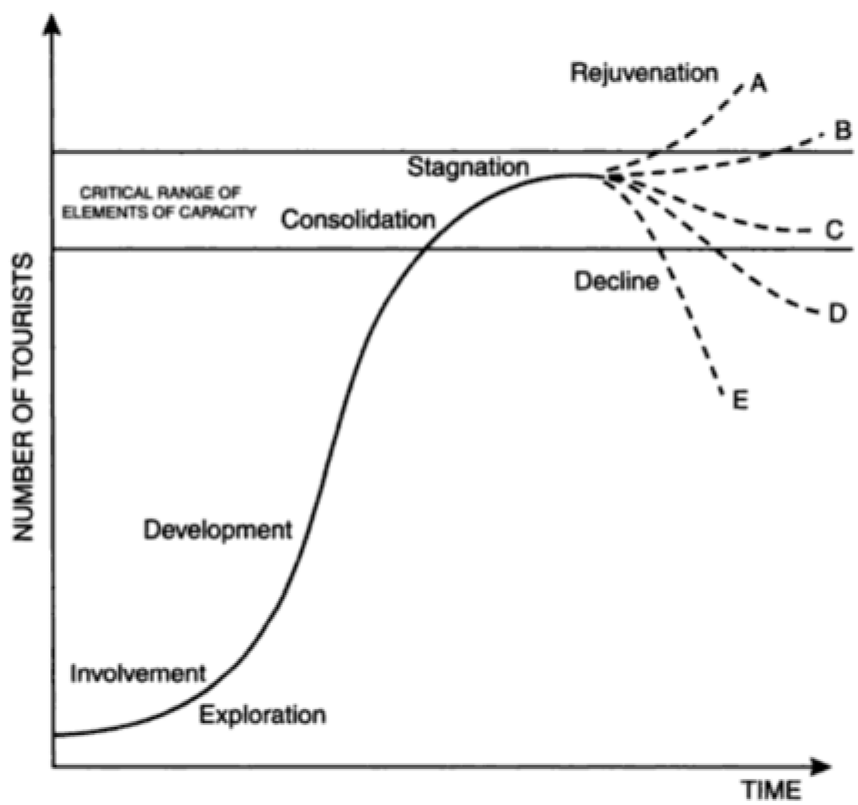


Figure 3. TALC Model developed by Butler (1980).

The TALC model is one of the most commonly used conceptual models applied to tourism areas (Baum 1998). Since Butler's publication , the model has inspired research in tourism areas ranging from Thailand to Atlantic City (Butler 2006). The wide-spread application of the model can be attributed to its framework of tourism stages identified in Figure 3. These stages are described below.

The “Exploration” Stage is the beginning stage, where few people discover an area prior to any tourism activities performed by locals and the local economy does not rely on tourism to function. The “Involvement” Stage is when local businesses are established to accommodate tourists (hotels, restaurants, etc.). Following the Involvement stage, in the “Development” Stage the area begins to develop rapidly due to larger businesses investing in the location. This rapid development causes a dramatic increase in the amount of tourists visiting the area. Following the Development Stage, the economy of the area becomes tourism-focused and transitions to the “Consolidation” stage. During Consolidation other non-tourism related businesses such as agriculture may suffer due to the tourism-centric economy. The impacted area's non-tourist infrastructure and buildings may begin to deteriorate and become unattractive, for example. Following the Consolidation Stage, the "Stagnation” Stage begins with the amount of tourists leveling off due to competition from other resorts, deterioration of the tourism area's buildings, and local businesses dependent on tourists feeling economically threatened. Following the Stagnation Stage, the TALC model presents two opposing scenarios (stages): (1) “Rejuvenation” and (2) “Decline”. Rejuvenation may occur following Stagnation if new investment into the area is made, attracting more tourists to the area. If Rejuvenation does not occur, a Decline may follow Stagnation, where the amount of tourists visiting the area can decline at various rates.

For my study, I modified Butler's model to create a conceptual "Developed Barrier Island Life Cycle" model (

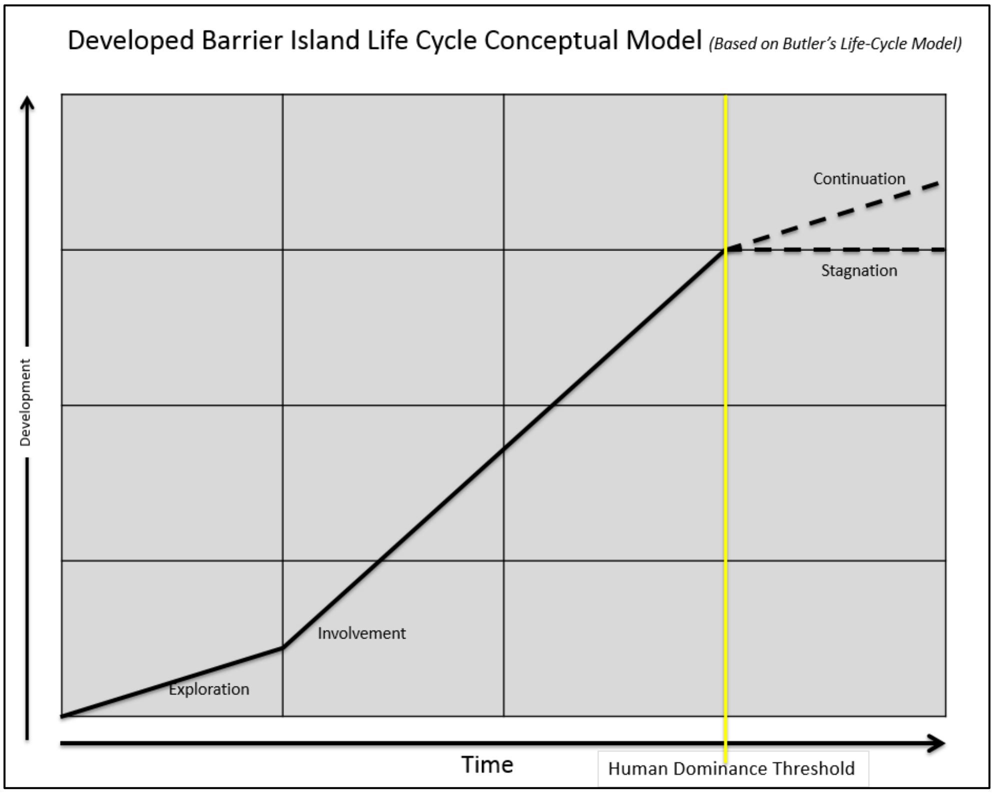


Figure 4) that shows how the amount of development varies through time and defines when island and study area-scale human dominance occurs. The conceptual model retains several terms and stages in Butler's model, but the y-axis now displays the amount of development rather than number of tourists.

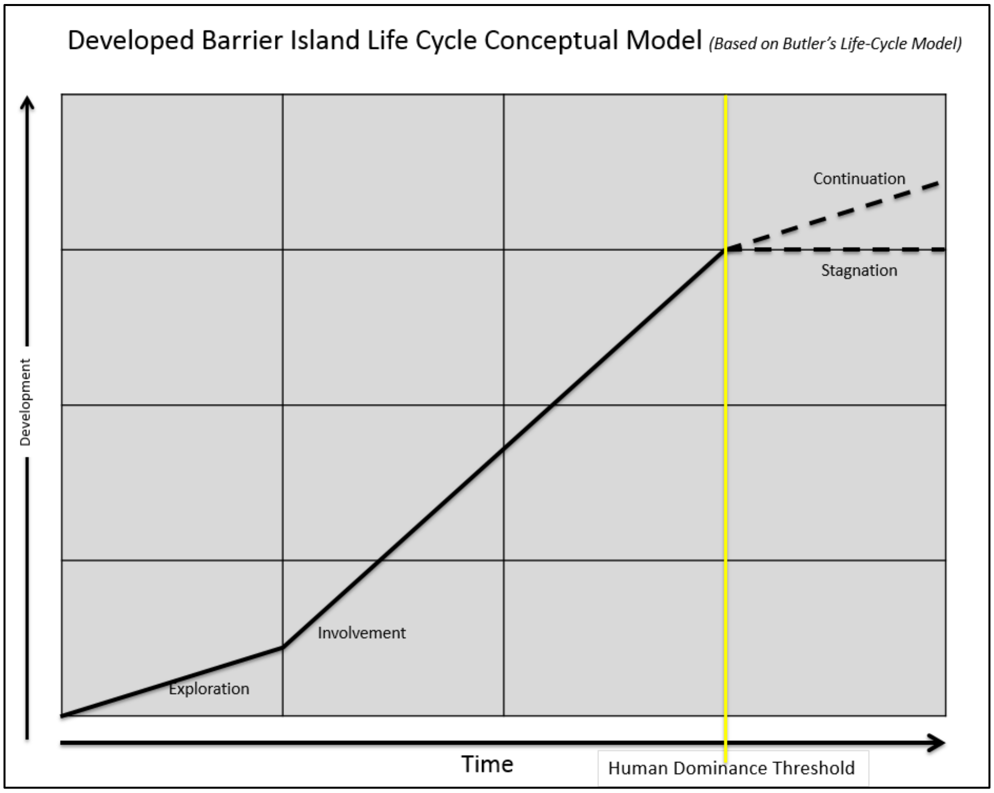


Figure 4. Developed barrier island life cycle model.

During the "Exploration" Stage of my model the barrier island is predominantly uninhabited, with only sparsely populated enclaves. The Exploration Stage lasts until interest in a barrier island as a resort results in access to the island via bridges for automobiles and railroads. This triggers the "Involvement" Stage when rapid development occurs, typically beginning in areas proximal to island access points and spreading alongshore. During this stage, as physical processes continue to alter the barrier island's horizontal shoreline position, development of buildings, roads, and other infrastructure establish the "landward limit of shoreline position." As a result, there is an increase in the amount of "hard" shore protection structures (groins, jetties, seawalls, and bulkheads) to maintain the position. The model suggests that as development increases through time, the horizontal shoreline position can periodically migrate seaward, but not landward towards developed areas. Seaward shoreline migrations are typically associated with beach replenishment projects, aimed at increasing the buffer between development and the ocean by constructing engineered beach-dune systems to act as sacrificial “soft” zones. During the Involvement Stage, filling wetlands and tidal lagoons, clearing maritime forests, and creating artificial lagoons adjacent to filled wetlands are common practices to increase the island’s land area for the construction of buildings and roads. Over time, environmental regulations (i.e. the Wetlands Act of 1970), creation of federal or state wildlife refuges and state parks such as Forsythe National Wildlife Refuge and Island Beach State Park (Figure 5) limit land area available for further development.

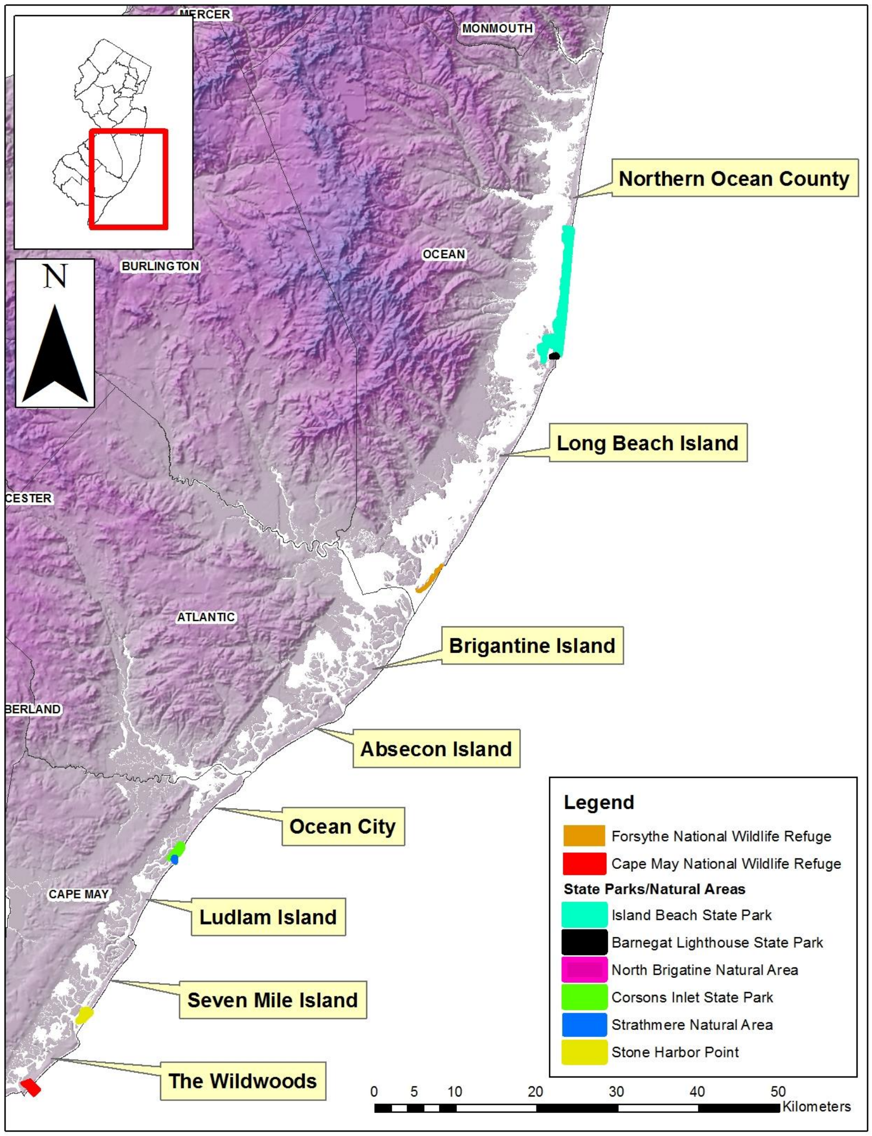


Figure 5. Map of New Jersey's barriers highlighting federal and state natural areas and parks. This includes: Forsythe National Wildlife Refuge (orange) on Long Beach Island, Cape May National Wildlife Refuge (red) on The Wildwoods, Island Beach State Park (light blue) on Northern Ocean County, Barnegat Lighthouse State Park (black) on Long Beach Island, North Brigantine Natural Area (purple) on Brigantine Island, Corsons Inlet State Park (green) on Ocean City, Strathmere Natural Area (blue) on Ludlam Island, and Stone Harbor Point Natural Area (yellow) on Seven Mile Island.

At this time the barrier's “Human Dominance Threshold” is reached, indicating the island has experienced a change in state and is now managed as a static system. On undeveloped portions of the island, physical processes continue while the human dominated portions continue to be stabilized by shore protection structures. Once the threshold is reached, the island may begin the “Continuation” Stage, or the “Stagnation” Stage. During the both the Continuation Stage and Stagnation Stage dynamic and physical processes continue, so shoreline stabilization practices increase (installation of “hard” structures such as groins, jetties, bulkheads, and seawalls or “soft” engineering practices such as beach replenishment) to maintain the static system. During the Continuation Stage humans keep altering the landscape (but to a lesser degree than before the threshold is reached) and the amount of development (land clearing, construction of buildings, roads, shore protection, etc.) continues to increase, but at a slower rate, until the Stagnation Stage. The Stagnation Stage is reached when the developed land area of the barrier island no longer continues to increase. During the Stagnation Stage human alterations occur within established developed areas and may begin immediately after the human dominance threshold is reached.

My study revealed island-scale thresholds establish temporal boundaries that denote a significant change in state where human activities overshadow natural processes. The implication is that human alterations are consistent across all barriers, regardless of geomorphic classification.

1.2 Hypothesis and Research Objectives

1.2.1 Hypothesis

Barrier islands are subject to thresholds where human factors override physical factors causing a state change on small and large scales.

1.2.2 Research Objectives

- Provide a model for determining human dominance thresholds for developed barrier islands at small and large scales.
- Describe how human dominance relates to specific human variables through time.
- Describe how human dominance thresholds relate to geomorphic factors at small and large scales.

Chapter 2: Methods

2.1 Overview

Determining human dominance thresholds for all barrier islands in New Jersey required compiling multiple GIS datasets derived from existing land use/land cover, road centerlines, building footprints, and shore protection structures. Each of the datasets was edited in a GIS to represent multiple aerial photograph dates (Table 1).

Table 1. Source datasets used for this research.

Source Data			
Dataset	Type	Source	Scale/Resolution
1986 Land Use Land Cover	Vector, Polygon	NJDEP	1:24,000
1995 Land Use Land Cover	Vector, Polygon	NJDEP	1:24,000
2002 Land Use Land Cover	Vector, Polygon	NJDEP	1:24,000
2012 Land Use Land Cover	Vector, Polygon	NJDEP	1:2,400
2010 Building Footprints	Vector, Polygon	NJDEP	1:2,400
2012 Roads	Vector, Polyline	NJDOT	1:2,400
1993 Shore Protection Structures	Vector, Polyline	NJDEP	1:24,000
2012 Natural Color Aerial Imagery	Raster	NJGIN	1:2,400
2002 Infrared Aerial Imagery	Raster	NJGIN	1:2,400
1995 Infrared Aerial Imagery	Raster	NJGIN	1:12,000
1986 Aerial Imagery	Raster	NJDEP	1:24,000
1977 Tidelands Basemaps (Aerial Imagery)	Raster	NJGIN	1:24,000
1962 Aerial Imagery	Raster	Stockton University	1:24,000
1955 Aerial Imagery	Raster	Stockton University	1:24,000
1944 Aerial Imagery	Raster	Stockton University	1:24,000
1931 Aerial Imagery	Raster	NJGIN	1:24,000
1920 Aerial Imagery	Raster	Stockton University	1:10,000

By quantifying human and physical land cover types into human dominance threshold factors (Table 2) for each aerial dataset year, human dominance thresholds were determined for individual 100m wide zonal analysis bins (termed “bins”) along each barrier in the study area (Figure 6). Determining thresholds within individual bins aided in identifying spatial patterns between when and where human dominance thresholds are reached along distinct segments of a barrier. Delineating variable datasets in addition to land cover types (i.e. buildings, roads, shore protection structures) for each aerial dataset

(Table 2) and quantifying each within 100m bins aided in understanding how human activities contribute to human dominance of barrier islands.

Table 2. Human and physical land cover types and variable datasets extracted from land cover datasets and aerial photography.

Human Dominance Threshold Factors (per Bin)			
Land Cover Types	*Variable Type*	*Delineation*	*Unit of Measure*
Urban	Human	Polygon	Area, Square Meters
Barren Land	Physical	Polygon	Area, Square Meters
Wetlands	Physical	Polygon	Area, Square Meters
Other Delineated Calculations (per Bin)			
Variable Datasets	*Variable Type*	*Delineation*	*Unit of Measure*
Building Locations	Human	Point	Count, number points
Roads	Human	Polyline	Length, Meters
Shore Protection Structures	Human	Polyline	Length, Meters

Figure 6. Zonal analysis bins for the study area (left) and zoomed in (right).

The “GIS and Zonal Analysis” Section (Section 2.3) provides more detail on this methodology.   GIS provided the ideal platform for quantifying land cover types within bins and calculating human dominance threshold factor ratios (Equation 2) for determining when human dominance thresholds were reached at the bin, island, and study area-scales.

2.2 Aerial Photography

Aerial photographs are the most commonly used data source in shoreline mapping and delineation (Moore 2000). Aerial photography has also been used to classify coastal land cover for change analyses (Klemas et al. 1993). Errors in the photographs exist when delineating shorelines and land cover features, but when performing temporal analyses over time scales of nearly 100 years, an aerial photograph's coverage of a particular area is more important than any uncertainty associated with accuracy (especially when using historical datasets). Moore (2000) recommends using the highest quality vertical aerial photographs available. In many cases, there are only few available historical photographs and even fewer of these are available digitally. In this case, images must be georectified in a GIS environment. A georectified or georeferenced image is an image "fitted" to a reference coordinate system using ground control points (Moore 2000). Although aerial images do not provide the means for extracting elevation data, feature delineation from vertical aerial photography can help understand historical change and spatial relationships.

Georeferenced digital aerial photograph datasets are available for all barrier islands in New Jersey for 1920, 1931, 1933, 1944, 1955, 1962, 1977, 1986, 1995, 2002, and 2012. These photographs were used to extract land cover and human variable datasets in ESRI ArcGIS software.

2.3 GIS & Zonal Analysis

A Geographic Information System (GIS) provides a means for geographers to perform digital mapping analyses and disseminate data to aid in decision making (Bernhardsen 1997). The industry standard GIS software is Environmental Systems Research Institute (ESRI) ArcGIS software package (Orsby et al. 2001). ArcGIS has been used in many fields for spatial analysis, including social sciences (Anselin 1999), criminal justice (Anselin et al. 2000), real estate (Anselin 1998), and physical and environmental sciences (Rosenzweig et al. 2008).

A GIS consists of a series of map “layers” which contain any kind of data with a spatial reference. There are two types of data structures in a GIS: raster and vector (Raper & Maguire 1992). Raster data consists of a continuous area of adjoining cells much like a photograph’s pixels. Each pixel contains a value (number) that can represent a measurement (e.g., elevation) or a color. The second kind of data structure, vector, is used to represent features in the form of points, lines, and areas (Mitchell 1999).

When performing spatial analysis in a regional setting, researchers commonly aggregate data into analysis areas or “zones” using vector data. Zonal analysis is a conventional approach to spatial analysis (Openshaw 1977). Aggregating spatial data into zones for analysis has also been used extensively in population studies (Martin 1996). In the coastal zone, Mihalasky et al. (2007) used uniform zones for quantifying beach-dune attributes (e.g., dune width, dune elevation, beach width) using aerial photography and LiDAR (Light Detection and Ranging) elevation data at spatial scales of 250ft to calculate susceptibility to coastal storm events. Using the zonal analysis approach of Mihalasky et al. (2007), land cover types can be quantified in discrete, 100m wide bins.

Analyzing zones also allows optimal map display of spatial variation and clustering of human dominance thresholds along barriers (Jackson et al. 2000; Openshaw 1977).

To quantify ratios between human and physical land cover types for a given barrier island through time, discrete, uniform 100m wide zonal analysis bins were created along each barrier island in ArcGIS (Figure 6). The 100m scale was used by Jackson et al. (2000) to analyze spatial variations in barrier island evolution based on human variables (e.g., number of buildings, number of shore-normal structures, number of shore-parallel structures) and physical variables (e.g., beach width, dune width, distance from nearest inlet).

