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A Geo-Economic Framework for Dune Construction and Long-Term Coastal Resiliency in New Jersey

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A GEO-ECONOMIC FRAMEWORK FOR DUNE CONSTRUCTION AND LONG-TERM COASTAL RESILIENCY IN NEW JERSEY

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ABSTRACT

A GEO-ECONOMIC FRAMEWORK FOR DUNE CONSTRUCTION AND LONG-TERM COASTAL RESILIENCY IN NEW JERSEY

by Jesse C. Kolodin

Following the extensive coastal impacts (i.e., storm surges) caused by Hurricane Sandy in 2012, the State of New Jersey chose to install large-scale engineered berm-dune structures as their main coastal resiliency strategy. Initially, the project was entirely funded with federal emergency relief funds, but will require state and local beachfront communities to pay a percentage cost-share for future renourishment projects. The thesis specifically focuses on three adjacent beachfront communities within the barrier island stretch of Long Beach Island, NJ (i.e., Beach Haven, Long Beach Township, and Ship Bottom), all of which had been provided engineered dunes in 2016. Following installation, municipal assessed property values increased in all three communities, demonstrating that these municipalities' value the protection provided by engineered berm-dune systems. What is unclear, however, is whether these communities can afford their cost-share of future maintenance. In this work, we first develop a "geo-economic" modeling framework to better understand the relationships between stakeholder values towards protection and their long-term feasibility to maintain engineered berm-dunes. Second, we use a hedonic modeling approach to quantify the beneficial elasticities (or percentage change) that engineered dunes have on the average stakeholder's property value. These results suggest that as communities increase their cumulative wealth as a consequence of dune protection, they are more capable of having the adequate funds to budget for future projects. The three communities in our study raised property values following dune construction, while their budgets associated with beach renourishment funds remained steady, suggesting a potential budgetary fallout may occur following future storm events. Third, we build a decision support tool that uses a set of parameters for a particular community to measure the economic feasibility of coastal protection strategies, such as dune renourishment. To estimate future sediment volume demands, a proxy of sediment erosion, we employ high-resolution passive and active remote sensing tools attached to unmanned aircraft systems (UAS), or commercial drones. These tools will help to better constrain future costs related to erosion as sea-level rises and the frequency of large storms potentially increase. The cost-benefit analysis tool can help better inform decision makers to provide a more considerable outlook for future resiliency efforts.

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List of Abbreviations

FEMA – Federal Emergency Management Agency
USACE – U.S. Army Corps of Engineers
LBI – Long Beach Island, NJ
UAV– Unmanned Aircraft Vehicle
SWFL – Still Water Flood Level
NFIP – National Flood Insurance Program
HPM – Hedonic Pricing Model
MIP – Marginal Implicit Price

SB – Ship Bottom, NJ
LBT – Long Beach Township, NJ
BH – Beach Haven, NJ
NPV – Net Present Value
GUI – Graphical User Interface
SfM – Structure from Motion
RGB – Red, Green, Blue Light Spectrum
UAS – Unmanned Aircraft System
DEM – Digital Elevation Model
LiDAR – Light Detection and Ranging
GSD – Ground Sampling Distance
NJDEP – The New Jersey Department of Environmental Protection