2.4 Delineating Coastal Land Cover Types

To calculate human/physical factor ratios based on the equation presented by Bull (1980), polygon land cover datasets representing three (3) land cover variables were created. The three (3) land cover variables used to quantify human/physical factor ratios were: (1) barren land, (2) wetlands, and (3) urban. These three variables encompass all land cover types found on developed barrier islands. Definitions of the three land cover types are presented by New Jersey Department of Environmental Protection (NJDEP, 2002) modified from the Anderson Classification System (1976) are:

> Barren Land (physical factor) – "Barren Land is composed of bare soil, rock, sand, silt, gravel, or other earthen material with little or no vegetation."
>
> Wetlands (physical factor) – "This cover type is predominantly vegetated by herbaceous plants adapted to the varied environmental conditions imposed by the tidal environment: water level fluctuations, salinity, and sediment deposition. Also included are those non-tidal areas closely associated with adjacent coastal wetlands such as salt marsh transition zones and coastal vegetated dunes."

> Urban (human factor) – "Urban or Built-up Land category is characterized by intensive land use where the landscape has been altered by human activities. Although structures are usually present, this category is not restricted to traditional urban areas."

For this study, physical and human variables were delineated by modifying the criteria above to specifically address human cleared lands prior to development. The Anderson Classification System's (1976) definition of Barren Land includes all barren land, including human-cleared lands. This study includes visible human cleared land in the urban variable because human-cleared land identified in an aerial dataset indicated development was occurring at that time. The areas that each defined land cover type account for in this study are:

- Barren Land (physical variable) – beaches, un-vegetated dunes, or other barren areas with little or no vegetation and no evidence of human alteration (i.e. land cleared for development).
- Wetlands (physical variable) – tidal marshes, maritime forest, vegetated dunes, or other undeveloped vegetated areas with no evidence of human alteration (i.e. recreational areas).
- Urban (human variable) – areas where human alteration is clearly visible such as developed coastal communities, parking lots, roads, barren land, or vegetated land with clear evidence of human alteration (i.e. cleared land for development, recreation areas/parks).

Existing land use land cover GIS data provided by NJDEP for 2012, 2002, 1995, and 1986, were used in conjunction with georeferenced aerial datasets listed in section 2.2 obtained from various sources (Table 1). These aerial datasets represent continuous coverage along New Jersey's barrier islands on a roughly decadal time-scale.

Using GIS, all existing land use land cover datasets were clipped to the extent of the study area and reclassified by the three land cover types. For the aerial dataset years prior to the earliest existing land use land cover dataset (i.e. 1986), the 1986 reclassified land cover dataset was manually edited and updated for the entire study area for the 1920, 1931, 1944, 1955, 1962, and 1977 aerial datasets. All land cover datasets for the aerial dataset years prior to 1986 were created at the 1:24,000 scale for consistency (1986 land use land cover is provided at the 1:24,000 scale). For existing land use land cover datasets and new datasets based on aerial photography, shoreline boundaries were also manually delineated to the wet-dry line seen on a given datasets corresponding aerial dataset.

2.4.1 Delineating Variable Datasets

The aerial images were also used in GIS to manually delineate variable datasets (Table 2) to further understand how specific human actions contribute to Barrier Islands reaching human dominance thresholds. These human-type variable datasets included roads, building locations, and shore protection structures (i.e. groins, jetties, seawalls, and bulkheads). Variable dataset results were aggregated at the island-scale and plotted with the percentage of human-dominated bins through time.

Existing downloadable GIS data for roads (2012), building footprints (2010), and shore protection structures (1993) provided by the NJDOT and NJDEP were used as baseline datasets and were updated for each aerial dataset year by manually editing each layer. See section 2.5 for a detailed description of how these variables were delineated and quantified.

2.4.2 Variable Dataset Summary

Each year’s land cover dataset attributes were quantified within each zonal analysis bin in ArcGIS using the “Zonal Statistics” tool. I assumed a direct relationship between increased internal human structures on barrier islands through time and increased attempts at shoreline stabilization, which would result in the establishment of the shoreline’s landward limit. Note that for Equation 2, all beach-dune systems, including engineered beaches-dunes, are included in the physical factor due to the difficulty distinguishing between an “unaltered” beach-dune system and an engineered beach-dune system for shore protection. Since an engineered beach-dune system is a “soft engineering” approach for shore protection, physical processes continue to apply. Beach-dune systems are not static shore protection structures. See Chapter 4 for discussion on engineered beach-dune systems and shoreline variability.

2.5 Quantifying Land Cover Types and Variable Datasets

The identified land cover types and variable datasets in Table 2 were quantified with all 100m bins in the study area (1,464) using the ArcGIS “Zonal Statistics” tool. To delineate each variable, source data were manually edited to match the variables visible within all aerial dataset years in this study.

Quantifying the area of the three (3) delineated land cover types described in section 2.4 for all aerial dataset years listed in Table 1 was performed in ArcGIS on a per-bin basis (Figure 7). For each bin, the total area (meters squared) of barren land and wetlands were combined into the total area of the physical factor. The total area (meters squared) of the urban polygons were combined into the total area of the human factor.

Each factors' values for each bin were used to calculate human dominance thresholds described in section 2.6.

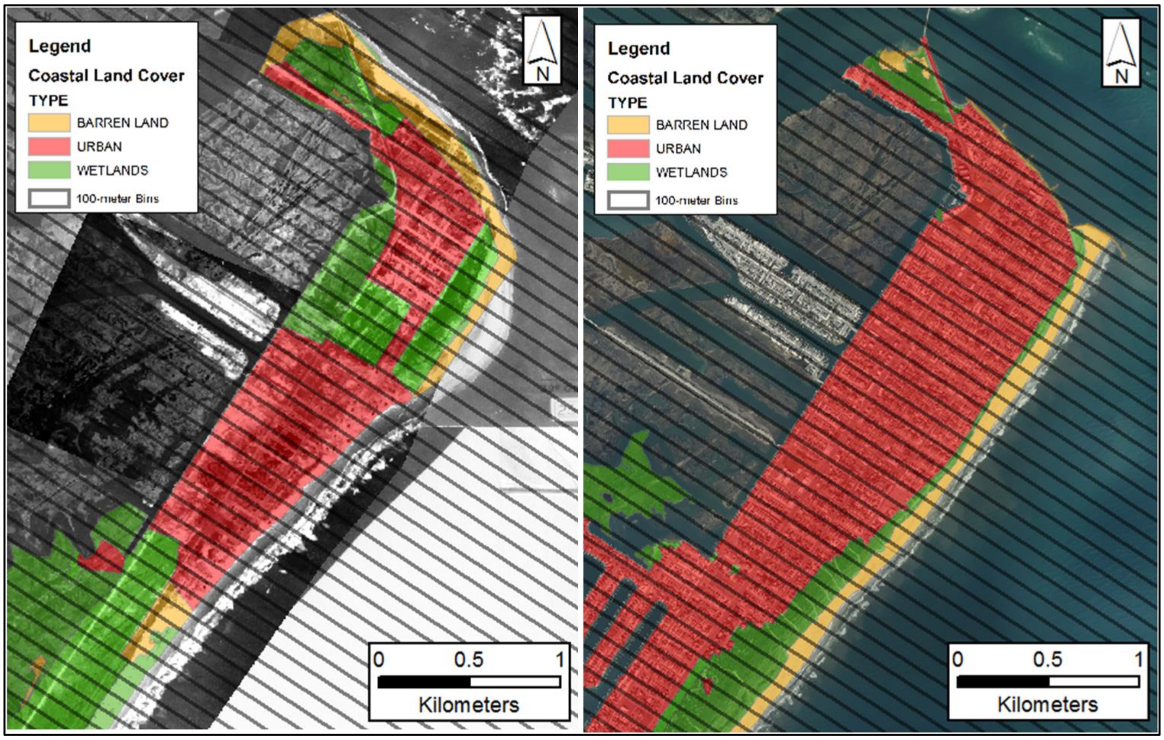


Figure 7. Northern section of Seven-Mile Island's delineated land cover types (polygons) from 1920 (above, left) and 2012 (above, right). The total area of physical variables (barren land and wetlands polygons) and human variables (urban polygons) were quantified within each 100m bin (grey polygons) for each aerial dataset year.

Building footprint polygons for 2010 provided by the NJDEP were converted to centroid (termed location) points in ArcGIS using the "Feature to Point" tool. The 2010 building location points were manually added or deleted to correspond to buildings visible along each barrier island for all aerial dataset years in the study (Figure 8). The total amount of building location point counts was quantified for every aerial dataset year on a per-bin basis for the entire study area using the "Zonal Statistics" tool in ArcGIS.

Figure 8. Northern section of Seven Mile Island's identified building locations(red points) from 1920 (above, left) and 2012 (above, right). The total amount of identified buildings were quantified within each 100m bin (grey polygons) for aerial dataset year in the study.

Road centerline polylines for 2012 provided by the NJDOT were manually added or deleted to represent the roads visible along each barrier island for all aerial dataset years in the study (Figure 9). The total length of road centerline polylines (meters) was quantified on a per-bin basis for the entire study area using the "Zonal Statistics" tool in ArcGIS.

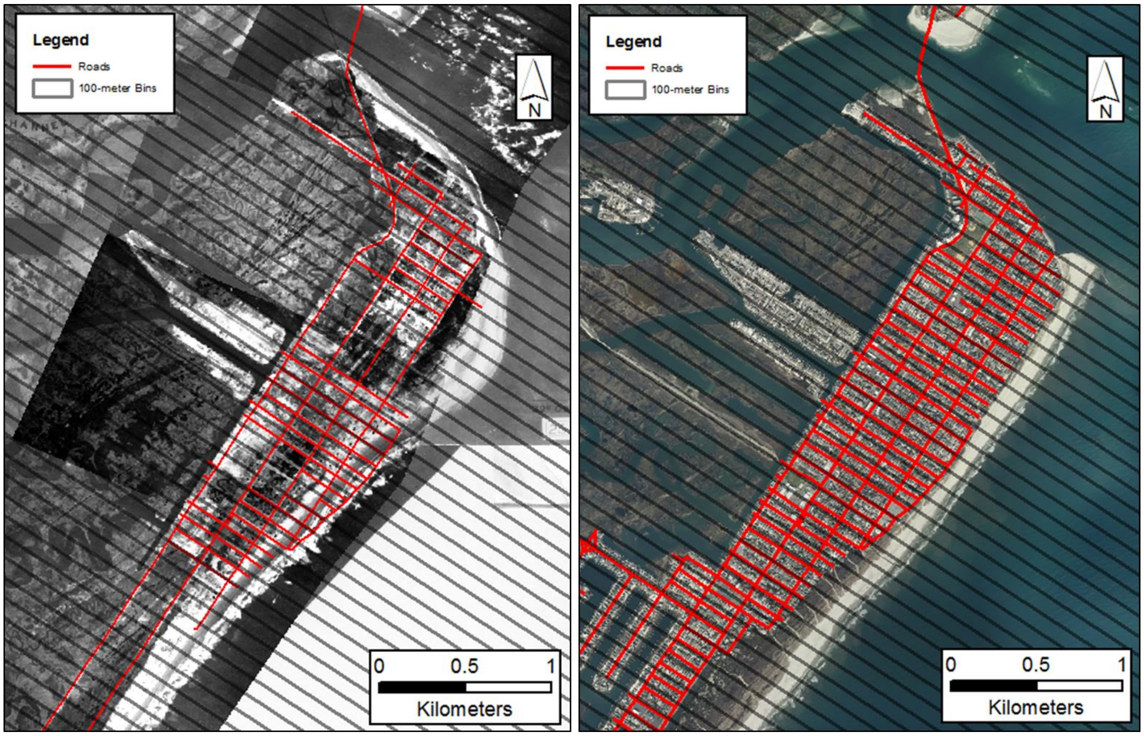


Figure 9. Northern section of Seven Mile Island's delineated road centerlines(red lines) from 1920 (above, left) and 2012 (above, right). The total length of road centerline polylines were quantified within each 100m bin (grey polygons) for each aerial dataset year in the study.

Shore protection structure polylines for the year 1993 provided by the NJDEP were manually added or deleted to correspond to jetties, groins, seawalls, and bulkheads visible along each barrier island for all aerial dataset years in the study (Figure 10). The total length of shore protection structures (meters) was quantified for every aerial dataset year on a per-bin basis for the entire study area using the "Zonal Statistics" tool in ArcGIS.

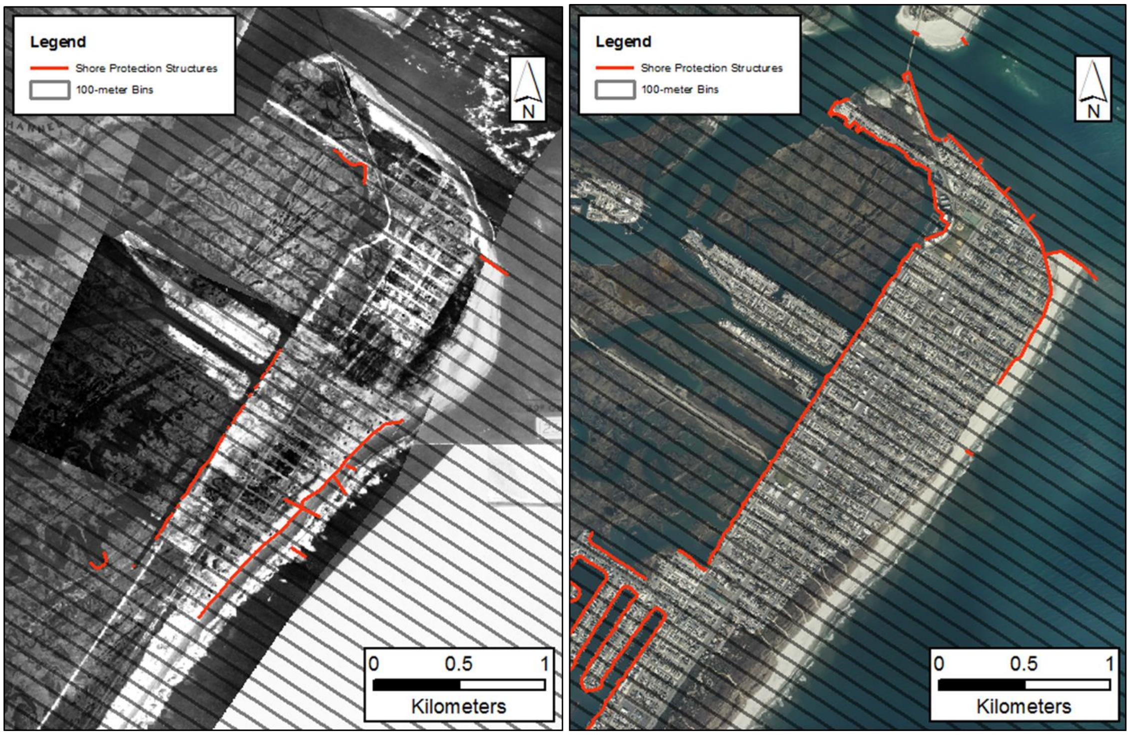


Figure 10. Northern section of Seven Mile Island's delineated shore protection structures(red lines) from 1920 (above, left) and 2012 (above, right). The total length of delineated shore protection polylines were quantified within each 100m bin (grey polygons) for every aerial dataset year in the study.

2.6 Calculating Human Dominance Thresholds per Bin

Within each 100m bin for the entire study area (1,464 100m bins total), the area (square meters) of the human factor (urban polygons) and the physical factor (barren land polygons, wetlands polygons) were calculated using zonal statistics in ArcGIS for every land cover dataset year as described in section 2.5. For every aerial dataset year, human/physical factor ratios were calculated for every 100m bin by dividing the area of human land cover polygons (human factor) within a given bin by the summed area of physical land cover polygons (physical factor) within a given bin (Equation 2). The dataset year when the human dominance threshold was reached for a given bin was determined by identifying the earliest dataset where the human/physical ratio was greater than one (1).

2.7 Determining Barrier Island-Scale Human Dominance Thresholds

For each barrier island within the study area, human dominance threshold tables and plots were created to display the percentage of human dominated bins for each year analyzed (Table 3 and Figure 11 in Chapter 3), and the rate of human dominance per year (i.e. percentage of human dominated bins per year, Table 4). The human dominance thresholds for each barrier island were determined by identifying the aerial dataset year that represented a significant change from an increasing percentage of human dominated bins to a relatively small or no change in the percentage of human dominated bins (identifying a change in state). Given the roughly 10-year time span between aerial datasets, is it not possible to determine the actual year when a threshold was reached without annual aerial photographs for the whole coast. This study can only determine the year a threshold was reached *by*. Thresholds were identified by calculating rates of human dominated bin percentages between aerial dataset years and determining the maximum rate of human dominance (Table 4). Normalized variable dataset values for buildings, roads, and shore protection structures were plotted with the percentage of human dominated bins through time for each island and the study area. Values were normalized to simplify the human dominance threshold plots because the length of roads, number of buildings, and length of shore protection structures had widely varying values along the y-axis. Normalizing these data placed values within a relative data range (between 0 and 1) for comparison between variable datasets and the percentage of human dominated bins for each island through time.

The percentage of human dominated bins through time can also be described as the amount of development through time, as described in

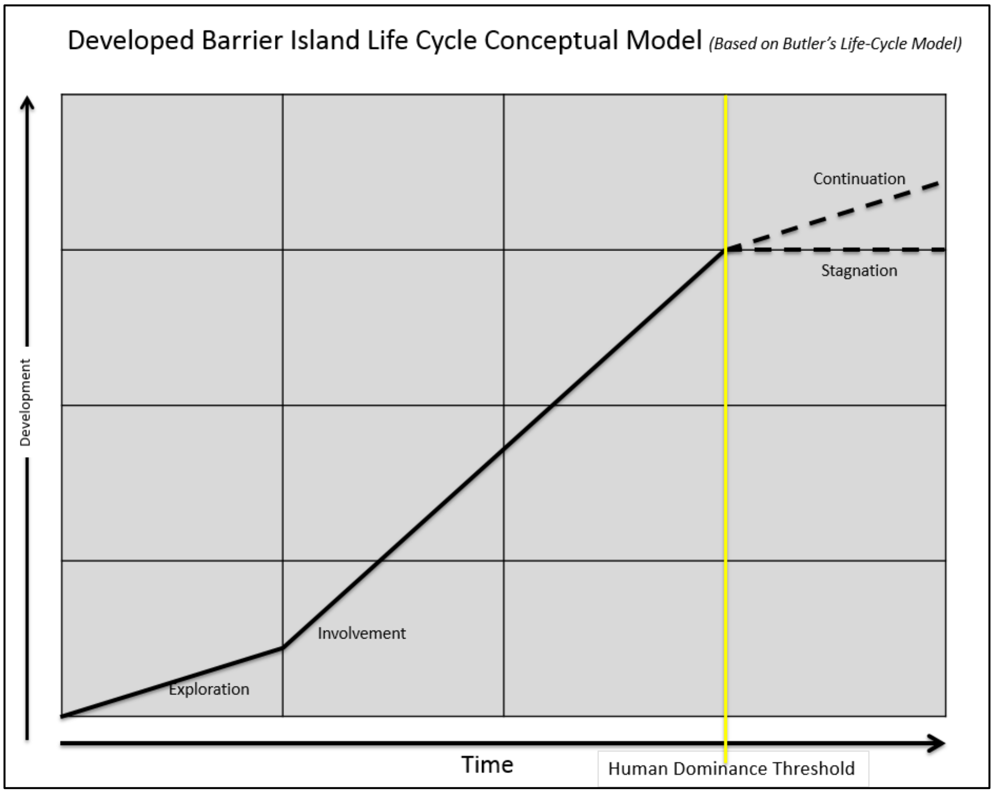


Figure 4. Since "development" encompasses buildings, roads, and infrastructure (i.e. variable datasets), a human dominated bin can also be described as a "development" dominated bin.

2.8 Correlating Barrier Island Mobility with Human Dominance Thresholds

This research provides a model of how human dominance thresholds relate to geomorphic factors at varying spatial scales. Shoreline mobility can help explain shoreline evolution (Stive et al. 2002). Dolan et al. (1978), stated that shoreline variability can be represented as the standard deviation of the shoreline position relative to the linear trend. For this study, shoreline mobility as termed by Dolan et al. (1978), was quantified for each island and within every 100m bin for each island in GIS by calculating the standard deviation of the total land cover area (combined urban, barren land, and wetland areas) for each year's land cover dataset. Since land cover datasets encompass an entire barrier island, this standard deviation value is referred to as island mobility (Table 5). Quantifying island mobility at the island-scale and 100m bin-scale helped in determining whether there is a relationship between island mobility and the spatial distribution of human dominance thresholds for the individual bins, barrier islands, and the entire study area.

This study used the "correlation" function in Microsoft Excel to determine whether there is a relationship between island mobility and when a human dominance threshold is reached (termed "Developed Barrier Geomorphic Correlation"). The correlation function calculates the Pearson product moment correlation coefficient and is useful in determining the relationship between two properties. Correlation coefficients are expressed in values between -1 and 1 (Microsoft 2016). A positive correlation coefficient indicates if a human dominance threshold was reached later, an island or given bin would have higher island mobility value. A negative coefficient would indicate if a human dominance threshold was reached earlier (smaller value), the corresponding island mobility value would be higher due to the indirect relationship.

Chapter 3: Results

3.1. Study area and island-scale human dominance threshold results

Results combining the human-dominance ratios for the 1,464 bins within the study area for each aerial dataset year (Table 3) reveal the human dominance threshold was reached by 1962 (Table 4). Table 3 shows the total percentage of human dominated bins through time for individual barriers and the study area. Displaying these percentages in the table is helpful in comparing how individual islands and the entire study area become human dominated. It is particularly helpful when comparing island-scale thresholds to understand how islands with an initial high percentage of human dominated bins (i.e. Absecon Island) differed from islands with an initial low percentage of bins (i.e. LBI). Table 4 shows the rates of percentage of human dominated bins per year for each barrier and the entire study area. The maximum rate between two analysis years determined the year a human dominance threshold was reached by. Figure 11 shows that from 1920 to 1955, there was a gradual increase in the percentage of human dominated bins for study area. Between 1955 and 1962, there was a sharp increase and then the percentage levels off with no significant increases (or decreases) in the percentage of human dominated bins for the remainder of the years. Most islands follow this trend of sharp increase and leveling off (regardless of the year when an individual barrier's human dominance threshold is reached).