INTRODUCTION

Just in the past few decades, along the mid-Atlantic coastline, mitigation strategies and responses to potential future storm surge impacts have adapted to meet an accelerating rate of natural change to the shoreline position and geometry (Titus et al. 1991; Yohe et al. 1995; Yohe and Schlesinger 1998; Valverde et al. 1999; Psuty and Ofiara 2002; Landry et al. 2003; Titus 2009; Lazarus et al. 2011; Hapke et al. 2013, Fallon et al. 2017; Beasley and Dundas 2018). These changes are, in part, governed by natural geomorphic responses of erosion due to increasing rates of anthropogenic-induced sea-level rise (Vermeer and Rahmstorf 2009; Engelhart and Horton 2012; Kopp et al. 2019), combined with the exacerbation of storm frequency and intensity (Emanuel 2010; Emanuel 2013; Kirshen et al. 2020). Furthermore, human development and urban planning along these vulnerable landscapes has traditionally followed resiliency projects that add a sense of protection (Titus et al. 1991; Valverde et al. 1999; Psuty and Ofiara 2002; Hapke et al. 2013; Beasley and Dundas 2018, Gault 2019). The fundamental reasoning behind these management decisions and incessant policy measures amongst developed beachfront communities, is to continue the generation of future benefits (i.e., tax revenue and recreational benefits), with a reduction in potential damage costs in mind (USACE 1999, Parsons and Powell 2001, Hoagland et al. 2012, USACE 2014, FEMA NFIP 2020). Whereas, the cost of maintaining the shoreline in order to keep up with sea-level rise is merely a fraction of that return. When confronted with coastline change, a basic management question is whether to protect existing coastal development or to fall back as sea level rises and the shoreline retreats (Yohe et al. 1994; Yohe and Schlesinger 1998; Landry et al. 2003; Titus 2009; Lazarus et al. 2011). Generally, instead of retreating, coastal communities have decided to "hold the line" (Titus et al. 1991; Valverde et al. 1999; Psuty and Ofiara 2002; Slott et al. 2006; Hapke et al. 2013; Beasley and Dundas 2018) constructing either soft (berms or dune renourishment) or hard (seawalls, groins, jetties, dikes, or revetments) engineering structures. Soft or hard structures can protect individual properties and infrastructure from damage, allowing economic benefits of coastal living and tourism to continue to be realized (Silberman and Klock, 1988; McNamara and Werner, 2008; Smith et al., 2009).

In the years following Hurricane Sandy, the State of New Jersey constructed large-scale engineered berm-dune structures to mitigate future storm-related damages to residential properties and the state's coastal tourism industry (USACE 2014). The specific design for berm-dune construction followed the Federal Emergency Management Agency's (FEMA) "540-rule," with berm-dunes built in excess of ~7m tall. Initial implementation costs were covered by the federal Sandy Recovery Improvement Act (Amendment 850 113th Congress 2013-2014), and construction was carried out by the US Army Corps of Engineers. The project envisioned that seven periodic renourishment episodes would be necessary to maintain the berm-dune over a 50-year period. However, under the standard cost-share breakdown between federal (50%), state (37.5%) and local (12.5%) governments (Bates 2015; O'Neil 2015), it is unclear whether local beachfront communities would be capable of continuing to contribute their shares over the 50-year project life.

The overarching focus of this study is to examine the relationship between "540-Rule" berm-dune construction and the potential benefits that local stakeholders receive, assuming a positive relationship directly relates with protection (Dundas 2017). We focus most of our study on the ~18mile barrier island complex of Long Beach Island (LBI), New Jersey (Ship Bottom, Long Beach Township, and Beach Haven) who recently received protective "540-Rule" dunes in the spring of 2016. Analysis of time-series (2015-2019) residential property values (Ocean County Sr1a Data 2019) shows that a significant value increase occurred immediately after the berm-dune installation in 2017. We first develop a back-of-the-envelope method to quantify the upper-most marginal elasticity, or the highest possible percentage that is added to an average property value from the construction of a “540-Rule” dune. To better understand the relationship dune construction has on residential property values, we then use a hedonic pricing model to estimate potential variations in property values in response to dune geometry and other property characteristics. Additionally, these hedonic relationships may also correlate with trends in resiliency at the stakeholder level. Lastly, we construct our modeling framework to act as a useful tool, or graphical user interface that decision-making managers can determine their long-term feasibility of periodic berm-dune maintenance. To assist in determining potential geomorphic changes to the shoreline, a high-resolution monitoring program with the use of Unmanned Aircraft Vehicles (UAV) can track changes to the average rates of berm-dune erosion, or the localized demands for renourishment sediment volumes. Therefore, the research proposed in this dissertation can be separated into three objectives, or chapters:

Chapter 1: Theoretical Research Analyzing Engineered Coastal Berm-Dune Renourishment in New Jersey: Can Coastal Communities Continue to Hold the Line?

Chapter 2: Understanding the Hedonic Relationship between Engineered Dune Construction and Coastal Property Values

Chapter 3: Developing a Decision Support Tool to Assess the Feasibility of Beachfront Communities to Maintain Engineered Dunes in the Long-Term

Our modeling framework allows for exploration of the relationships that currently exist, or may exist in the future, within the beachfront communities’ efforts to feasibly mitigate future storm surge impacts. Hedonic model results can confirm how beachfront communities are notionally capable of maintaining their 12.5% share of berm-dune renourishment costs, as asset values of coastal properties increase. Furthermore, natural external forces would increase shoreface erosion, such as accelerating sea-level rise and increasing frequency and severity of tropical cyclones or Nor'easters that could affect the feasibility of maintenance over the long-term (Kolodin et al. 2021 *accepted for publication*). These adverse factors can limit the supply of locally available sediment, especially when combined with the newly transformed shoreline berm-dune geometry. With the increased demand of sediment, there will be growing costs to maintain these protective structures in the future (Hoagland et al. 2012; McNamara et al. 2015). Furthermore, exploring the portability of this model helps discretely measure the potential stakeholder reactions to a changing environment, which can alter their willingness to pay for future mitigation projects such as berm-dune renourishment. For instance, a lull in storm activity may trigger an ever-decreasing sense of immediate risk (Leichenko et al. 2014), and a community of this nature could experience a net loss before the end of the project's lifetime (i.e., its aggregate nourishment costs would exceed its aggregate coastal protection benefits, as revealed through the market for coastal properties). With potentially increasing frequencies of storm activity and intensity, stakeholder perceptions could therefore lean in the opposite direction, towards valuing protection over other amenities (Kriesel et al. 2000; Gravens et al. 2007; Eckel et al. 2009; Turner 2012; Cameron and Shah 2015; Leichenko et al. 2015; Dundas 2017).

CHAPTER 1 – ANALYZING ENGINEERED COASTAL BERM-DUNE RENOURISHMENT IN NEW JERSEY: CAN COASTAL COMMUNITIES CONTINUE TO HOLD THE LINE?

The contents of this chapter appear in:

Kolodin, J.; Lorenzo-Trueba, J.; Hoagland, P.; Jin, D.; Ashton, A. (2021). "Analyzing Engineered Coastal Berm-Dune Renourishment in New Jersey: Can Coastal Communities Continue to Hold the Line?" *Anthropocene Coasts*. Canadian Science Publishing Co. *accepted for publication*

1.0 Summary

Following the significant coastal changes caused by Hurricane Sandy in 2012, engineered berm-dunes were constructed along the New Jersey coastline with the objective of enhancing protection from future storms. Following construction, assessed property values on Long Beach Island, NJ, increased in three beachfront communities. The projects were financed entirely through federal disaster assistance, but a percentage of future maintenance costs must be covered by the local communities. Whether or not communities would be willing or capable of financially contributing to maintenance remains unclear because 1) some homeowners prefer ocean views over the protection afforded by berm-dune structures and 2) stakeholder risk perceptions could change over time. To investigate the relationships between berm-dune geometries, values of coastal protection, and values of ocean views, we developed a geo-economic model of the natural and anthropogenic processes that shape beach and dune morphology. Model results suggest, depending on stakeholder wealth and risk perception, coastal communities may exhibit significant differences in their capabilities to maintain engineered dunes. In particular, communities with strong preferences for ocean views are less likely to maintain large-scale berm-dune structures over the long term. Should these structures be abandoned, the vulnerability of the coast to future storms will increase.