Table 3. The total percentage of human dominated bins for individual barriers and the study area.

	Percentage of Human Dominated Bins per Island (all years)									
	1920	1931	1944	1955	1962	1977	1987	1995	2002	2012
Northern Ocean County	27.49%	41.36%	44.24%	44.24%	58.64%	58.90%	58.90%	58.90%	58.90%	58.90%
Long Beach Island	4.68%	27.49%	43.27%	43.27%	75.44%	79.82%	79.82%	82.46%	82.75%	82.75%
Brigantine	0.00%	36.52%	38.26%	39.13%	39.13%	45.22%	45.22%	46.96%	46.96%	47.83%
Absecon Island	69.06%	84.17%	89.93%	89.93%	89.93%	92.81%	93.53%	93.53%	94.24%	94.24%
Ocean City	24.44%	30.37%	30.37%	37.78%	41.48%	55.56%	56.30%	57.04%	57.78%	58.52%
Ludlam Island	8.55%	18.80%	22.22%	29.06%	47.86%	48.72%	48.72%	50.43%	51.28%	52.14%
Seven Mile Island	44.74%	44.74%	59.65%	62.28%	75.44%	85.09%	85.09%	85.96%	86.84%	86.84%
Wildwoods	50.00%	52.50%	52.50%	56.67%	61.67%	66.67%	66.67%	67.50%	69.17%	70.83%
Total	**25.34%**	**40.16%**	**46.72%**	**48.57%**	**63.11%**	**67.49%**	**67.62%**	**68.72%**	**69.19%**	**69.54%**

Table 4. The human dominated bin rates for individual barriers and the study area. The maximum rate of percent bins dominated per year between two analysis years determine when the human dominance threshold is reached.

	Human Dominated Bin Rates										Maximum Rate, Percent Dominated Bins/Year	Year Threshold Reached
	1920	1931	1944	1955	1962	1977	1987	1995	2002	2012		
Northern Ocean County	0.00%	1.26%	0.22%	0.00%	2.06%	0.02%	0.00%	0.00%	0.00%	0.00%	2.06%	1962
Long Beach Island	0.00%	2.07%	1.21%	0.00%	4.59%	0.29%	0.00%	0.33%	0.04%	0.00%	4.59%	1962
Brigantine	0.00%	3.32%	0.13%	0.08%	0.00%	0.41%	0.00%	0.22%	0.00%	0.09%	3.32%	1931
Absecon Island	0.00%	1.37%	0.44%	0.00%	0.00%	0.19%	0.07%	0.00%	0.10%	0.00%	1.37%	1931
Ocean City	0.00%	0.54%	0.00%	0.67%	0.53%	0.94%	0.07%	0.09%	0.11%	0.07%	0.94%	1977
Ludlam Island	0.00%	0.93%	0.26%	0.62%	2.69%	0.06%	0.00%	0.21%	0.12%	0.09%	2.69%	1962
Seven Mile Island	0.00%	0.00%	1.15%	0.24%	1.88%	0.64%	0.00%	0.11%	0.13%	0.00%	1.88%	1962
Wildwoods	0.00%	0.23%	0.00%	0.38%	0.71%	0.33%	0.00%	0.10%	0.24%	0.17%	0.71%	1962
Total	0.00%	1.35%	0.50%	0.17%	2.08%	0.29%	0.01%	0.14%	0.07%	0.03%	**2.08%**	**1962**

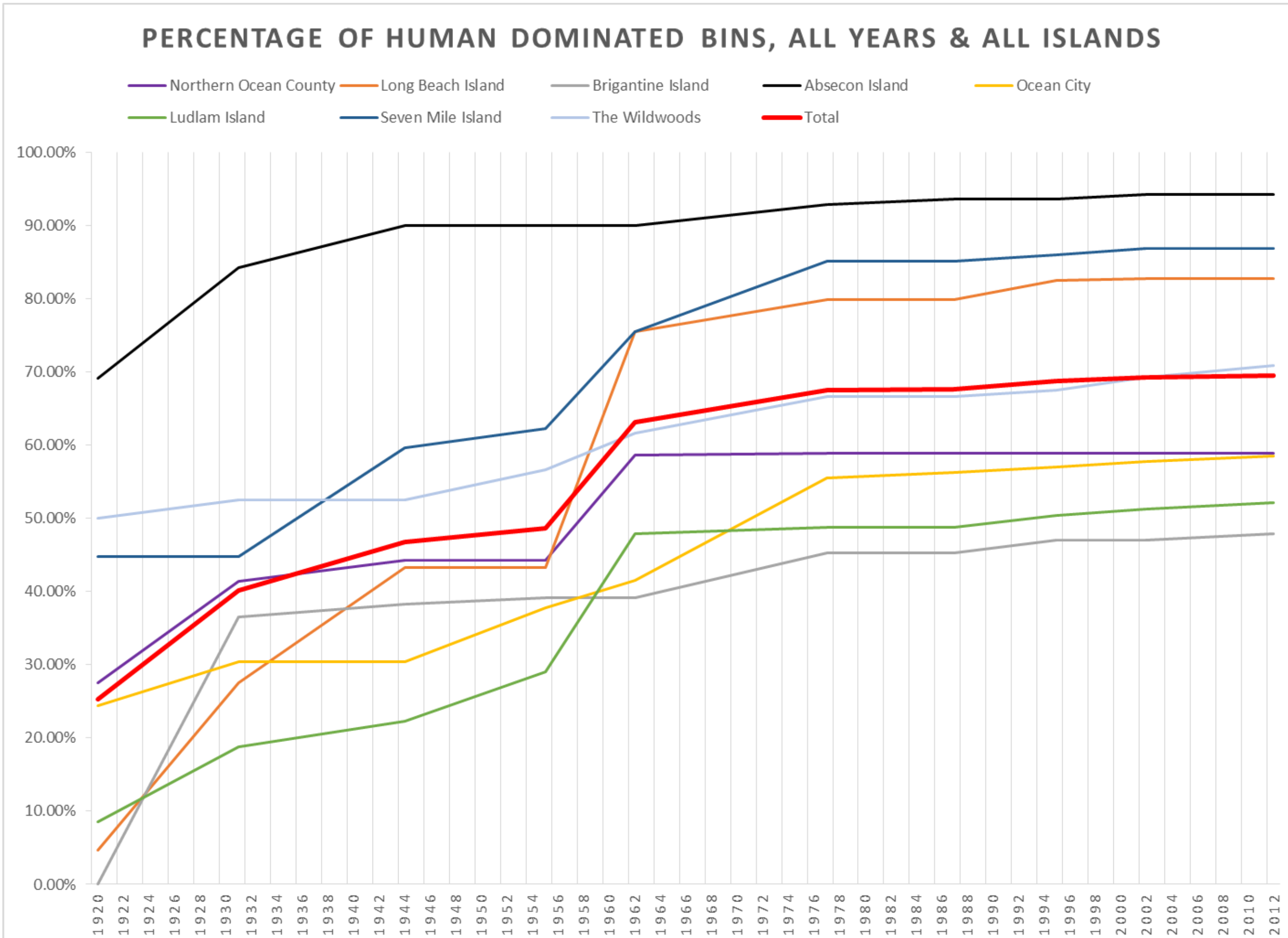


Figure 11. Percentage of human dominated bins through time (i.e. “development”)

3.2 Study area-scale threshold results compared to human variables

When comparing the total percentage of human dominated bins to individually quantified human variable datasets (i.e. roads, buildings, shore protection) in Figure 12, a pattern closely resembling the "Developed Barrier Island Life-Cycle" model

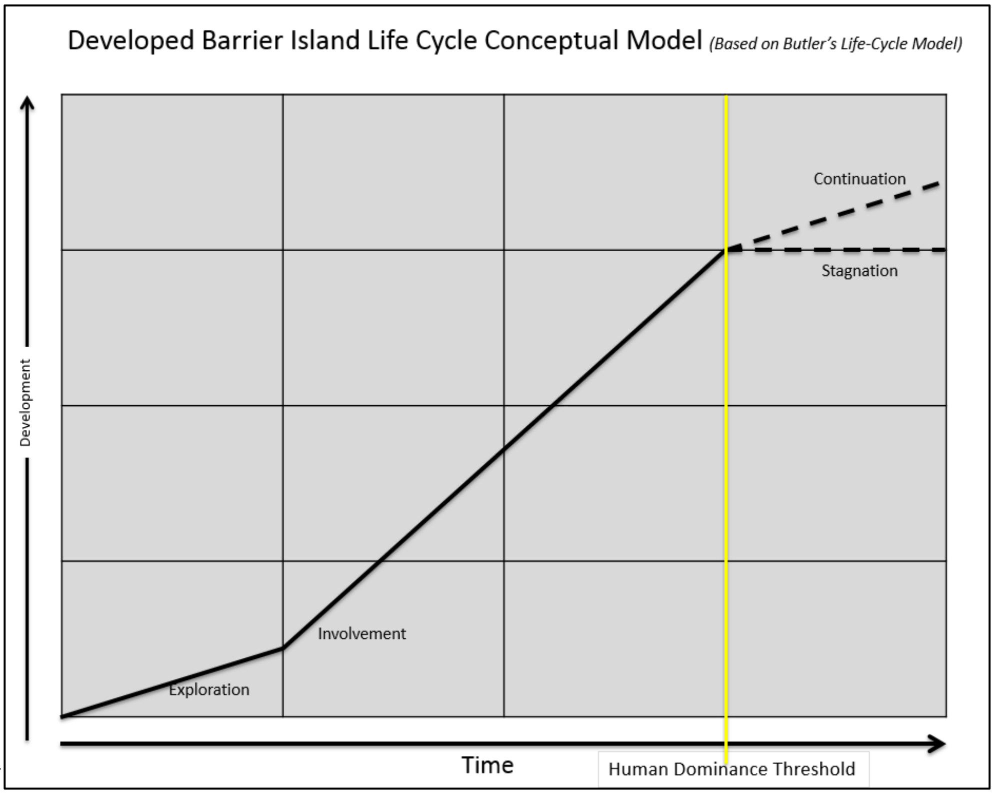
(

Figure 4) emerges, i.e. when the human dominance threshold is reached (1962), the amount of buildings and roads (development) begins to level off, while shore protection continues to increase until 1995 when it levels off. The leveling off of the amount of shore protection may be due to only accounting for hard structures (groins, jetties, seawalls, and bulkheads) and not beach replenishment. The maximum amount of hard structures was reached in 1995, and beach replenishment was the primary means of shore protection following 1995, indicating that shore protection is a continuing process throughout the study area as displayed in Figure 12. Nordstrom (1994) provides detailed illustrations affirming these observations, and notes that beach replenishment projects have been the primary means of shore protection since the 1970s.

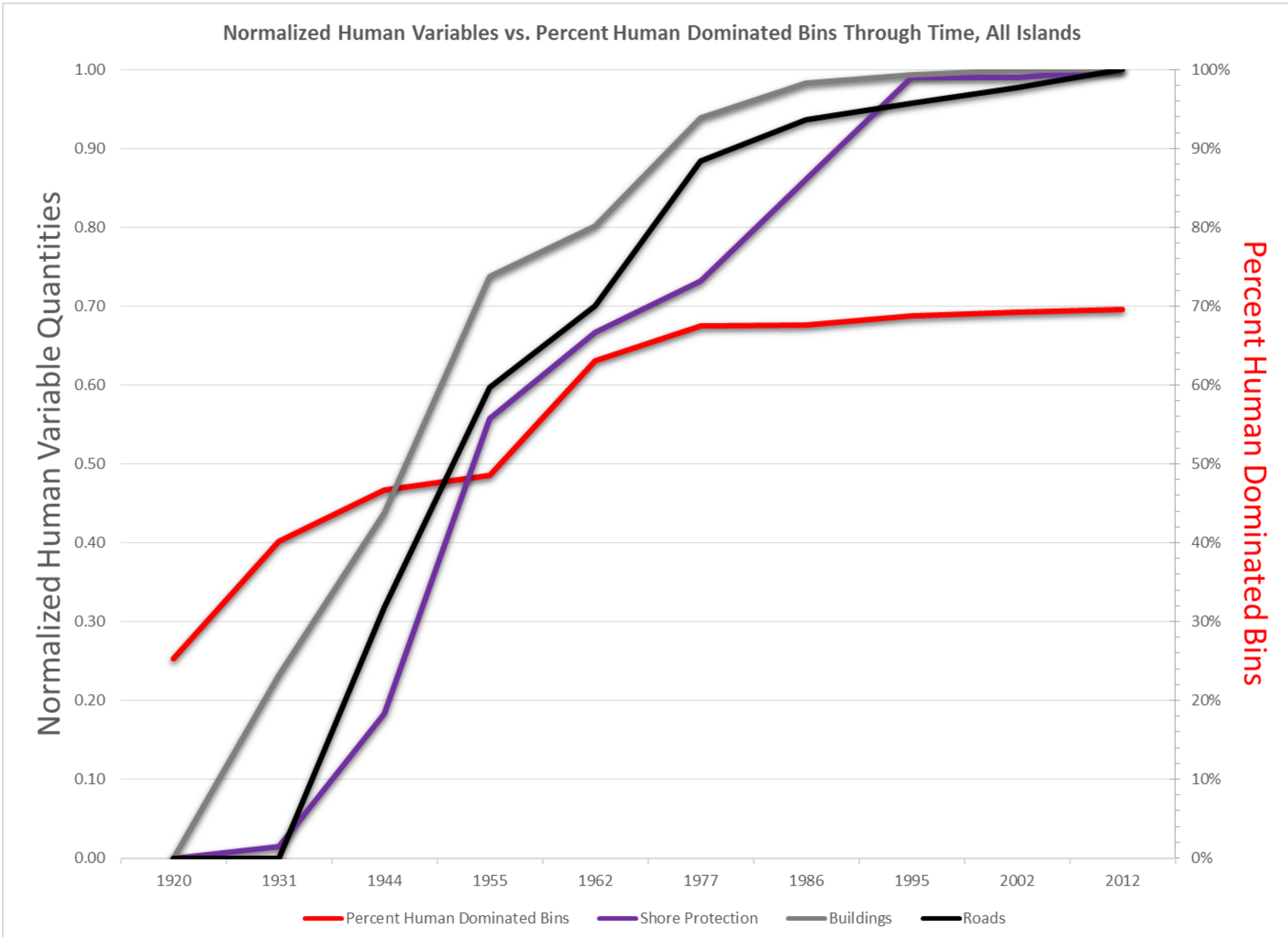


Figure 12. Total percent human dominated bins for all islands (red line) compared to normalized human variables for length of shore protection structures (purple line), number of buildings (gray line) and length of roads (black line).

3.3. Individual Island Results

Human dominance thresholds for each island in the study area are highlighted in Table 4.

3.3.1 Island mobility compared to thresholds

The purpose of the correlation analysis was to show how geomorphic factors are related to human dominance at various spatial scales. The results in Table 5 show a relatively high positive correlation values between "Island Mobility" and the human dominance threshold year at the island scale (0.67). This suggests that at the island scale, geomorphology plays a larger role in when a barrier island becomes human dominated. This may also indicate a greater amount of shore protection was required to reduce shoreline position variability, causing the threshold to be reached later.

Table 5. Island scale correlation of human dominance thresholds and island mobility values.

	Island Mobility vs. Threshold	
	Island Mobility	Year Threshold Reached
Northern Ocean County	0.37	1962
Long Beach Island	0.36	1962
Brigantine	0.32	1931
Absecon Island	0.24	1931
Ocean City	0.33	1977
Ludlam Island	0.34	1962
Seven Mile Island	0.38	1962
Wildwoods	0.38	1962
	Correllation Value	
	0.67	

To understand the sensitivity of how geomorphic factors such as island mobility affect the determination of the human dominance threshold at the island and study area-scales, a finer-scaled correlation calculation was performed on a per-bin (100m) basis for each island. This was achieved by correlating each individual bin's threshold year with its corresponding island mobility value. Table 6 summarizes the per bin correlation between island mobility and human dominance threshold years.

Table 6. Correlation values between thresholds and island mobility at the bin scale.

Correlation values per bin							
NOC	LBI	Brigantine	Absecon	Ocean City	Ludlam	Seven Mile	WW
-0.07	0.42	0.22	-0.25	-0.04	-0.16	-0.13	-0.28

The results of the bin-scale correlation analysis show variability in the relationships between island mobility and threshold year. The results for Northern Ocean County, Absecon Island, Ocean City, Ludlam, Seven Mile Island, and The Wildwoods show relatively low negative correlation values ranging from -0.07 (Northern Ocean County) to -0.28 (Wildwood). This indicates that for these islands, there may be an inverse relationship at the bin-scale between threshold year and island mobility. In other words, individual bins may have high island mobility, but become human dominated earlier in time. LBI and Brigantine were the only islands with positively correlated results, indicating a direct relationship at the 100m scale between threshold year and island mobility (i.e. per-bin high island mobility, but human dominated later). The differences between the correlation values may be directly attributed to the initial percentage of human dominated bins in 1920. As shown in Table 3, the initial percentages of human dominated bins in 1920 for NOC, Absecon, Ocean City, Ludlam Island, Seven Mile Island, and the Wildwoods range between 8.55% (Ludlam Island) and 69.1% (Absecon Island). These values are significantly higher than those values for LBI (4.68%), and Brigantine (0.0). Initial development patterns in 1920 and earlier may have been more related to island access as opposed to shoreline variability. Figure 12 shows shore protection for the study area didn't start to significantly increase until 1931, indicating protection was needed following human dominance in areas with relatively high island mobility. Thus, island mobility did not dictate where development took place in 1920. For LBI and Brigantine, positive correlation values indicate an increased amount of shore protection structures were built to reduce shoreline variability following increased development of the islands, resulting in bins becoming human dominated later time as a means to stabilize shorelines.

The differences in correlation values at varying scales indicate a direct relationship between island mobility and threshold year at the island scale (human dominance occurs later in time), but the 100m bin scale shows human dominance occurs earlier regardless of geomorphic factors such as island mobility. The implication is that geomorphic factors such as island mobility do not dictate the spatial distribution of when human dominance occurs along a barrier island.

The following sections present and discuss island scale and 100m bin scale threshold results for each barrier in the study area. The figures included in each section are: (1) island scale percentage of human dominated bins compared to human variables (i.e. roads, buildings, shore protection) through time and (2) maps displaying spatial variation of when thresholds were reached per bin. Island scale results show how this study provides the foundation for the Developed Barrier Island Life-Cycle model and determining when thresholds are reached. The 100m bin scale results demonstrate how geomorphic threshold ratio calculations can be applied to developed barrier islands for determining human dominance thresholds at finer scales.

3.3.2 Northern Ocean County

The northern Ocean County (NOC) barrier-spit is located within the "wave-dominated" geomorphic region and has different geomorphic characteristics than the other barriers to the south. The NOC barrier is connected to the mainland in the north and has two bridges connecting the barrier spit to the mainland. The threshold was determined to be reached by1962. Figure 13 compares human variables to the total percentage of human dominated bins through time for NOC. While the barrier follows a similar pattern to the combined results, the human variables show a significant increase from 1920 to 1955, then level off. Buildings and roads remain relatively level following 1955, shore protection again dramatically increases after the threshold is reached between 1977 and 1995.

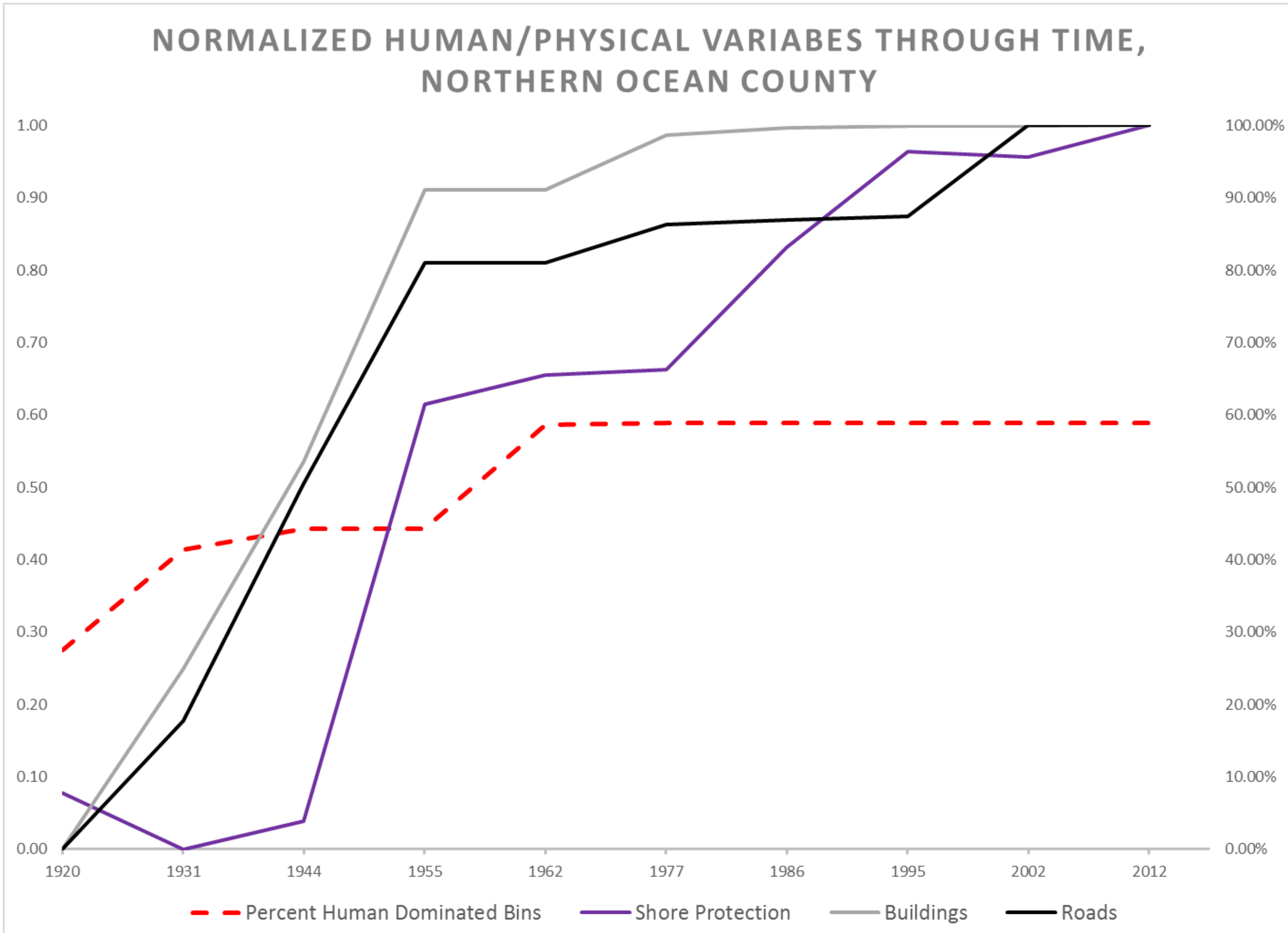


Figure 13. Northern Ocean County's percentage of human dominated bins (dashed red line) compared to normalized human variables(i.e. length of shore protection structures, number of buildings, length of roads) through time.