1.1 Introduction

Coastal erosion is expected to increase with the significantly higher rates of sea-level rise expected over the coming centuries due to anthropogenic global warming (Vermeer and Rahmstorf 2009; Engelhart and Horton 2012; Kopp et al. 2019). When confronted with coastline change, a basic management question is whether to protect existing coastal development or to fall back as sea level rises and the shoreline retreats (Yohe et al. 1994; Yohe and Schlesinger

1998; Landry et al. 2003; Titus 2009; Lazarus et al. 2011). Generally, instead of retreating, many coastal communities have decided to “hold the line” (Titus et al. 1991; Valverde et al. 1999; Psuty and Ofiara 2002; Slott et al. 2006; Hapke et al. 2013; Beasley and Dundas 2018) constructing either soft (berms or dune renourishment) or hard (seawalls, groins, jetties, dikes, or revetments) engineering structures. Soft or hard structures can protect individual properties and infrastructure from damage, allowing economic benefits of coastal living and tourism to continue to be realized (Silberman and Klock 1988; McNamara and Werner 2008; Smith et al. 2009). This paper focuses on berm-dune renourishment, which involves the regular practice of adding sediment to the berm-dune system to increase beach width and dune height. These practices have played an important role in holding the line and can potentially play an essential role in the future (Elko et al. 2021), particularly in New Jersey (Psuty and Rohr 2000; Psuty and Ofiara 2002; Barone et al. 2014; Dundas 2017), where highly valued development and infrastructure lay behind the berm-dune systems.

After the impacts of Hurricane Sandy in late October 2012, the State of New Jersey (NJ) adopted large-scale, engineered berm-dune structures as its primary coastal protection strategy (Figure 1.1). Berm-dune structures were built by the US Army Corps of Engineers (USACE), following the FEMA “540-Rule”, with engineered dunes 22’ (~7m) high and berms 125’ (~38m) wide (Figure 1.2; Dewberry and Davis 1989; USACE 2014). Prior to Hurricane Sandy, only a few beachfront communities along New Jersey’s coastline had large dunes of this scale (Barone et al. 2014; Dundas 2017). The cost of implementing engineered berm-dunes along the New Jersey coast was estimated to be $5.08 billion (USACE 2014; Young 2014). With the estimated coastal and inland damages caused by Hurricane Sandy totaling $37 billion (Halpin 2013), the USACE found the construction cost of these berm-dunes as economically justified (USACE

2014). As a disaster relief response, the federal government entirely covered the initial construction of the new berm-dune system with funds provided through the Sandy Recovery Improvement Act (113th Congress 2013). Looking to the future, however, it is unclear whether beachfront communities in New Jersey will be willing to continue to cover the costs associated with maintaining engineered berm-dune systems. In order to maintain these newly engineered landscapes, the USACE estimates it will need to renourish the berm-dunes every 7 years with locally available off-shore resources. Additionally, as federal contributions potentially decline (Amendment 850, 113th Congress 2013-2014), nourishment costs will increase as sediment becomes scarce (McNamara et al. 2011), and sea-level rise accelerates, beachfront communities would be faced with rising renourishment costs. Moreover, the preferences of property owners for protecting their coastal properties may vary with individual wealth, perceptions about the risks of property loss, access to information, or other circumstances (Leichenko et al. 2014; Leichenko et al. 2015).

Figure 1.1 - Berm-dune construction Beach Haven, NJ.

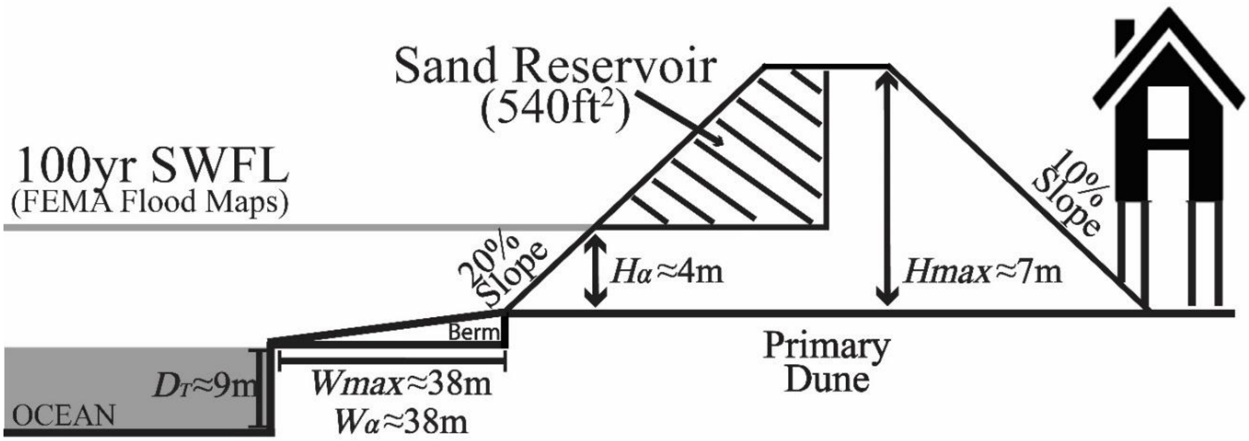

Figure 1.2 – USACE FEMA "540-Rule" engineered berm-dune construction design criteria. Where the seaward portion of the primary frontal dune has a 540ft^2 (~50m^2) sand reservoir above the 100-year SWFL (Dewberry and Davis 1989; USACE 2014).

While New Jersey's "540-Rule" berm-dune projects were intended to protect coastal communities from erosion and storm surge impacts (Sopkin et al. 2014), some local stakeholders expected that this intervention would affect property values adversely, due to losses of both ocean views and private rights of access to the beach (Insurance Journal 2013; Zernike 2013; Schapiro 2015; Spoto 2013). This concern was not limited to New Jersey, as researchers found a negative relationship between assessed property values and dune elevation in other locations, such as in coastal Massachusetts, USA (Eberbach and Hoagland 2011). In contrast, Dundas (2017) found that some beachfront communities with engineered berm-dunes built on Long Beach Island, NJ, prior to Hurricane Sandy, experienced increases in property values. Such increases were interpreted as reflecting the value that property owners placed on protection from coastal flooding and shoreline erosion.

To better assess whether it is economically justifiable for beachfront communities to cover the costs associated with engineered berm-dune systems in the long term, here we present a geo-economic model developed to capture the interplay between natural processes and beach nourishment practices (Figure 1.3). We then apply the model to different scenarios of nourishment cost and risk perception amongst three communities in Long Beach Island, NJ: Beach Haven, Ship Bottom, and Long Beach Township (the latter of which is composed of four different divisions) (Figure 1.4). Additionally, we apply the framework to model the choices made by beachfront communities about whether to continue to contribute to the maintenance of these berm-dune projects moving into the future.

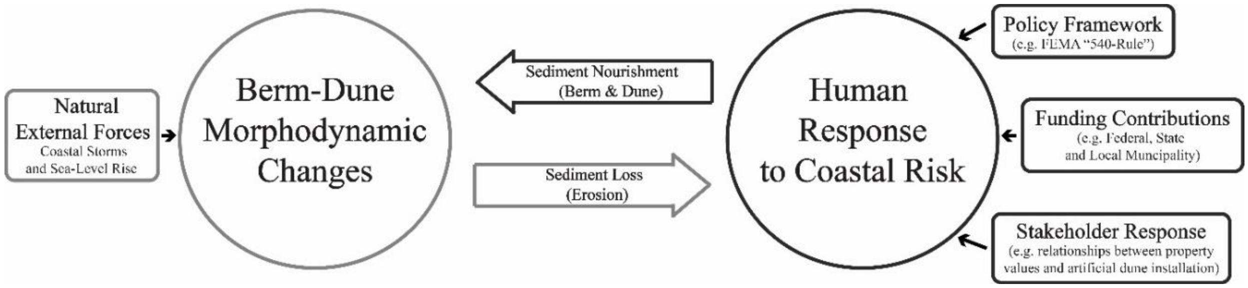

Figure 1.3 – Coupled natural-human berm-dune flow chart.

Figure 1.4 – Map of Long Beach Island, NJ (Ocean County) and the three beachfront communities used in the study (Google Imagery, 2020).

1.2 Geo-Economic Model

We constructed a geo-economic model to examine how the decisions made by a representative beachfront property owner interact with the morphodynamics of the berm-dune system. First, we present a model of the morphodynamic evolution of the system, which includes dune migration, beach and dune erosion, and renourishment of the beach and dune. Second, an economic model determines the property owner's decision of whether or not to maintain the berm-dune through renourishment using an optimal control problem approach. The model components are then coupled to create a geo-economic model of the coupled human-nature system.