Figure 14 provides a closer examination of the human dominance threshold years for individual bins along NOC. Along the northern and southern extremes of the developed portion of the island, thresholds were reached in 1920 and 1931, with the majority being 1920. In the central portion of the island, the remainder of the bins reach the threshold in 1962. Island Beach State Park encompasses the southern half of the barrier spit. The park has been operated by the state of New Jersey since 1953. Prior to the state's purchase, it was privately owned land, with only three structures. Since development in this portion of the barrier spit has been prohibited since 1953, no bins have reached the human dominance threshold.

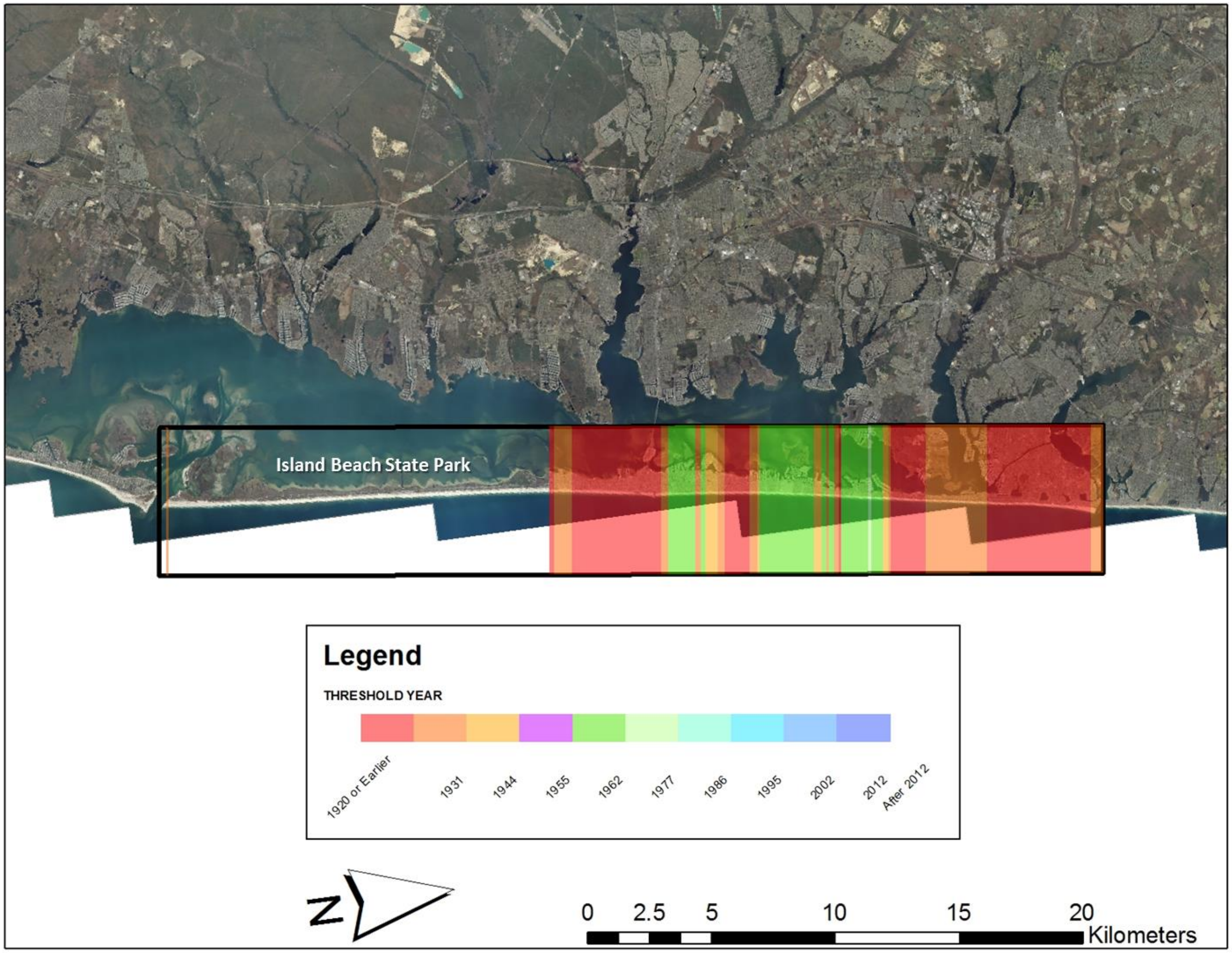


Figure 14. Map of northern Ocean County human dominance thresholds per zonal analysis bin.

3.3.3 Long Beach Island

LBI is the southernmost barrier within the “wave dominated” geomorphic region along New Jersey’s Atlantic Coast. The barrier only has one bridge connecting the island to the mainland. The human dominance threshold for LBI was reached by 1962. While there was a leveling off of development following 1962, there was a much larger increase in the percentage of human dominated bins from 1955 to 1962 when compared to NOC (Figure 15). This may be primarily due to the construction of the bridge in 1958. The earliest dataset (1920) also showed that LBI had far less development than NOC. This is likely due to the northern portion of the NOC barrier spit being connected to the mainland, providing readily available access for development.

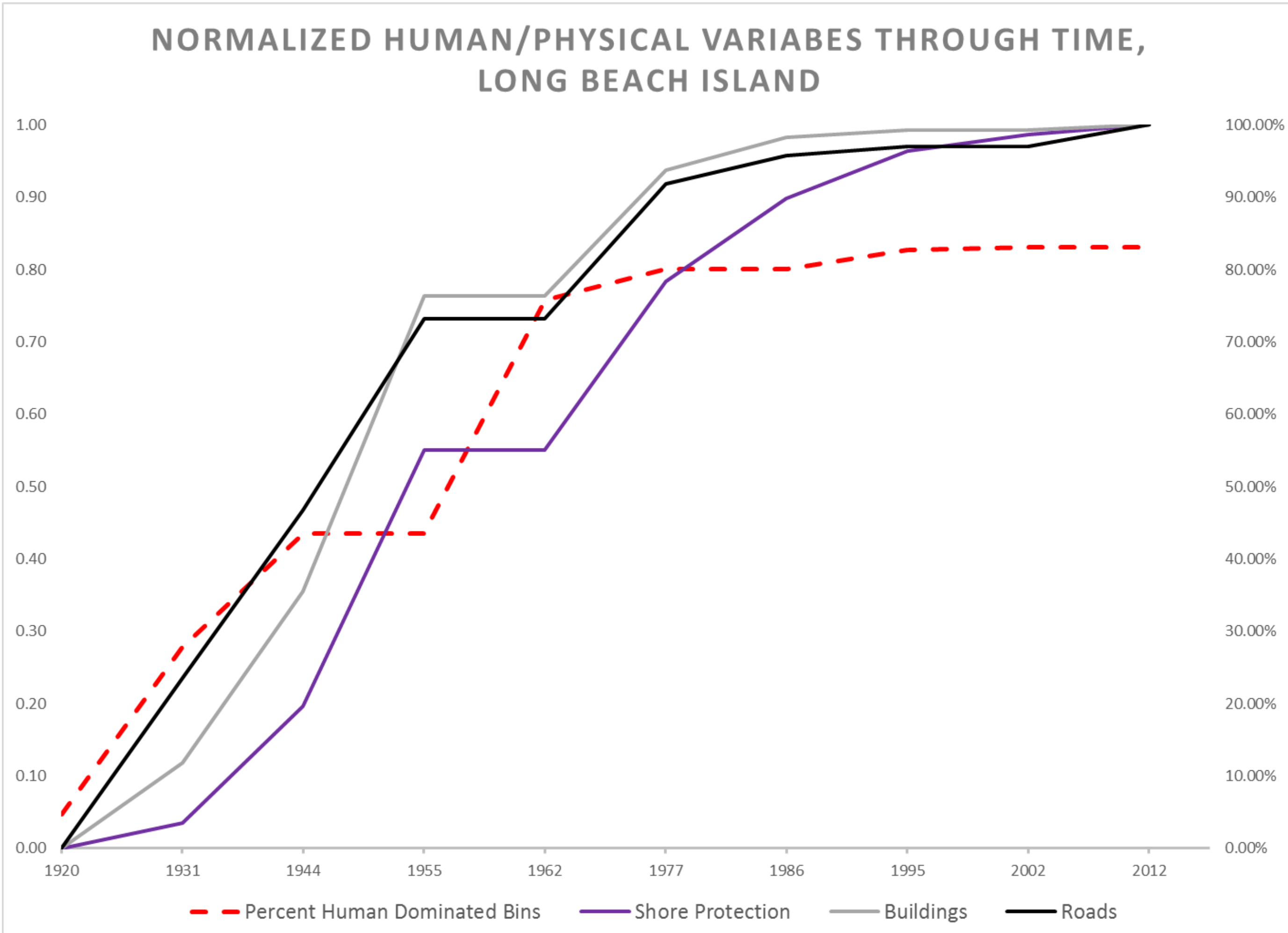


Figure 15. LBI's percentage of human dominated bins compared to normalized human variables.

Figure 16 displays the threshold year on a per-bin basis for LBI. The bin data reveals a similar pattern to NOC, with the exception of the northern extent of the island (Barnegat Light) having far less bins reach the threshold by 1920. Also similar to NOC, the southern portion of the island had a significant number of bins with thresholds in 1920 and 1931. The central portion of the island's bins had dominance thresholds reached primarily in 1962. This is most likely due to the construction of the causeway providing access to the center of the island in 1958.

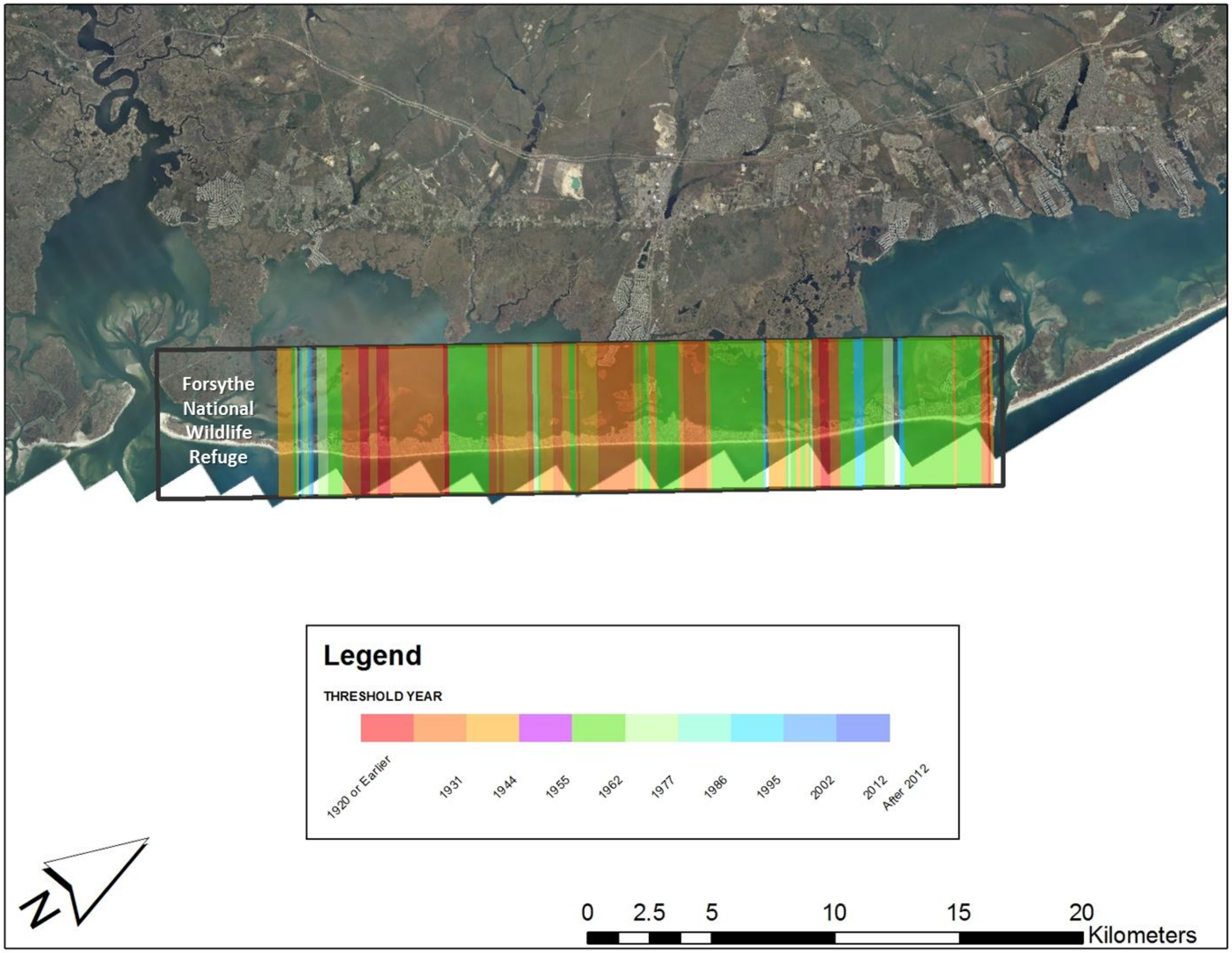


Figure 16. Map of LBI human dominance thresholds per zonal analysis bin.

3.3.4 Brigantine Island

Brigantine Island is the first developed barrier island along New Jersey's "mixed energy" geomorphic region. The human dominance threshold for Brigantine Island was reached by 1931. In 1921 there were no human dominated bins found along the island. However, by 1931, the human dominance threshold had been reached (Figure 17). This was primarily due to the island being completely uninhabited in 1920 and then having most of the developable land cleared for construction of homes and roads by 1931. The construction of the bridge connecting Brigantine Island to Absecon Island in 1924 provided access for development. Buildings and shore protection continued to increase significantly after the human dominance threshold was reached, with the amount of building leveling off in 1986. Installation of shore protection continued to increase until 1995, and then slightly decreased between 2002 and 2012 due to some structures not being visible in aerial photographs as two federal shore protection projects were completed in 2006 and 2011, covering existing protection structures with sand (Farrell et al. 2015).

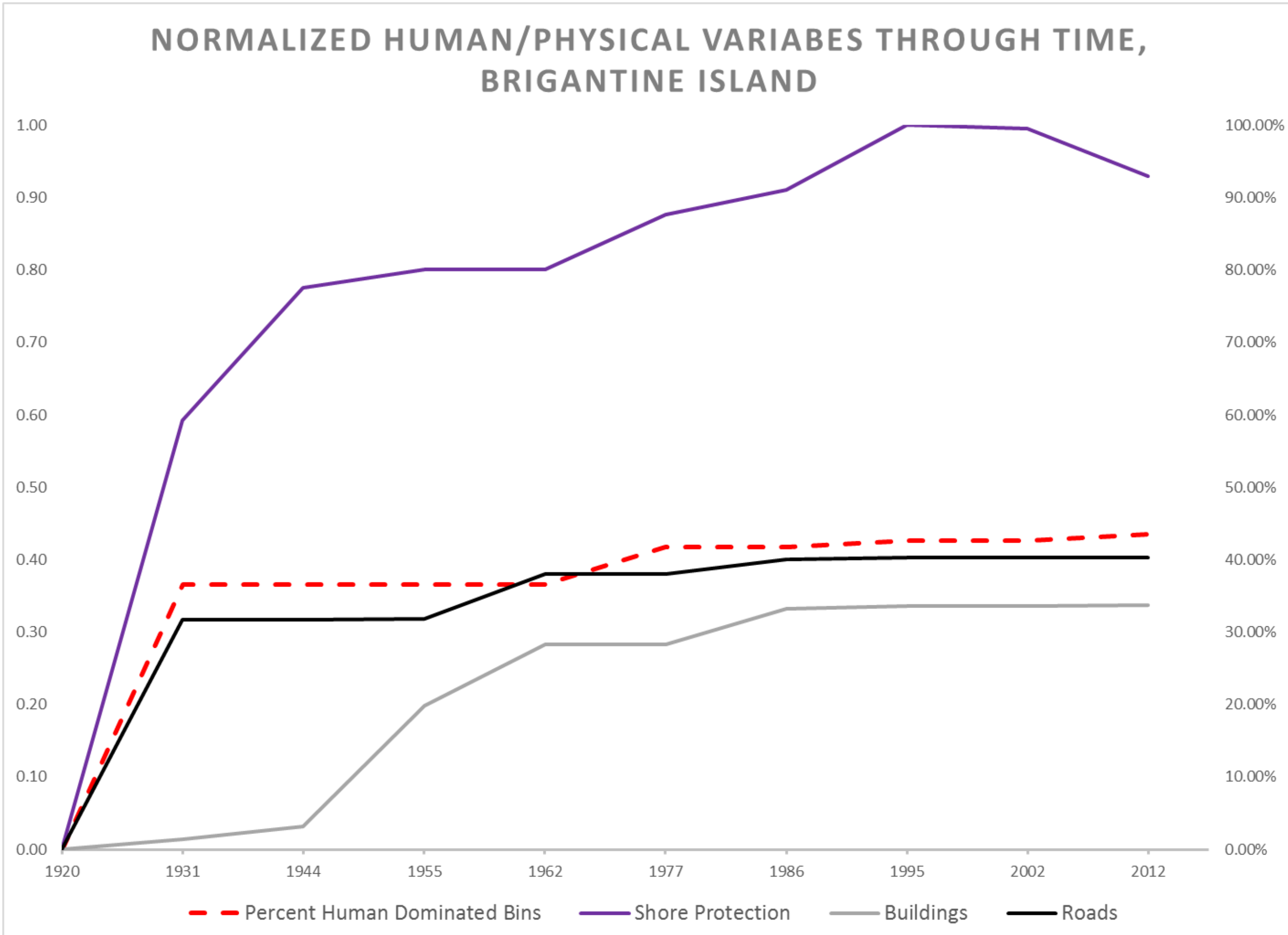


Figure 17. Brigantine Island’s percentage of human dominated bins compared to normalized human variables.

Figure 18 shows that the majority of bins in the central portion of the island reached the human dominance threshold by 1931. Due to the large marsh complex along the southern portion of the island, many bins have not reached the threshold. Several bins just to the south of the central portion of the island reached thresholds in 1962 due to increased residential development. The bins in the northern portion of the island have not reached thresholds since development of that portion of the island, known as the "Brigantine Natural Area" is restricted under the NJDEP's Green Acres Program.

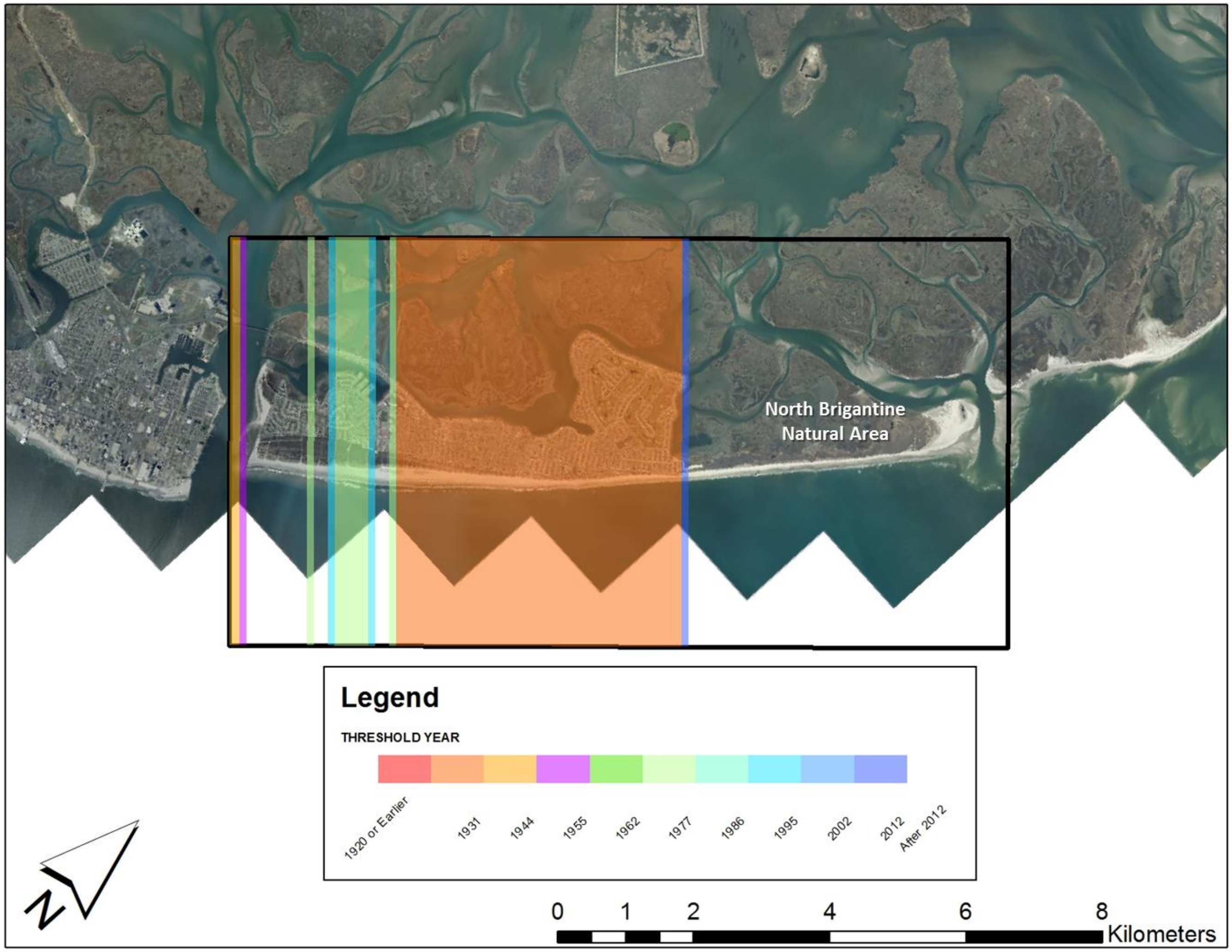


Figure 18. Map of Brigantine Island human dominance thresholds per zonal analysis bin.

3.3.5 Absecon Island

Figure 19 shows that by 1920 approximately 58.99% of the bins had reached human dominance thresholds. The amount of human dominance in 1920 can be attributed to the construction of the first railroad from Philadelphia to Atlantic City in the 1850s (Koedel 1979). Despite the island reaching its human dominance threshold in 1931, significant road development and building construction increased until 1944, then leveled off. Shore protection in Absecon Island increased dramatically between 1931 and 1955, with very little increase between 1920 and 1931. There was a slight decrease in the amount of shore protection visible in Absecon Island between 1955 and 1962 and then a major decrease in visible structures between 1962 and 1977. As described above, this was due to the invisibility of timber groin structures in the aerial photographs, presumably due to the structures being covered by sand, removed, or destroyed by the 1962 northeast storm. The U.S. Army Corps of Engineers (1996) documented that between 1963 and 1970, approximately 1,515,000 cubic yards of sand (1,158,300 cubic meters) were placed on Absecon Island. Following 1977, the amount of shore protection structures visible in photographs rapidly increased until a slight decrease between 1995 and 2012. The decrease can be attributed to structures being covered by sand and not visible in aerial photographs since the Corps constructed a shore protection project in 2004.

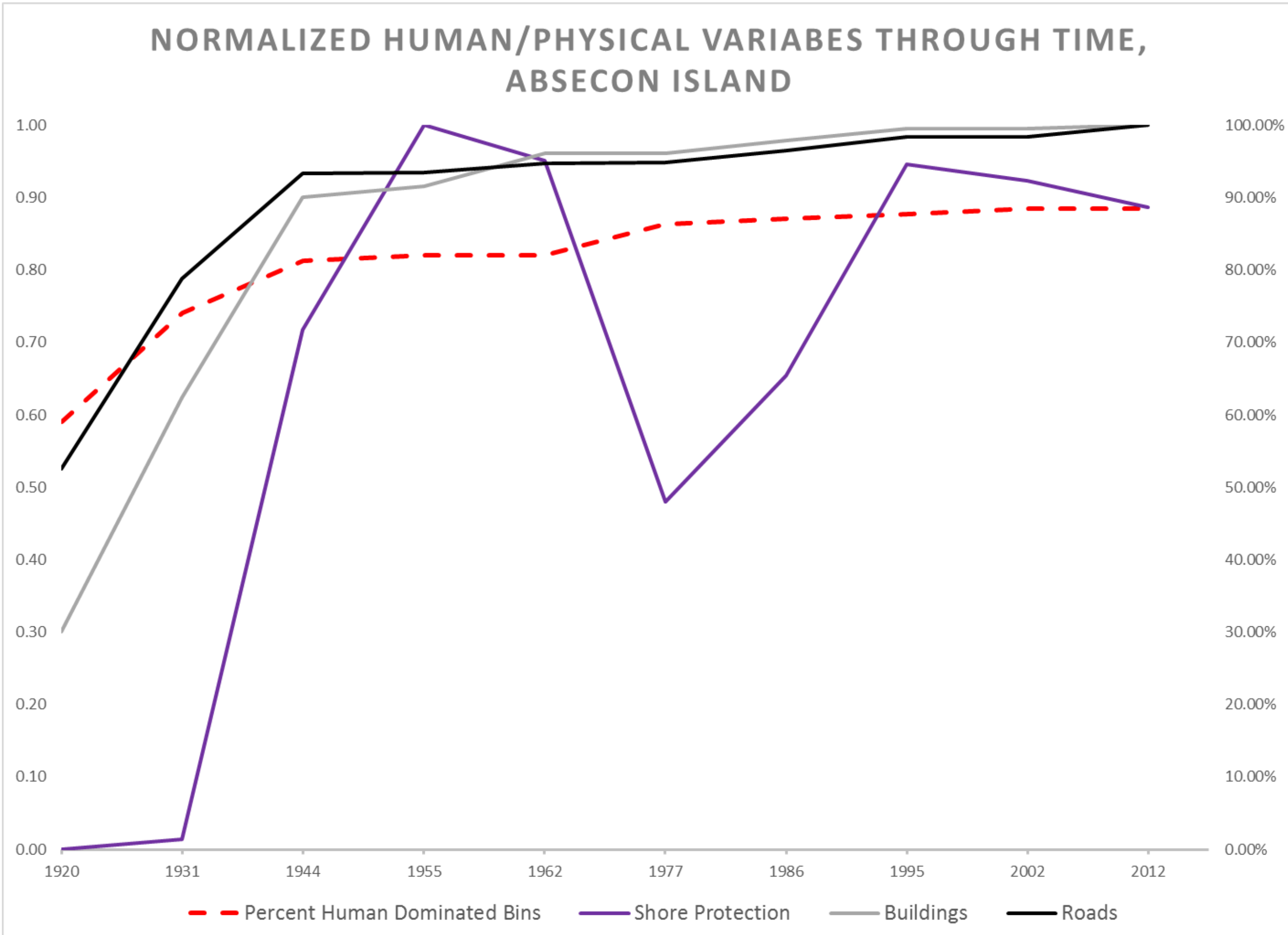


Figure 19. Absecon Island's percentage of human dominated bins compared to normalized human variables.

Figure 20 shows human dominance threshold years per 100m bin for Absecon Island. The vast majority of bins on Absecon Island reached thresholds by 1920, with the exception of a small central portion of the island where no threshold has been reached (due to presence of a large marsh landward of development). Access to Absecon Island via railroad in the 1880s, and four bridges located along the northern and southern portions of the island, are most likely the reasons for the island reaching thresholds earlier in those areas compared to the central portion of the island.

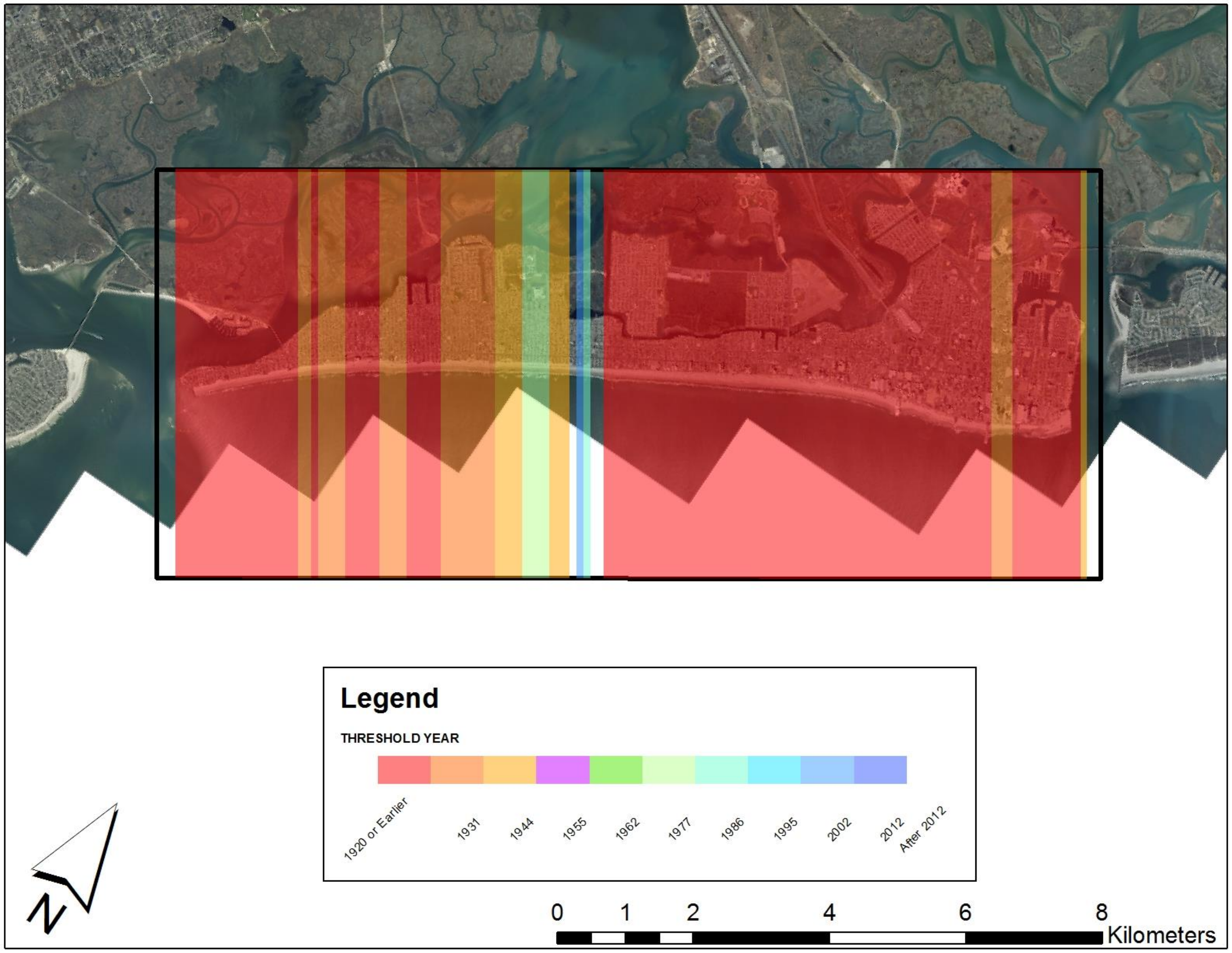


Figure 20. Map of Absecon Island’s human dominance thresholds per zonal analysis bin.

3.3.6 Ocean City

Figure 21 shows Ocean City's initial percentage of human dominated bins in 1920 was relatively high (35.56%). Unlike Absecon Island, Ocean City did not reach its human dominance threshold until 1977. Between 1920 and 1977, Ocean City experienced a gradual increase in the percentage of human dominated bins, and then leveled off following 1977. The amount of roads and number of buildings experienced a similar trend, gradually increasing until 1977, and then only moderately increasing. Conversely, the amount of shore protection in Ocean City increased dramatically between 1944 and 1962, then had a minor decrease in 1977. Shore protection gradually increased between 1977 and 2002, and leveled off between 2002 and 2012. Similar to shore protection at other islands, significant decreases in the amount of shore protection (as between 1920 and 1931) are due to timber groin structures not appearing in the aerial photographs. These may not be visible due to the structures being removed, covered by sand, or destroyed by a coastal storm event.

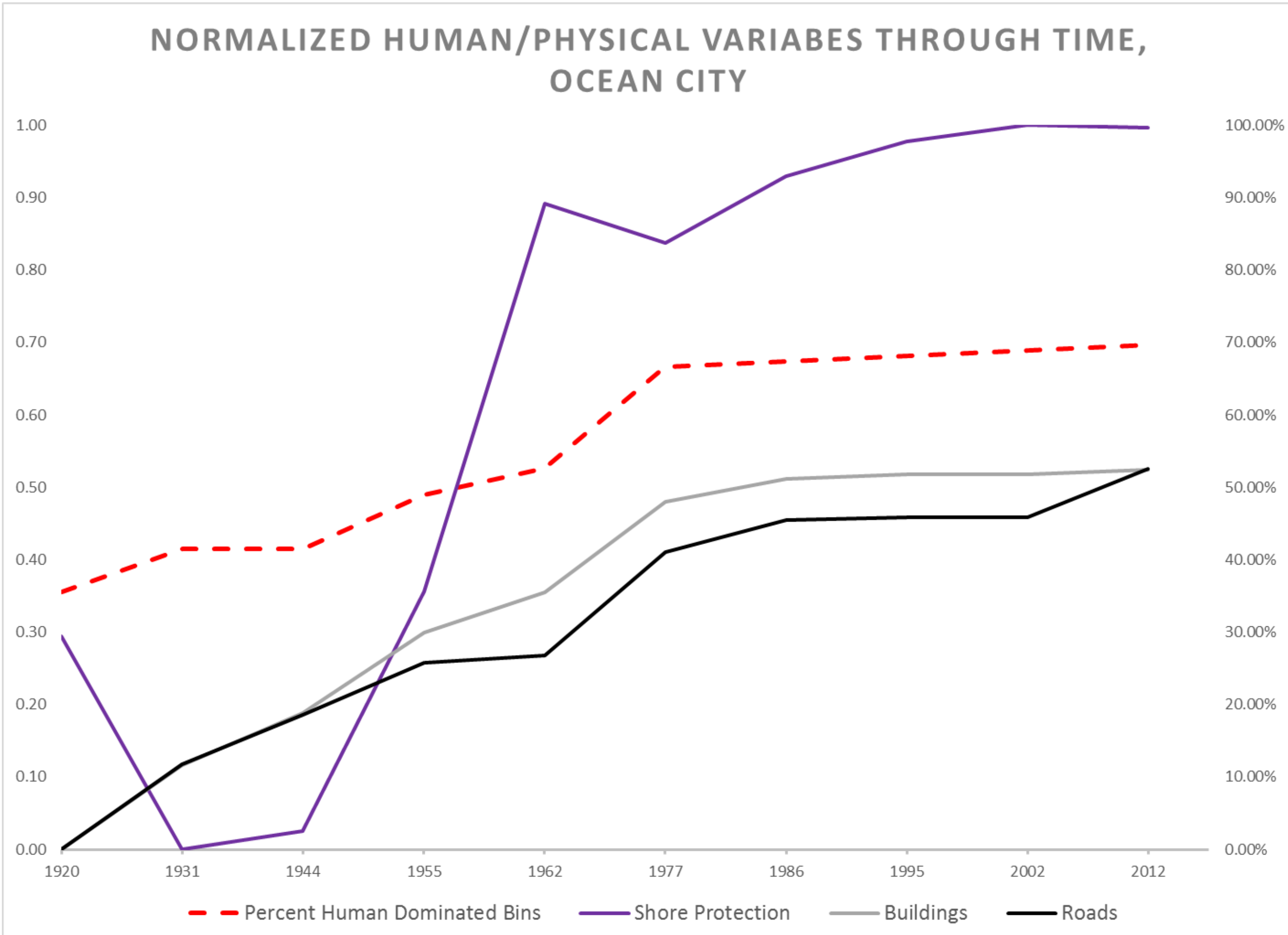


Figure 21. Ocean City's percentage of human dominated bins compared to normalized human variables.

Figure 22 displays human dominance thresholds for each 100m bin along Ocean City. The island has five separate bridges connecting it to the mainland or adjacent barrier islands. As noted in Figure 21 and displayed in Figure 22, the 35.56% of 1920 dominated bins occur exclusively in the northern portion of the island, with the northernmost extent proximal to Great Egg Inlet having several bins with thresholds in 1931. The northern portion of the island was human dominated prior to other areas of Ocean City because the Pennsylvania Railroad connected the barrier to the mainland at this location in 1887 (Rutgers University 2016). The central portion of the island's 100m bins primarily have thresholds ranging from 1955 to 1962. Due to the southern portion of the island's expansive marsh landward of current development and the extreme southern portion is a part of Corsons Inlet State Park, many of the bins in this area have not reached the human dominance threshold.

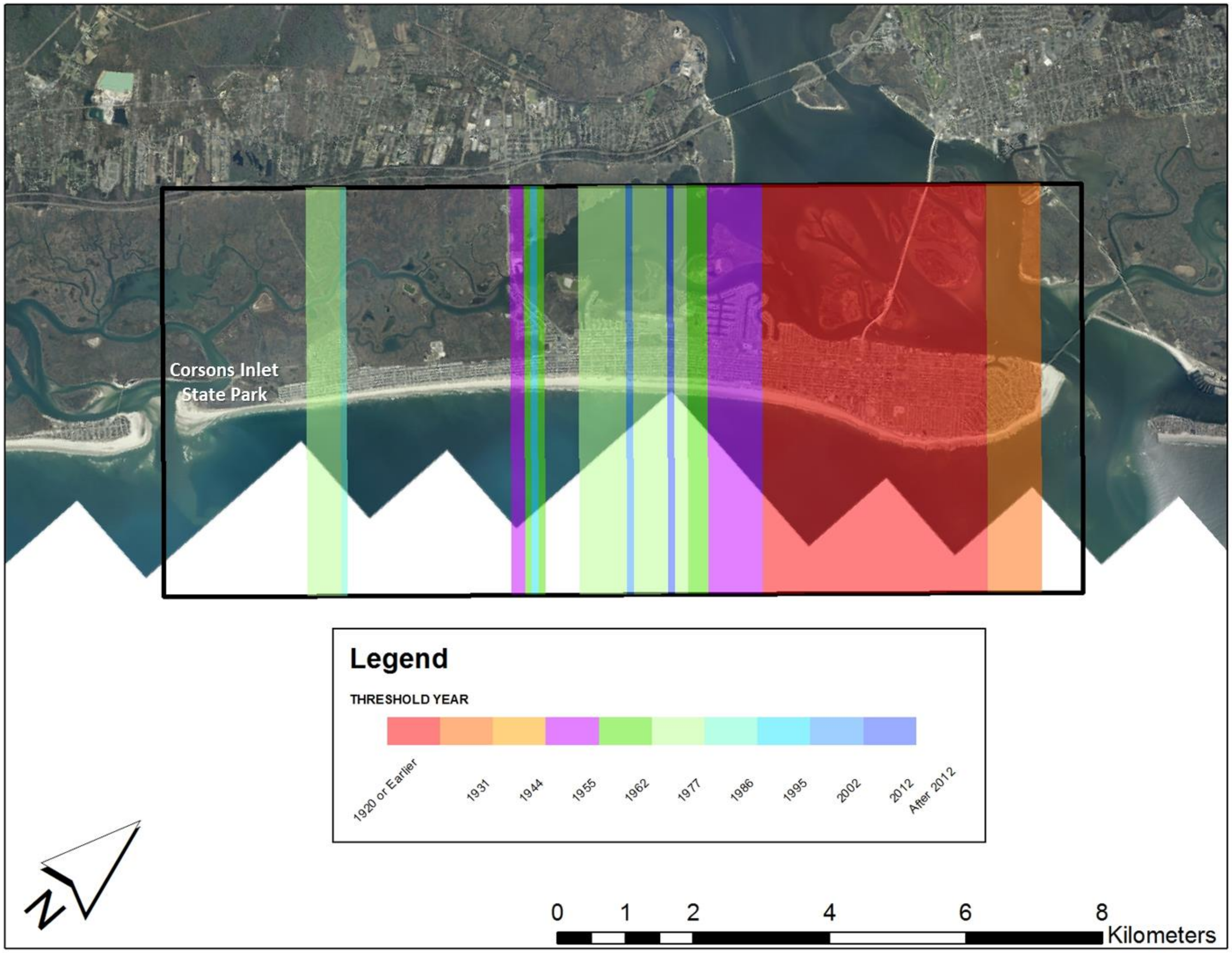


Figure 22. Map of Ocean City's human dominance thresholds per zonal analysis bin.

3.3.7 Ludlam Island

In 1920, Ludlam Island had a relatively small amount of human dominated bins (8.55%) presumably because initial development proximal to where the West Jersey Railroad connected to the barrier from the mainland and adjacent islands in the 1880s stopped in Sea Isle City in the south and Strathmere in the north (Allaback & Milliken 1995). The narrow Whale Beach section between the two communities is sparsely populated and has never become human dominated by infilling the wetlands between the barrier and the mainland (as was common along other barriers). Some uplands portions of this section are less than 120m wide and due to the railroad occupying much of this area along Whale Beach, the majority of development was limited Sea Island City and Strathmere (Nordstrom & Jackson 1995). Ludlam Island experienced a gradual increase in the percentage of human dominated bins until its threshold was reached in 1962. Figure 23 shows the amount of development of buildings and roads each leveled off after 1977. Shore protection increased between 1920 and 1955, but increased dramatically between 1955 and 1962. Following 1962, the amount of shore protection decreased significantly, but began to increase gradually after 1977. The dramatic increase in shore protection between 1955 and 1962 can be attributed to several factors including: (1) The 1962 northeast storm exposing many pre-existing structures that were previously covered in sand due to severe erosion, or (2) a significant amount of groin structures were installed between 1955 and 1962 and subsequently covered by sand between 1962 and 1977 due to natural inlet migration causing shoreline accretion along the adjacent ocean-facing beach. These factors are described in detail in section 4.2.1 and demonstrated in Figure 31.

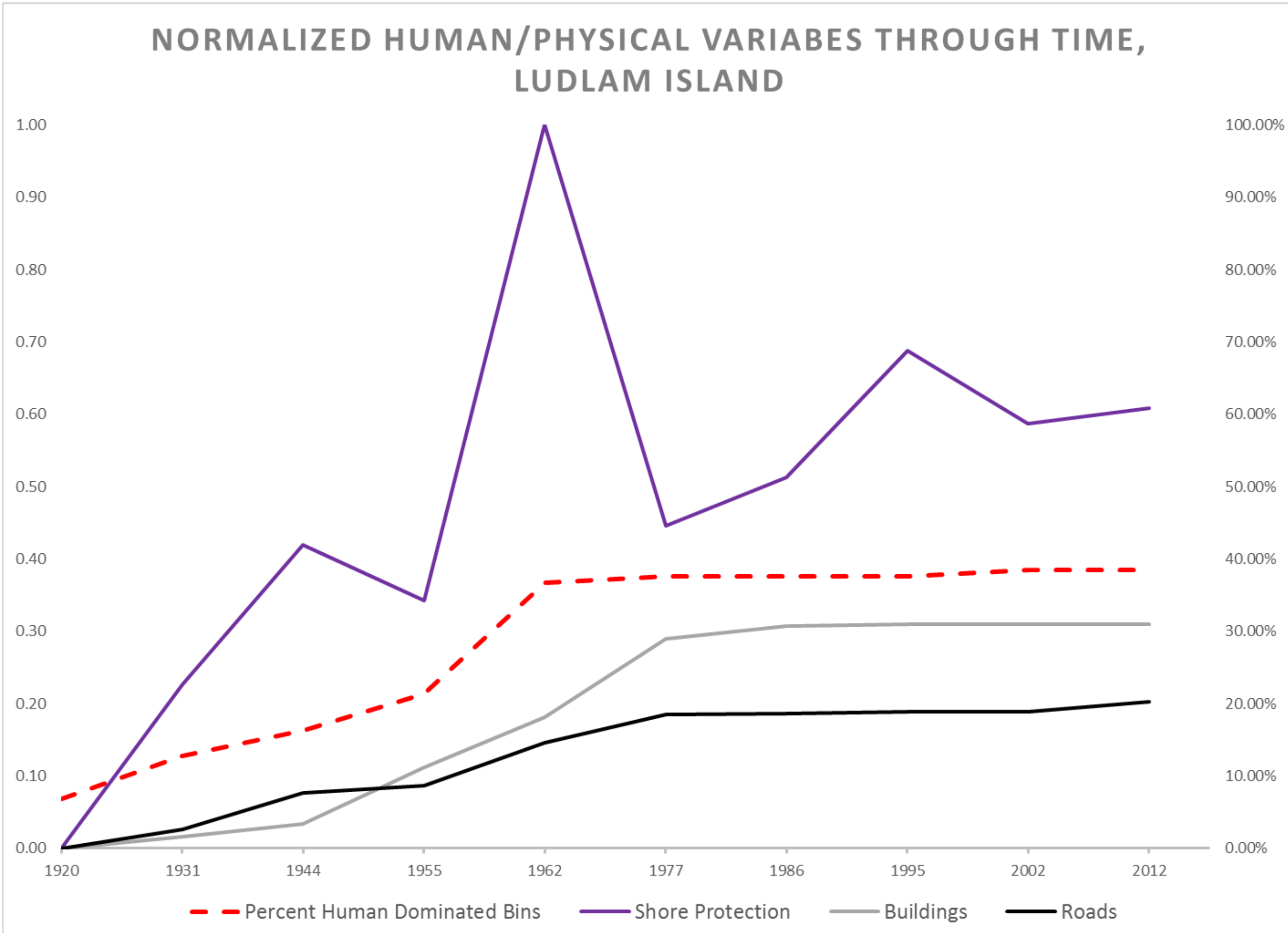


Figure 23. Ludlam Island's percentage of human dominated bins compared to normalized human variables.

Figure 24 shows human dominance thresholds for each 100m bin along Ludlam Island. Current development is limited to the extreme northern and south/south-central portions of the island. The remainder of the island is characterized as a sparsely developed barrier with a narrow back barrier marsh fronted by a narrow beach. The human dominance threshold for Ludlam Island was reached by 1962, with the majority of bins reaching their thresholds in the southern portion of the island in 1962 (Sea Isle City). The northern portion of Sea Isle City, located along the southern half of Ludlam Island reached is threshold between 1920 and 1944 and the northern Strathmere section of the island reached its threshold between 1920 and 1962. The bins in the central portion of the island do not show the human dominance threshold has been reached. The extreme northern portion of the barrier is part of the Strathmere Natural Area. This location is continually altered due to Corsons Inlet's main channel being unconfined and allowed to migrate to the north and south. This process is described in section 4.2.1 and displayed in Figure 31.

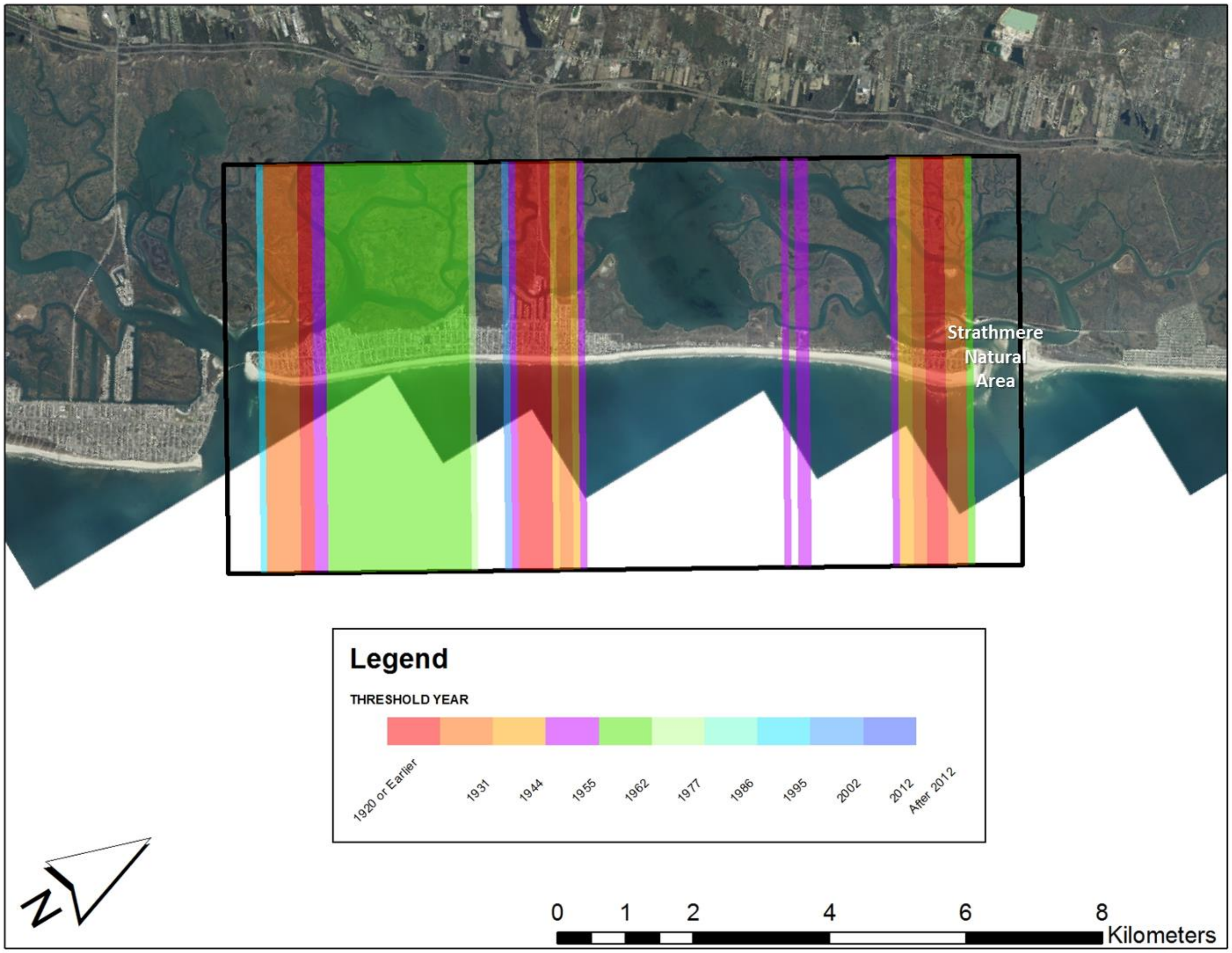


Figure 24. Map of Ludlam Island's human dominance thresholds per zonal analysis bin.

3.3.8 Seven Mile Island

Seven Mile Island's percentage of human dominated bins in 1920 was 44.74% and also experienced a gradual increase in human dominated bins until the island's threshold was reached by 1962 (Figure 25). Seven Mile Island's number of roads and buildings increased significantly between 1920 and 1977, and then leveled off between 1977 and 2012. Between 1920 and 1955, the amount of shore protection remained relatively stable, but increased dramatically between 1955 and 1977. After the island's threshold was reached, shore protection continued to increase until leveling off in 1995.

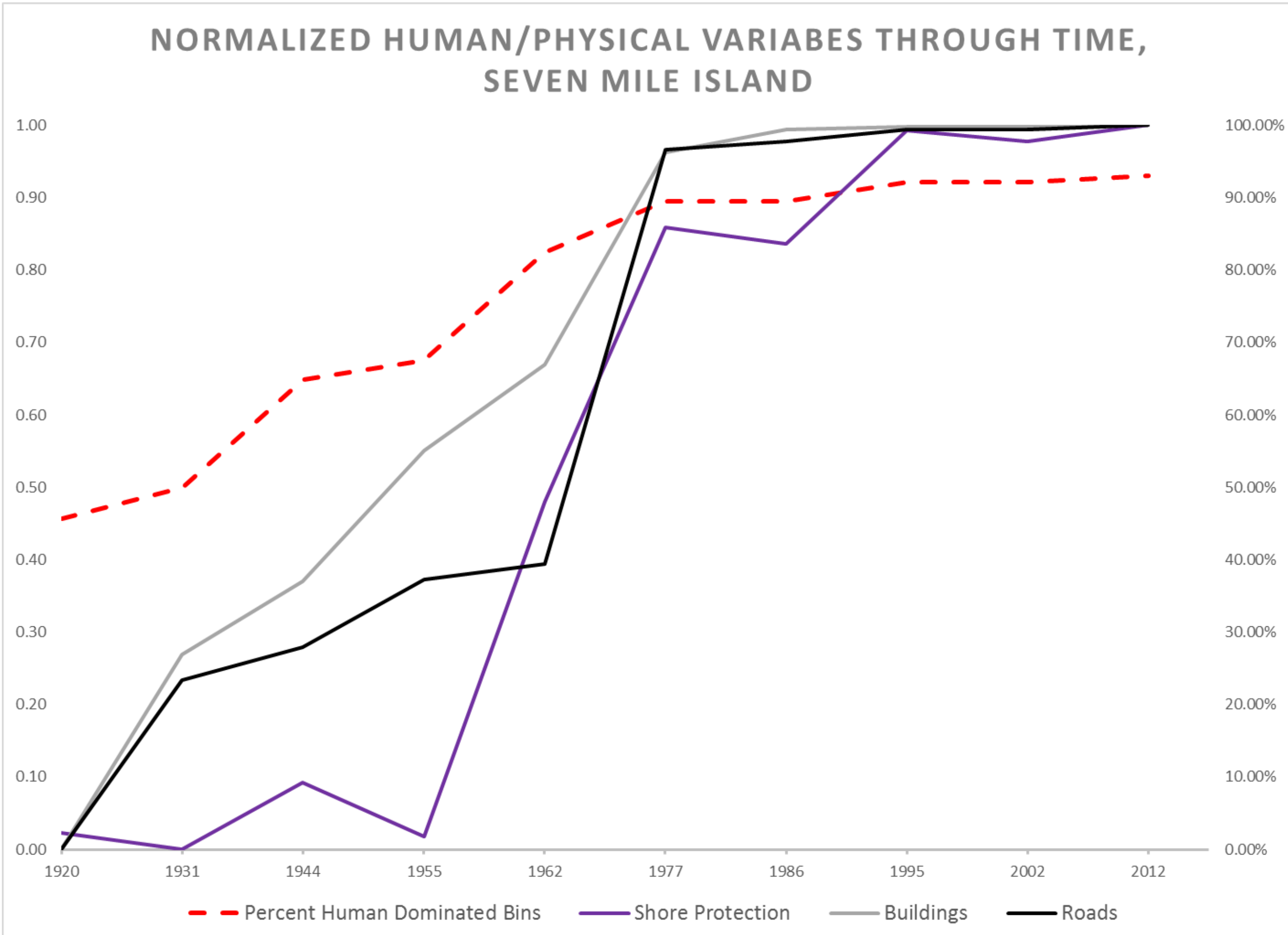


Figure 25. Seven Mile Island's percentage of human dominated bins compared to normalized human variables.

Figure 26 displays the human dominance threshold years per 100m bin for Seven Mile Island. Seven Mile Island has multiple bridges connecting the island to the mainland and adjacent barrier islands. The two communities on this island, Avalon and Stone Harbor, each have a main bridge connecting the center of each municipality to the mainland. Figure 26 shows that the northern and southern portions of the island were human dominated in 1920, with the center portion of the island dominated between 1944 and 1977.

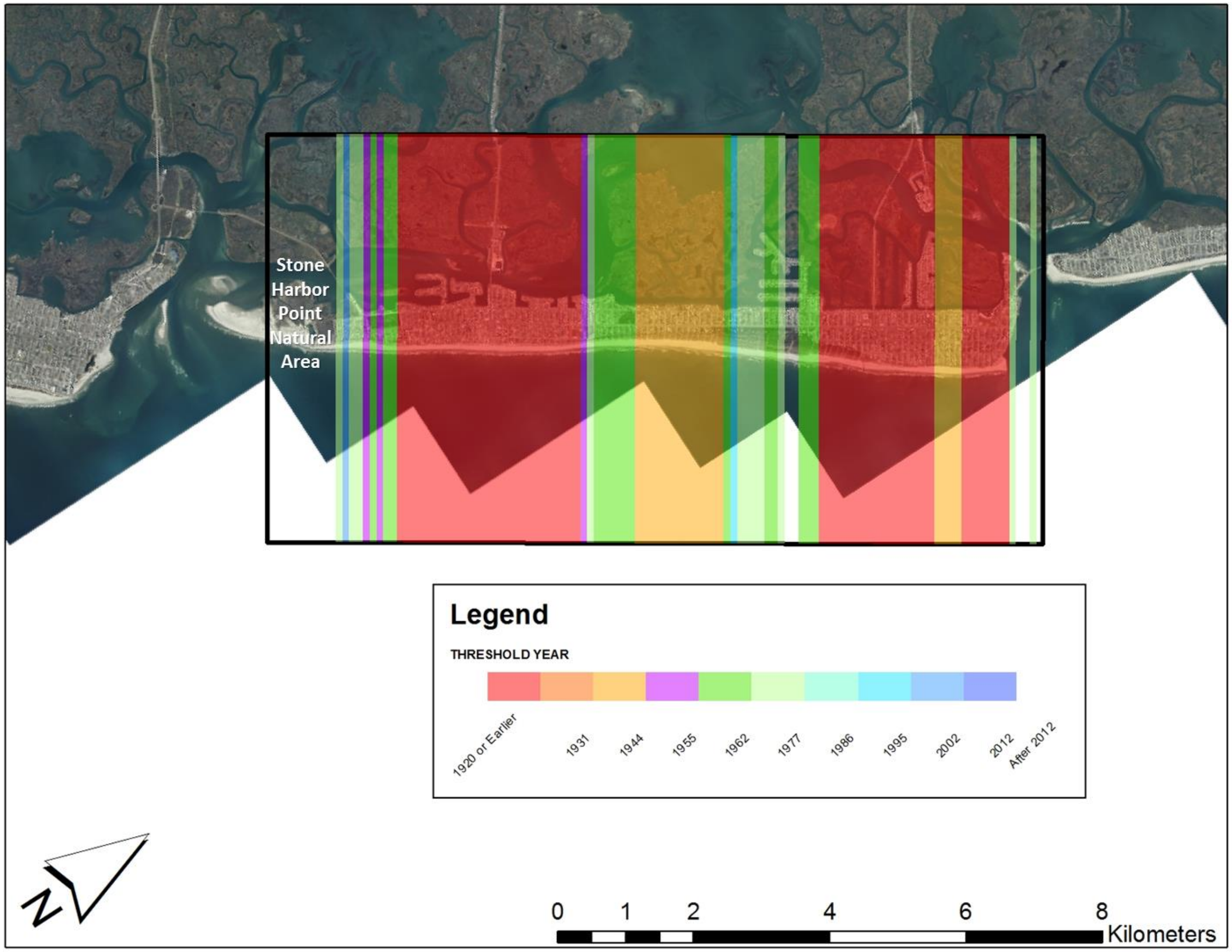


Figure 26. Map of Seven Mile Island's human dominance thresholds per zonal analysis bin.

3.3.9 The Wildwoods

Figure 27 demonstrates that the Wildwoods experienced the most gradual increase in development, with the island reaching its threshold by 1962. The percentage of human dominated bins in 1920 was 50%, and continued to increase until 1962, and then leveled off. In 1920 there was a small amount of roads and buildings, but shore protection was present indicating that much of the land was cleared for development of roads and buildings. Between 1920 and 1986, there was a steady increase in the amount of roads and buildings and then leveled of after 1986 with only slight increases (after the threshold was reached). Shore protection increased dramatically between 1931 and 1995 and then slightly decreased between 2002 and 2012. Farrel et al. (2011) documented that the Wildwoods shoreline has increased by 198m since 1986 as Cresse Avenue in the town of Wildwood (center of the island), and it is likely that many shore protection structures have been covered by sand.

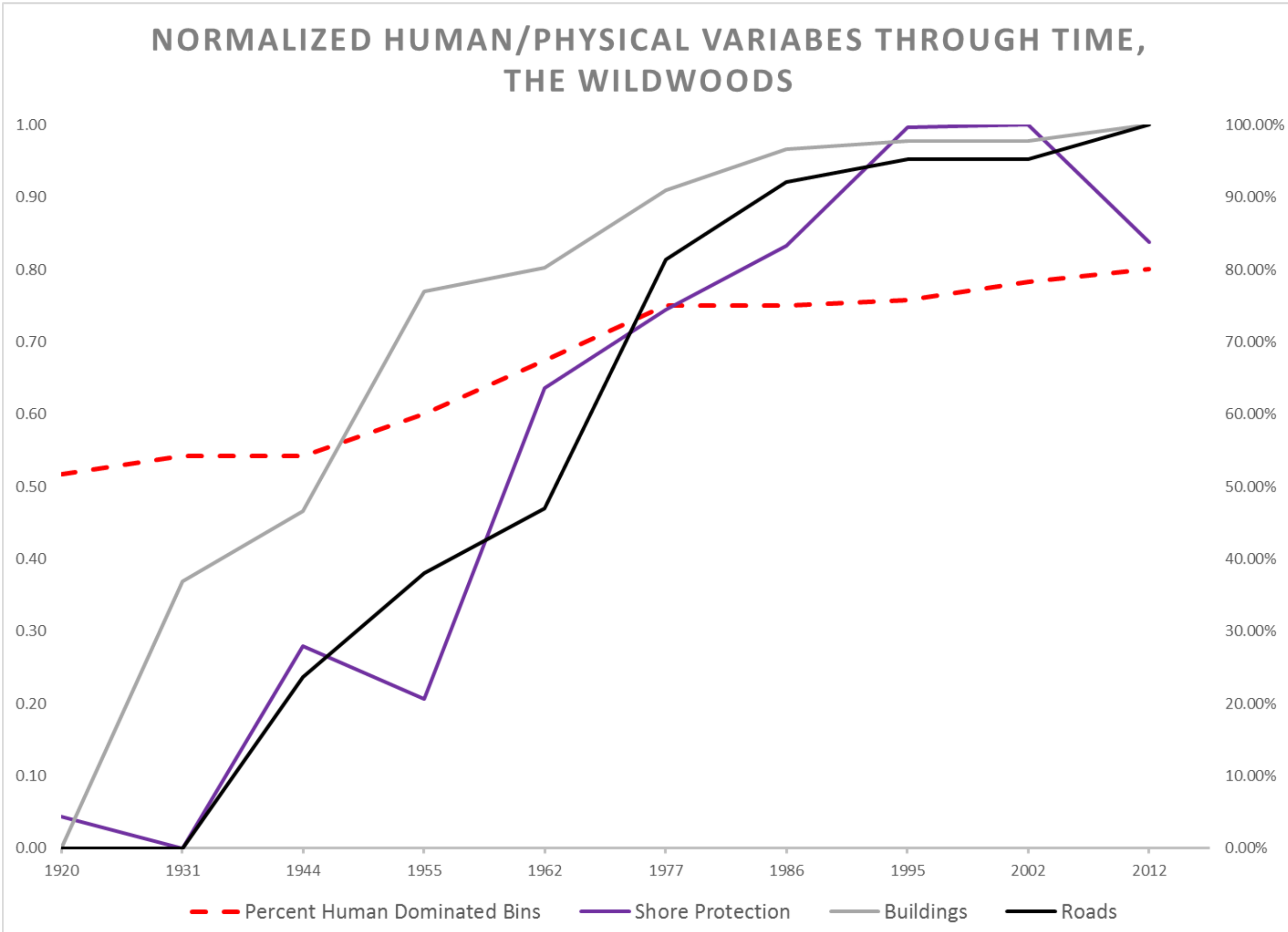


Figure 27. The Wildwood’s percentage of human dominated bins compared to normalized human variables.

Figure 27 shows that in 1920, 50% of the island's bins were human dominated. Following the natural closing of Turtle Gut Inlet along the southern portion of the island in 1922, the land area of the island increased and development of the southern portion of the island began. Figure 28 shows the human dominance thresholds for bins in this location were reached by 1977. The bins in the extreme southern portion of The Wildwoods are not human dominated. This section is managed by the Cape May National Wildlife Refuge. The extreme northern extent of the island shows those bins reached human dominance thresholds in 1962.

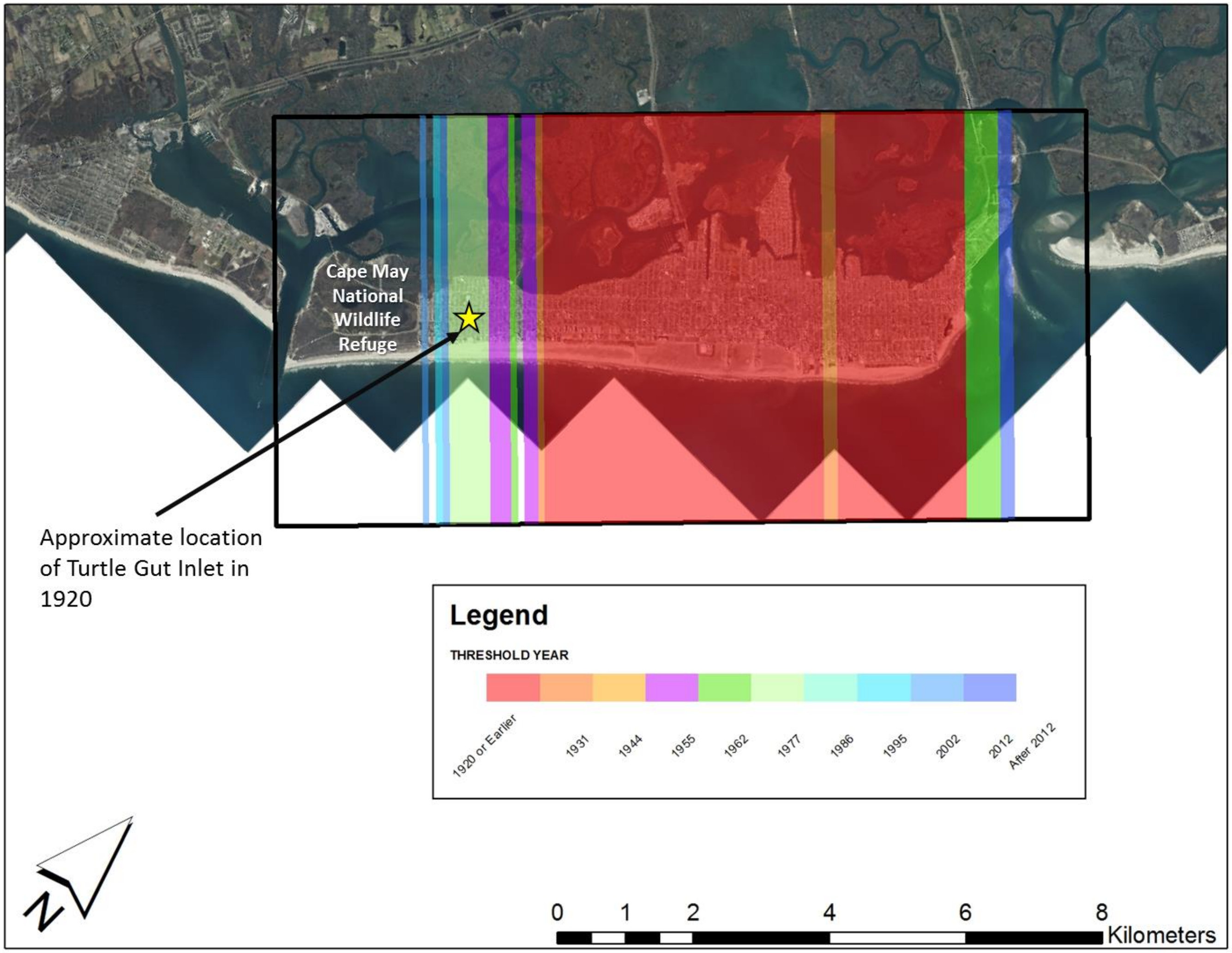


Figure 28. Map of the Wildwood's human dominance thresholds per zonal analysis bin. The approximate location of Turtle Gut Inlet (naturally closed in 1920) is highlighted by the yellow star.

3.4 Summary of Results

- Combined human dominance threshold results for the entire study area show that New Jersey's barrier islands were human dominated by 1962.
- At the island scale, correlation results show a direct relationship between island mobility and threshold year (human dominance occurs later), but the 100m bin scale shows human dominance occurs earlier in places regardless of geomorphic factors such as island mobility.
- The year and location of human dominance at bin and island scales were influenced by when and where access to the barrier islands via railroads and vehicle bridges was constructed regardless of geomorphic classification.
- Shore protection continued to increase along islands after thresholds were reached, while the amount of buildings and roads leveled off.
- Variability in the visibility of shore protection structures (and subsequent delineation) between aerial photograph dates can be attributed to coastal storm events, inlet dynamics, installation of inlet jetties, or beach nourishment projects.
- Adoption of environmental regulations such as the Wetlands Act of 1970 that restricted development in tidal wetlands, and the creation of state parks, natural areas, and national wildlife refuges, influenced the rate and location of human dominance along the barriers.

Chapter 4: Discussion

This chapter addresses: (1) how island-scale threshold results relate to the Developed Barrier-Island Life-Cycle model, (2) the significance of determining human dominance thresholds at 100m bin scales, (3) the influence of geomorphic factors on when thresholds are reached, (4) the influence of infrastructure construction on thresholds, (5) the influence of extreme coastal storm events on thresholds, (6) the influence of human variables on thresholds, and (7) how thresholds vary across the geomorphic regions.

4.1 Island-scale human dominance threshold results compared to the model

The percentage of human dominated bins (i.e. development) results for the entire study area and for the individual islands displayed in Figure 11 are representative of the Developed Barrier-Island Life-Cycle model. The time period for this study (1920 – 2012) did not measure the rate of development prior to 1920, even though New Jersey's barrier islands were home to communities and had railroad access since the 1880's. The absence of data prior to 1920 makes it impossible to determine the when the Exploration or Involvement Stages began for the barriers with human dominated bins in 1920. However, the time period was considered acceptable since island scale thresholds had not been reached by 1920. Nordstrom (1994) confirms this by stating that development on the barriers in the study area began to increase considerably in the first half of the twentieth century. The earliest aerial dataset used for this study (1920) covers this time period.

With the exception of Brigantine Island, the barriers in the study area were already in the Involvement Stage by 1920 (each had railroad access and human dominated bins). Brigantine Island did not have railroad access or a bridge prior to 1920 and was the only barrier in the study area with 0% human dominated bins in 1920. Due to the rapid development of Brigantine Island between 1920 and 1931 (threshold reached by 1931), the barrier island either had an extremely short Exploration Stage or bypassed the stage completely. The latter scenario is more likely, especially since the 1920 photographs to do show any development or enclaves along the barrier and by 1931 most of the land had been cleared for development. The Exploration Stage for the other barriers occurred prior to the introduction of railroad in the 1880's. Once the railroad provided an access point to a barrier, the Involvement Stage began as the railroads provided access to the north and south along the barriers, expanding from island access points (Nordstrom 1994). Development of roads, buildings, and shore protection structures expanded alongshore at railroad stations. The range in the rates of development during the Involvement Stage and when thresholds were reached varied depending the amount of access points to the barrier, the type of access point (railroad or vehicular), and when they were constructed. Section 4.4 provides a detailed discussion on the influence railroads and vehicular access bridges on thresholds. The only barrier that experienced the Stagnation Stage immediately following the threshold was Northern Ocean County. All the barriers had a Continuation Stage and experienced modest increases in the amount of human dominated bins until the end of the study's time period in 2012.

4.2 Significance of determining thresholds at small spatial scales

The delineation of land cover polygon datasets for each aerial dataset year representing human (e.g. urban polygons) and physical (e.g. barren land and wetland polygons) factors described in section 2.4 was critical for calculating human/physical factor ratios per bin for each year. Mapping bin-scale threshold results for each barrier aided in identifying where along the islands' human dominance occurred first and whether the rate of human dominance across a barrier was dictated by a barrier's geomorphic classification or when access via rail/automobile bridges increased. Moore's methodology (2000) for delineating the wet-dry line at the land/water interface along non-structured shorelines (i.e. sandy beaches, tidal marshes) provided an integral step in correlating human dominance thresholds with shoreline variability for the study area and individual barrier islands.

4.3 Influence of Island mobility on human dominance thresholds

Dramatic alterations to shoreline positions between aerial dataset years occurred by (1) constructing shore-parallel structures (e.g. bulkheads and seawalls), (2) infilling of backbarrier tidal marshes and creeks for the expansion of development, and (3) excavating backbarrier tidal marshes and creeks for the creation of lagoons. Hapke et al. (2013) acknowledged that human alterations to the natural system can override natural processes influencing the rate of shoreline change at discrete cross-shore transects. The correlation technique described in section 2.8 and the variability in results per bin presented in section 3.3.1 for individual barrier islands (Table 6) re-affirm this observation. Correlation results per bin for all islands except LBI and Brigantine Island show indirect correlations between island mobility and when a human dominance threshold was reached. Thus, human agency was a more important factor than shoreline change at the local scale. The Exploration and Involvement Stages occurred at these two islands later relative to the other islands, presumably due to limited access to the islands. Access dictated where initial development could take place overshadowed island mobility, resulting in thresholds reached later.

The relatively high correlation value (0.67) between island mobility and when a threshold is reached at the island scale indicates greater island mobility causes island-wide thresholds to be reached later. Correlating geomorphic factors such as island mobility to human dominance thresholds at regional scales reduces variability in correlation results and differs from 100m bin results. These results show spatial and temporal distributions of human dominated bins are primarily controlled by when and where access points were constructed.

4.4 Influence of infrastructure construction on thresholds

The construction or reconstruction of railroads and highways from New York and Philadelphia had an impact on when human dominance thresholds were reached for each island. The rail road access was provided to the most all of the barrier islands in the study area by 1887 (Figure 29) and initial development occurred where rail lines terminated at the barrier islands (Koedel 1979; Nordstrom 1994). Figure 16 demonstrates this pattern for LBI, as the railroad map in Figure 29 shows the access point at the center of the island and the railroad terminating in Barnegat Light to the north and

Beach Haven to the south. The railroad began operating in 1886 (Roberts & Youmans 1993). Both of those locations reached thresholds by 1920. The remainder of the island's bins became human dominated as development expanded from termination points through time. Once the railroad bridge was replaced by the Route 72 vehicular access bridge in 1958, the majority of the remaining bins became human dominated by 1962.

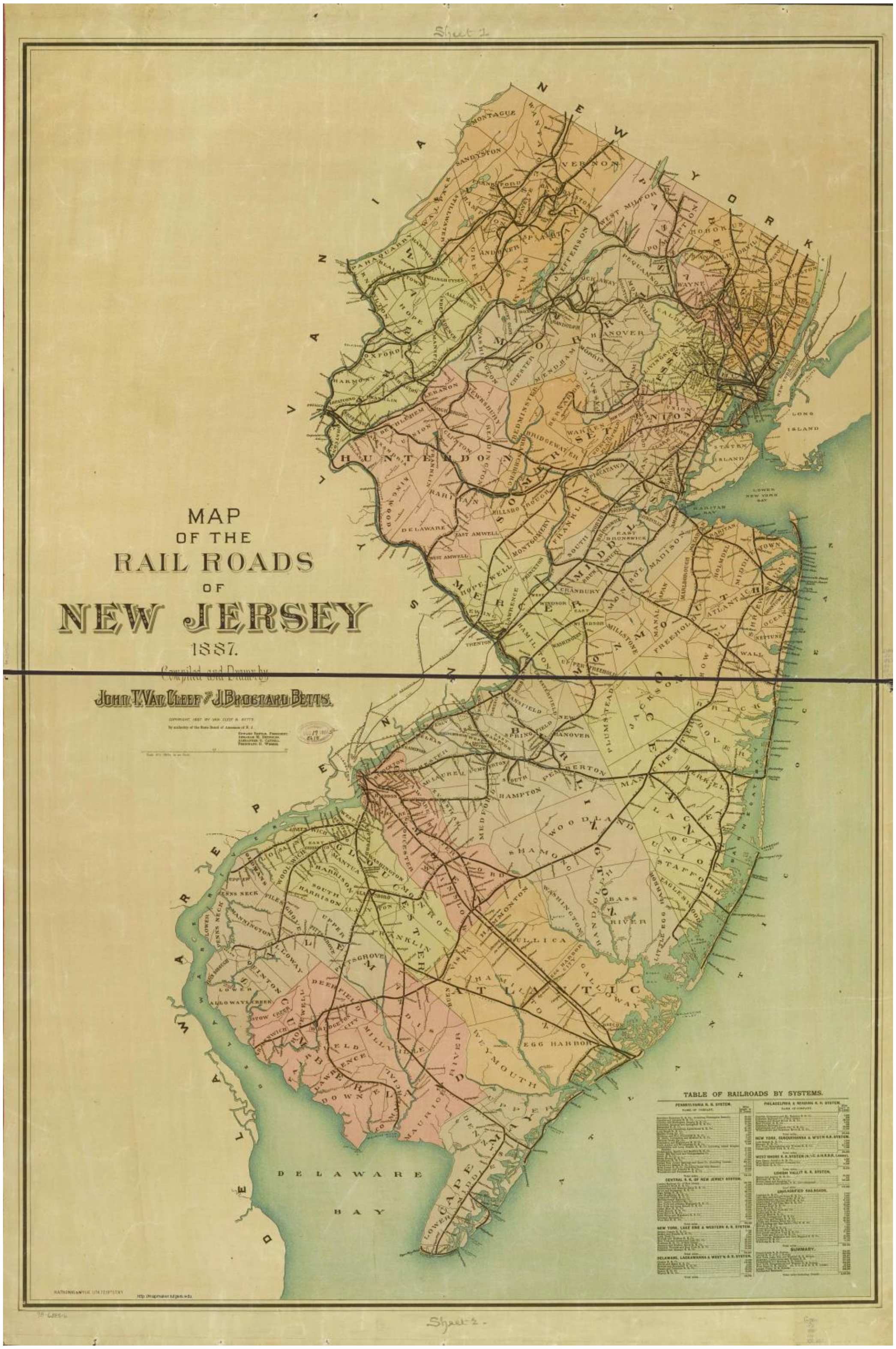


Figure 29. An 1887 railroad map of New Jersey drawn by Van Cleef and Betts provided by Rutgers University mapmaker website (2016).

The Garden State Parkway (GSP), formally known as the Route 4 Parkway, connects the New York metropolitan area to southern New Jersey along the coastline, and was completed in 1954 (NJ Turnpike Authority 2016). The Atlantic City (AC) Expressway was completed in 1964, connecting the Philadelphia metropolitan area to the New Jersey coastline, and connecting to the GSP for access to all barrier islands north and south of Absecon Island. With the construction of these major highways came the construction or reconstruction of bridges for vehicular access to the barrier islands. This increased accessibility spurred development adjacent to island access points and development spread alongshore north and south (Nordstrom 1994). Initial access points and development on the barrier islands were typically (1) in locations where the distance between mainland and barrier was minimal (LBI/Route 72 bridge), (2) along upland portions at the northern sections of the barriers (Ocean City/Route 52), or (3) where tidal marsh provided substrate for road/bridge construction (The Wildwoods/Route 47 bridge). Bridges located along upland portions at northern sections of barriers and where tidal marsh provided substrate for construction are particularly apparent in the southern mixed-energy geomorphic region (Nordstrom 1994). Bridges located where tidal lagoon widths are minimal are characteristic of the northern, wave-dominated geomorphic region. Table 7 lists the vehicular access bridges connecting the barriers to the mainland or adjacent islands as well as the year each bridge was constructed and the year the associated barrier island's threshold was reached.

Table 7. A list of the vehicular access bridges connecting New Jersey's barrier islands to the mainland or adjacent islands and their respective years built. Most vehicular bridges replaced existing railroad bridges constructed in the 1880s.

Vehicular Access Bridges, Year Built (North to South)			
Island	**Year Threshold Reached**	**Route**	**Year Built**
Northern Ocean County	1962	Rt 37	1950
Northern Ocean County	1962	CR 528	1884
Long Beach Island	1962	Rt 72	1958
Brigantine Island	1931	Brigantine Blvd	1924
Absecon Island	1931	Rt 30	1946
Absecon Island	1931	AC Expressway	1965
Absecon Island	1931	Rt 40	1929
Absecon Island	1931	Dorset Avenue	1929
Absecon Island	1931	Albany Avenue	1927
Absecon Island	1931	CR 563	1929
Absecon Island	1931	Rt 152	1915
Ocean City	1977	Gardens Pwky	1928
Ocean City	1977	Rt 52	1933
Ocean City/Ludlam Island	1977/1962	Rt 619/Corsons Inlet	1948
Ludlam Island	1962	Sea Isle Blvd	1954
Ludlam Island/Seven Mile Island	1962/1962	Rt 619/Townsends Inlet	1939
Seven Mile Island	1962	Rt 601/Avalon Blvd	1967
Seven Mile Island	1962	Rt 657/Stone Harbor Blvd	1930
Seven Mile Island	1962	Rt 619/Grassy Sound	1939
The Wildwoods	1962	Rt 147/N. Wildwood Blvd	1922
The Wildwoods	1962	Rt 47/Delsea Dr	1950
The Wildwoods	1962	Rt 621/Ocean Dr	1939

With the exception of threshold years for Absecon Island (1931), Brigantine Island (1931), and Ocean City (1977), all other barrier islands in the study area reached their thresholds by 1962. Northern Ocean County’s Route 37 bridge was completed in 1950 and the Route 72 bridge at LBI was constructed in 1958. Thresholds for both barriers were reached by 1962: a relatively short time after bridge construction. This pattern holds for Absecon and Brigantine Islands, where both islands reached their thresholds by 1931. Brigantine Island was uninhabited in 1920, but the construction of the Brigantine Boulevard Bridge in 1924 initiated rapid development which caused the island be human dominated seven years later. Since Atlantic City is located on Absecon Island and was one of the first resorts in the United States, much of the island was already human dominated in 1920 (69.06%) due to rapid development following the construction of the Pennsylvania Railroad in the 1880s. However, the entire island did not become human dominated until 1931, following the construction of the Route 40 (1929), Dorset Avenue (1929), Albany Avenue (1927), CR 563 (1929), and Route 152 (1915) vehicle bridges.

Ocean City was the last barrier to reach its threshold in the study area (1977). In 1920, 24.44% of Ocean City's bins were human dominated. The island experienced gradual development increases between 1920 and 1962, but had its highest development rate between 1962 and 1977, reaching the threshold by 1977. The two main bridges connecting the island to the mainland, Route 52 and Gardens Parkway, were constructed in 1928 and 1933, respectively. Compared to the islands around it, it is surprising the threshold occurred later, especially with the main bridges to the island being constructed at similar times to the Absecon Island bridges. The later threshold crossing relative to the other barrier islands in the study area can be attributed to several factors, including: (1) the expansive marsh complex of the backbarrier in the south not being filled in for development earlier, thus not allowing human dominance, (3) rapid rebuilding of the barrier island between 1962 and 1977 following the Ash Wednesday Storm of 1962, (4) the enforcement of the Wetlands Act of 1970 restricting infilling or alteration of tidal marshes following rapid development after the 1962 storm, thus halting expansion of development on barrier islands into backbarrier marshes (State of New Jersey 1970), and

(5) completion of the AC Expressway in 1964 increasing tourist access from Philadelphia between 1962 and 1977 (South Jersey Transportation Authority 2016).

Ludlam Island, Seven Mile Island, and the Wildwoods all reached their thresholds by 1962. With the exception of Seven Mile Island, both Ludlam Island and The Wildwoods had vehicular access bridges constructed at central island locations in 1954 (Sea Isle Blvd) and 1950 (Delsea Drive), respectively. Seven Mile Island's vehicular access bridges were constructed between 1930 and 1967 and had similar rates of human dominance (i.e. development) percentages to Ocean City. Seven Mile Island's initial human dominance percentage was 44.74% in 1920, indicating greater involvement of humans prior to 1920, similar to Absecon Island. The lag between the vehicular bridge access and human dominance can be explained by some of the same factors influencing Ocean City's human dominance threshold: (1) the expansive marsh complex of the backbarrier in the central portion of the island not being filled in for development earlier in time, thus causing threshold to be crossed later and (2) the rapid rebuilding of the barrier island following the Ash Wednesday Storm of 1962 (termed 1962 storm) expanding development alongshore from the northern and southern access points. Rapid rebuilding following the 1962 storm was not isolated to Ocean City and occurred throughout the study area. Nordstrom and Jackson (1995) found that coastal storm damage to a developed barrier island is often the impetus for humans to rebuild and expand buildings, infrastructure, and shore protection structures.

4.5 Influence of coastal storms on human dominance thresholds

Accounting for severe coastal storm events (tropical and extratropical) in the model is important because they can influence the rate humans expand and rebuild along barriers thus influencing when island scale thresholds are reached (i.e. Ocean City). The effects coastal storms have on existing human dominated segments of barriers at the local scale also demonstrate how human agency to maintain dominance of the landscape far surpasses physical alterations a barrier such as dune overwash and ephemeral inlet formation. Two examples representing the influence storms have had on human dominance of the barriers in the study area are presented below for the 1962 Northeast Storm and Hurricane Sandy (2012).

The 1962 storm was by far the most damaging storm to New Jersey's barrier islands within the study's time period. The storm's fetch was about 1600km, wind speeds were relatively low (25.5 m/s). The storm's duration of five tide cycles coupled with astronomical tides raised water levels to 1.2m due to storm surge (USACE 1962). The erosion of beach-dune systems due to storm surge combined with wave heights of 6.1m to 9.1m caused wide-scale overwash and breaches in the barriers (USACE 1962). Although the storm caused significant damage to the developed areas of the barriers, much of the impacted portions were rebuilt, and in many areas where overwash occurred, development expanded and there was a significant increase in the construction of hard shore protection structures. Figure 15 in section 3.3.3 demonstrates this process for LBI. Although LBI's threshold was reached by 1962, following the 1962 storm there was a significant increase in the amount of shore protection structures, roads, and buildings between 1962 and 1977. Nordstrom (1994) notes that even in the nineteenth century, preceding the earliest dataset for this study, the rate of redevelopment of buildings and infrastructure from human actions were greater than the rate at which natural processes could dominate the system and control the evolution of the landscape.

Although Hurricane Sandy occurred outside the limits of this study (storm made landfall after the 2012 aerial dataset was collected), it is important to discuss the storm's impacts to New Jersey developed barriers and how humans have responded to the physical changes to the study area's landscape since it was the second costliest storm in US history (Blake et al. 2013) and caused $29.5 billion in damages to New Jersey alone (US Department of Commerce 2013). Hurricane Sandy made landfall near Brigantine Island on October 29, 2012 with maximum sustained winds of 36.0 m/s (Blake et al. 2013). Wave heights reached 9.85 m at buoy station 44065 at the entrance to New York Harbor. Maximum observed water levels referenced to the North American Vertical Datum of 1988 (NAVD88) were 1.88 m at Atlantic City and 2.81 m at Sandy Hook (National Oceanic and Atmospheric Administration 2012). Storm surge and waves caused significant damages to the developed portions of the barriers in the study as documented by the Stockton University Coastal Research Center shoreline monitoring efforts (Barone et al. 2014). Although the storm caused significant damages to buildings and infrastructure from dune breaching and overwash, almost all areas where the storm altered the landscape of the barriers have been returned to their previous state. Along NOC in the Borough of Mantoloking, an ephemeral inlet was cut through the barrier and destroyed multiple homes. Results of this study show that this segment of Mantoloking became human dominated by 1931. Aerial images collected immediately after Hurricane Sandy in November 2012, 2013 and in 2015 show that the inlet was completely filled in and rebuilding has almost restored the area to pre-Sandy conditions (Figure 30).

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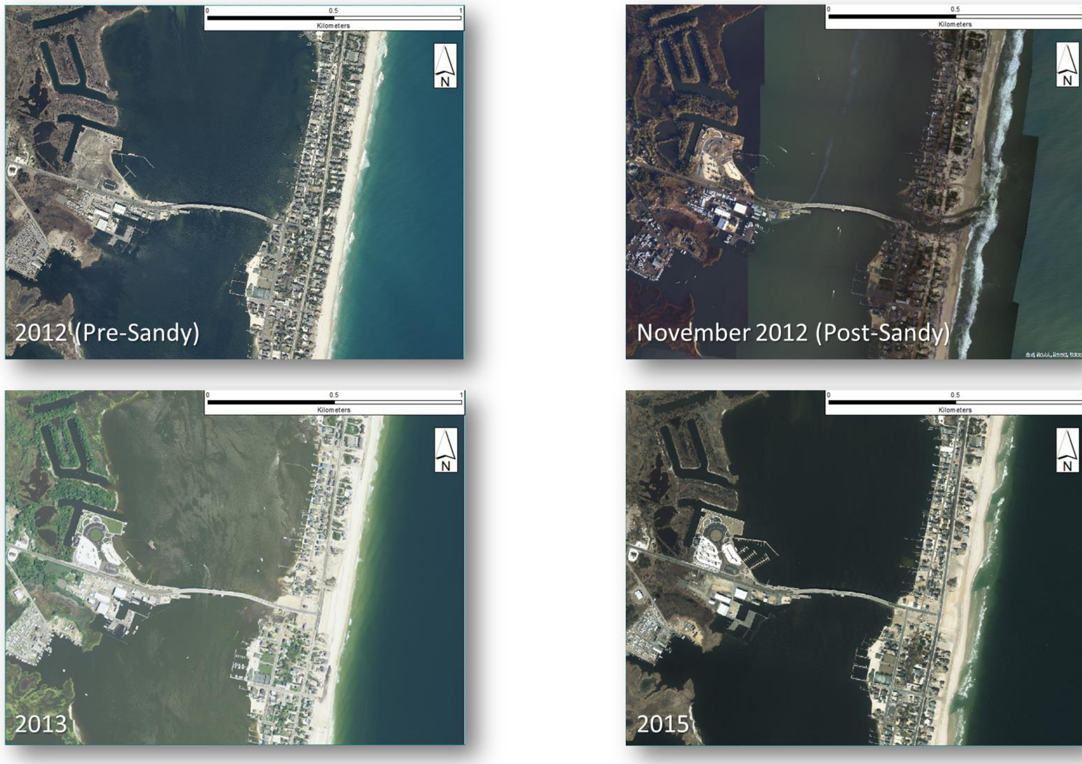

Figure 30. Aerial images of Mantoloking, NOC before and after Hurricane Sandy. Images provided by State of New Jersey and NOAA.

4.6 Influence of human variables on dominance thresholds

4.6.1 Shore Protection Structures

The northernmost two barrier islands (NOC and LBI) and three barrier islands (Ludlam Island, Seven Mile Island, The Wildwoods) all reached their thresholds by 1962. Regardless of when human dominance thresholds were reached within both geomorphic regions in the study area, once thresholds were reached the installation of hard shore protection structures increased to maintain shoreline positions and limit landward movement that would negatively impact development.

The delineation of shore protection structures from aerial photographs was dictated by several factors influencing a structure's visibility (or lack thereof) including: (1) natural inlet channel migration causing erosion along ocean-facing beaches and subsequent accumulation along inlet throats (or vice-versa) that alternatively expose and bury structures, (2) coastal storm events causing severe erosion and ultimately exposing previously covered structures, (3) beach replenishment projects for shore protection increasing beach width and burying structures, and (4) construction of jetties for inlet stabilization disrupting longshore transport of sand and causing significant increases in beach width and bury structures.

Figure 31 demonstrates two natural processes explaining how shore protection structures may or may not be visible between aerial photograph dataset years. Between 1944 and 1955, the northern portion of Ludlam Island's shoreline position was altered, with the main channel in Corsons Inlet shifting to the south, causing the shoreline along the inlet throat to erode and sand to accumulate along the ocean-facing beach, covering existing groins. Corsons Inlet is an unconfined tidal inlet (no jetties for stabilization), where the main channel is able to migrate to the north and south by several thousand meters. This cycle of erosion and accretion along inlet throats and adjacent ocean-facing beaches has been documented most notably by Oertel (1977) and Fitzgerald (1996). In the 1962 aerial photograph, far more shore protection structures were visible compared to the 1955 aerial photograph. The 1962 aerial photographs were taken immediately following the Ash Wednesday Storm of 1962, demonstrating how severe erosion caused by coastal storm events expose previously covered shore protection structures. An emergency federal beach replenishment project occurred along Ludlam Island in 1962 placed approximately 905,000cy (691,900cm) of sand along the ocean-facing and inlet shorelines (USACE 2012). The beach replenishment, the absence of a major coastal storm event, and the migration of Corsons Inlet main channel to the south between 1962 and 1977 allowed for the seaward advancement of the shoreline, covering shore protection structures with sand.

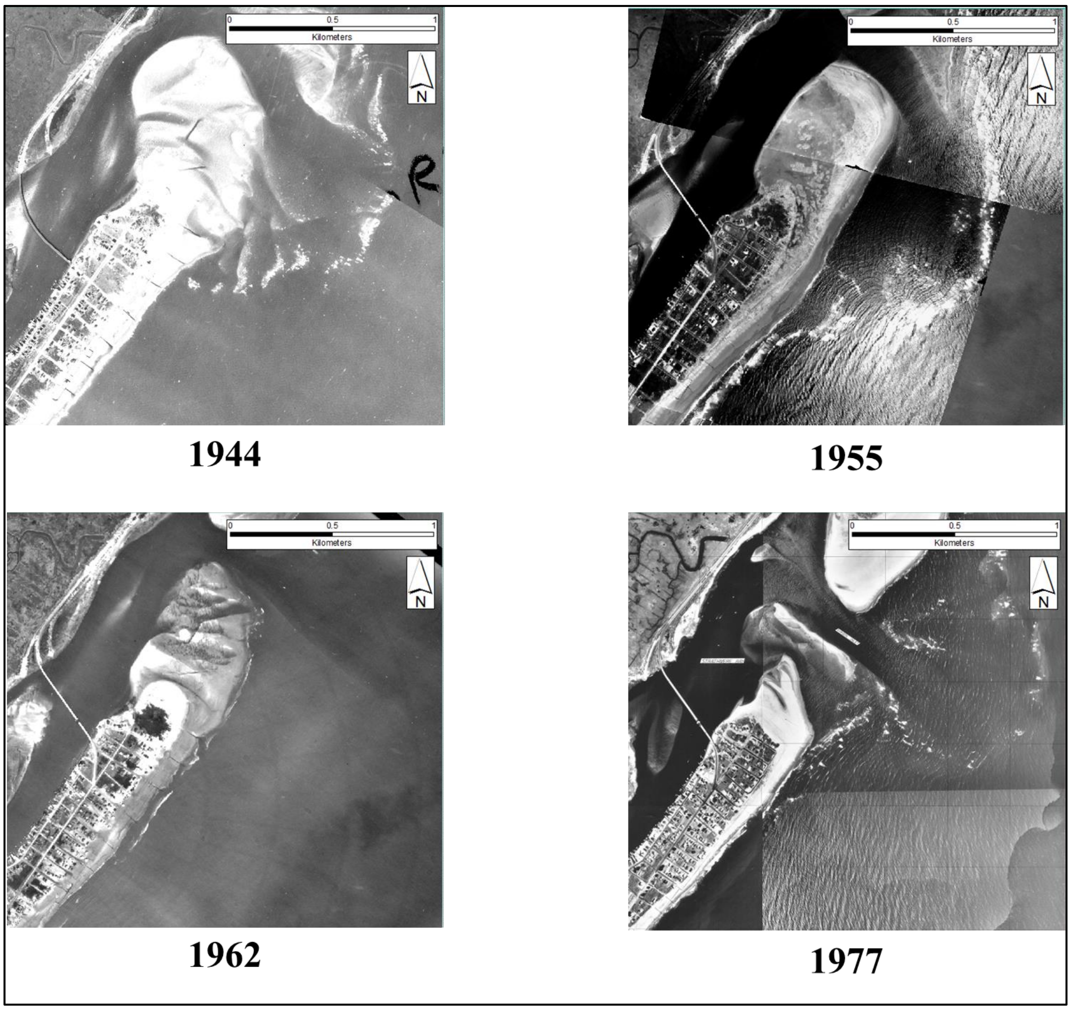

Figure 31. Aerial images of the northern portion of Ludlam Island adjacent to Corsons Inlet demonstrating how shore protection structures such as jetties can be visible and invisible between aerial dataset years.

The shore protection structure data shows the installation of hard shore protection structures begins to level off towards the end of the temporal range in 1995 for all islands. Since the preferred method of shoreline shore protection was beach replenishment beginning in the 1970s (Nordstrom 1994; Psuty & Ofiara 2002; ASBPA 2007), the rate of construction of "hard" shore protection structures began to level off following the 1970s. In some instances, after 1995 the amount of hard shore protection structures slightly decreased due to beach replenishment or the migration of inlet channels covering structures. Figure 32 shows the covering of shore protection structures between 1995 and 2002 due to a beach replenishment in 2001 on Ludlam Island (Farrell et al. 2005).

Figure 32. Aerial images of the northern end of Ludlam Island from 1995 (left) and 2002(right) showing how shore protection structures such as groins visible in the earlier photograph are not visible in the later photograph, and thus not delineated for the study.

Figure 33 demonstrates how construction of inlet jetties at Absecon Inlet dramatically increased beach width to adjacent islands (Brigantine Island and Absecon Island). The jetties interrupted the longshore sand transport into the inlet by trapping sand which subsequently increased beach width. By 1977, the groins visible in the 1955 aerial image north of the north jetty in Brigantine were covered by sand.

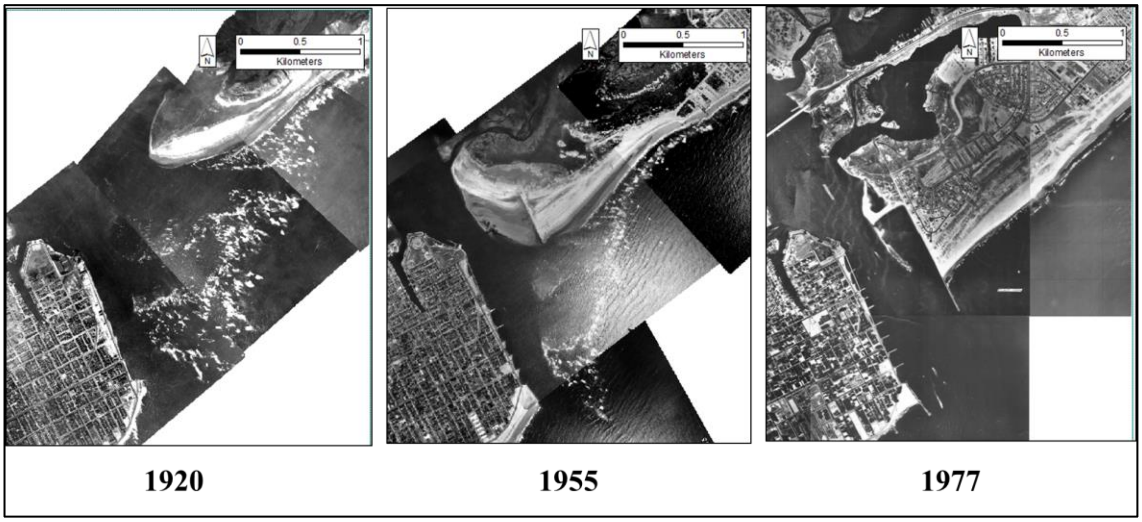

Figure 33. Aerial images from 1920, 1955, and 1977 (left to right) of Absecon Inlet bordered by Brigantine to the north and Absecon Island to the south. Construction of the north and south inlet jetties interrupted longshore transport of sand into the inlet, causing dramatic increases in beach widths and subsequently covering existing groins with sand.

4.6.2 Buildings and Roads

The effect of buildings and roads began to level off in 1977, the next aerial dataset year after the threshold was reached for the study area (1962). All islands follow this trend with the exception of Brigantine Island and Northern Ocean County regardless of when individual island thresholds were reached (see section 3.3). Cleared lands absent of buildings and roads were prominent when island thresholds were reached and can explain the delay in the amount of buildings and roads leveling off. Figure 34 shows this process for Ocean City, where human cleared lands in 1977 (year threshold reached), were developed with buildings and roads by 1986.

Figure 34. Aerial Images of Ocean City from 1977 (left) and 1986 (right) showing human cleared lands in the left central portion of the 1977 image, and residential development with buildings and roads in that same location in 1986.

The building and road development pattern in Northern Ocean County compared with the percentage of human dominated bins (Figure 13) shows the amount of buildings and roads leveled off prior to the threshold being reached. The amount of buildings and roads remained relatively stable until after 1962, with the exception of a slight increase between 1962 and 1977. Following this increase, the amount of buildings and roads remained relatively level until the amount of roads increased between 1995 and 2002. The amount of buildings and roads leveled off prior to the threshold being reached because much cleared land was added to Northern Ocean County without a considerable amount of buildings or roads being constructed (Figure 35).

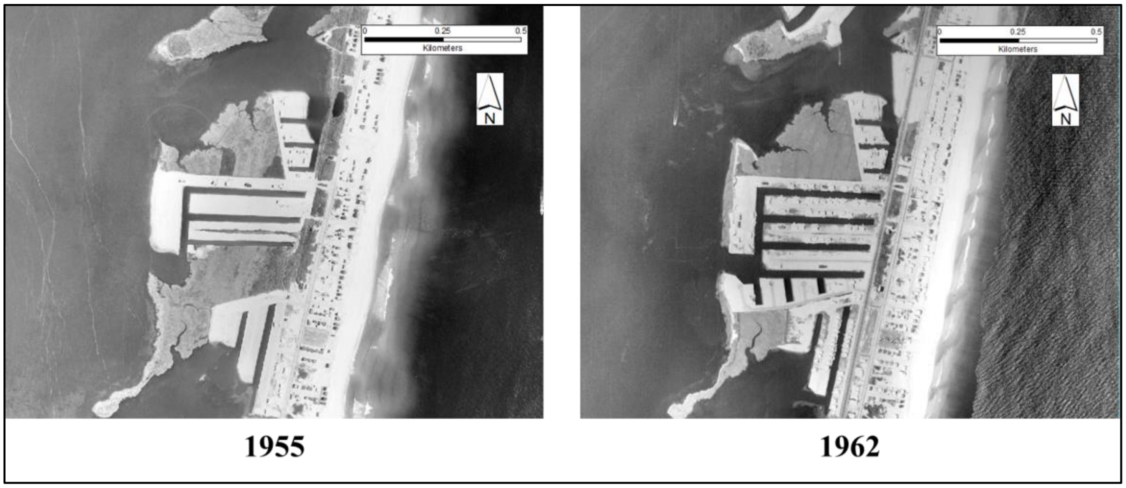

Figure 35. Aerial images of Northern Ocean County from 1955 (left) and 1962 (right)showing a considerable amount of cleared land added to the barrier, but limited amounts of buildings and roads added.

Brigantine Island’s building and road development patterns were not contemporaneous like other barriers in the study area. The island’s close proximity to Absecon Island and direct connection to Atlantic City following the bridge construction in 1924 at the southern extreme allowed for rapid land clearing and road construction (with the exception of the northern end) by 1931. This coincided with the island reaching its threshold that year. Not surprisingly, the amount of buildings increased dramatically after the threshold was reached until 1962 when the amount of buildings leveled off (Figure 17).

4.7 Human dominance thresholds compared to geomorphic regions

The morphology of the barriers within the two geomorphic regions in the study area did not dictate when a given area of a barrier island became human dominated. Rather, morphology played a significant role in where humans accessed the barriers during the involvement stage via railroad and vehicle bridges following initial exploration and establishment of small enclaves. Nordstrom (1994) noted initial construction of buildings occurred at the uplands portions of the barrier at inlets and at areas where the railroad made contact with the islands. In the northern wave-dominated geomorphic region, Northern Ocean County's northern end is attached to the mainland and provided direct access for development to expand south. Two additional bridges were constructed from the mainland to the backbarrier at locations where the width of the tidal lagoon between the mainland and the island was minimal. Similar to LBI, as described in section 4.1.3, initial development along Northern Ocean County took place at the railroad terminus. The 1887 railroad map (Figure 29) shows the railroad initially extended south from the northern end of the barrier-spit to its southern terminus in Seaside Heights, where a railroad bridge was built across the narrow tidal lagoon. Human dominance thresholds were reached by 1920 within the bins at these locations (Figure 14). Similar to LBI, the bins along Northern Ocean County gradually became human dominated, expanding alongshore from initial railroad termination points. Once the Route 37 bridge replaced the railroad bridge in 1950 at Seaside Heights, the remainder of bins in Northern Ocean County were human dominated by 1962.

The southern mixed-energy geomorphic region's barrier island morphology provided more access points for railroads and vehicular bridges than the wave-dominated geomorphic region due to the closely spaced inlets and expansive backbarrier marsh complex providing a substrate for initial construction of thoroughfares and bridges from the mainland to the barriers. Brigantine Island has only one access point at its southern end, but vehicular access points for the remaining barriers in the southern geomorphic region range from three (Ocean City, Ludlam Island) to seven (Absecon Island). With the exception of Seven Mile Island, all other islands in the southern geomorphic region had railroad access in 1887 and by 1911, all of the barriers had railroad access (Rutgers University 2016). The barrier islands in the southern geomorphic region followed a similar pattern to the northern geomorphic region in that bins located proximal to island access points from the railroads or vehicular bridges became human dominated first, with development spreading from access points alongshore to the north and south. In both geomorphic regions, the construction of new vehicle bridges replacing railroad bridges increased alongshore development from island access points, causing adjacent bins to become human dominated shortly after construction. This is the reason the northern two wave-dominated barriers and the southern two mixed energy barriers have similar island-scale thresholds. Ludlam Island's human dominated bin distribution by year in Figure 24 is a good example of this pattern, showing initial railroad access locations being human dominated in 1920 and several adjacent bins being human dominated in 1931 and 1944. The Sea Isle Boulevard Bridge was completed in 1954 and by 1962, the majority of the south-central section of Ludlam Island became human dominated, causing the island reach its human dominance threshold. Due to the expansive backbarrier marsh along Ludlam Island many of the bins along the north central section of the island are not human dominated because the physical factor (marsh, barren land areas) is greater than the human factor.

Chapter 5: Conclusion

This research provides a model of how geomorphic systems are subject to thresholds due to human alterations and how developed barrier islands experience a change in state. This suggests once a human dominance threshold is reached geomorphic classifications of barrier island types must include human factors or definitions. This is because the human activities that attempt to stabilize barrier islands are ubiquitous and recurring across geomorphic regions and various barrier sections (i.e. inlets, central portions of islands, backbarrier areas, etc.). Based on the results from this study, it can be concluded that:

1. The “Developed Barrier Island Life-Cycle” model can be applied at the island and study area scales, regardless of geomorphic classifications.
2. The evolution of developed barrier islands through increased human involvement indicates they experience a state change as human activities overshadow natural processes.
3. The geomorphic classification of a barrier island does not dictate when and where a given section of the barrier is human dominated. Rather, the morphology of the two barrier types plays a significant role in where humans initially access barrier islands and when they are initially developed.
4. Correlating geomorphic factors such as island mobility to human dominance thresholds at various scales determined that human agency was a more important factor than shoreline change at the local scale, but island mobility was a more important factor at the island and study area scales.

5. Human dominance at small spatial scales (the 100m bin scale in this study) can be attributed to construction of railroads, while the construction of vehicular access bridges induces island-scale human dominance.

This study can inform future studies along developed coasts by highlighting how human actions dominate the landscape at the local, island, and regional scales. This is important for current coastal zone management practices because shore protection efforts that attempt to mimic naturally functioning systems across entire barrier islands (such as beach replenishment) may need to be prioritized where development dominates the landscape at the local scale. Likewise, areas (bins) where thresholds have not been reached should be allowed to continue to evolve as natural systems.

The "Developed Barrier Island Life-Cycle" model implies that human dominance of barrier islands may be inevitable once the Involvement stage begins. For undeveloped barrier islands currently in the exploration stage, this research can inform where and how development could occur during the involvement stage, but can also provide insight into where development should not occur in places where island mobility negatively impacts development.

The process of how human activities overshadow geomorphic signals is not well understood, especially at local scales (Hapke et al. 2013) and models that attempt to describe natural barrier island evolution are not applicable to human dominated systems (Nordstrom 1994; Morton 2002; Morton et al. 1995; Moore et al. 2007; Morton 2008). Existing models that attempt to define human dominated barrier island thresholds (Stutz & Pilkey 2005) do not quantitatively address the *process* and *stages* of human dominance across barrier islands at varying scales. Rather, existing models only address *if* a barrier is dominated at the island scale. This dissertation addresses these gaps by applying a model that quantitatively describes stages of human dominance and when human dominance thresholds are reached at local to regional scales. It is assumed that the model can be applied to other developed barrier coastlines, however further research is needed to understand how other developed barrier coastlines become human dominated at smaller scales.

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