1.2.1 Berm-Dune System Evolution

Similar to previous models for the evolution of barrier islands, beach and foredune ridges, and fluvial deltas (Lorenzo-Trueba and Ashton 2014, Ciarletta et al. 2019, Anderson et al. 2019), we define an idealized geometric cross-section representing the berm-dune system (Figure 1.5). For the dune, we assume an average steady-state triangular configuration characterized by a foreslope ψ_S and a backslope ψ_B, as opposed to a more general trapezoidal shape (Figure 1.2). Although a simplification of the typical trapezoidal shape of constructed dunes, our approach captures the first order relationship that an increase in dune height coincides with a linear increase in the width of the dune toe.

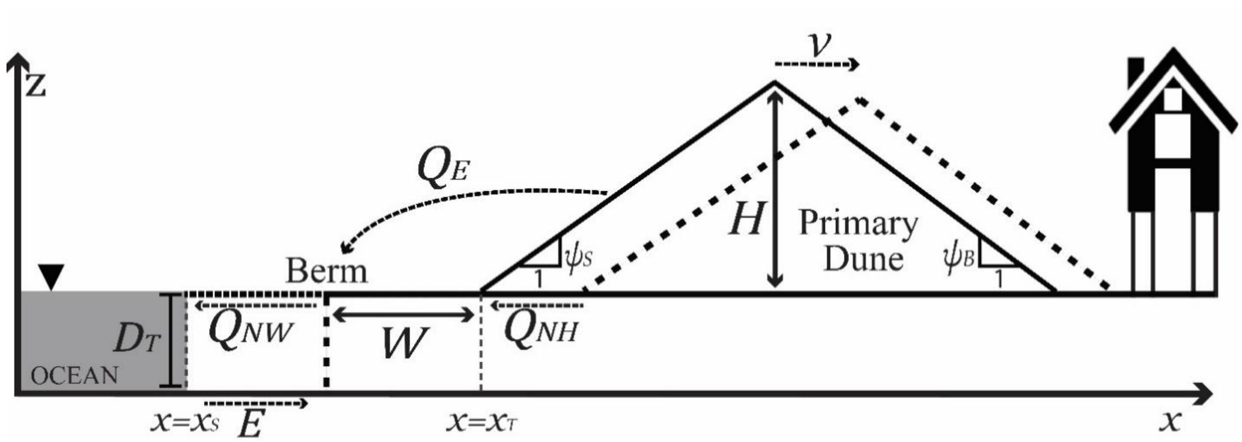

Figure 1.5 - An idealized triangular berm-dune profile demonstrating the coupled natural-human evolution and stabilization of the system through the system processes and state variables.

Additionally, consistent with the so-called “Bruun rule” (Bruun 1962, 1988) and more recent efforts (Ciarletta et al. 2019), we assume an average steady-state configuration for the shoreface with depth D_T as shown in Figure 1.5. This common approach further assumes that the shoreface is defined by an offshore “depth of closure” (Hallermeier 1981) beyond which sediment exchanges with the shelf become negligible over the timescale of interest, in this case we consider a morphodynamic depth of closure that represents an approximately decadal temporal scale (Ortiz and Ashton 2016). This idealized berm-dune geometry allows the evolution of the system to be fully described as a function of the locations of the shoreline x_S and dune toe (on the ocean side) x_T, and the dune height H. We use an origin located at the initial shoreface toe location, with x increasing horizontally landward and z vertically upward (Figure 1.5).

Starting from an initial geometric configuration, the evolution of the berm-dune system can be determined from the rates of migration of the shoreline dx_s/dt and dune toe dx_T/dt , and the rate of change of the dune height over time dH/dt. In turn, these rates of change are determined by the processes controlling the evolution of the berm-dune system, including the natural processes of dune migration and beach and dune erosion, coupled with renourishment of the beach and dune. The net dune erosion rate Q_E ($m^3/m/yr$) to the shoreface reflects the net losses from the competition between infrequent wave-driven events that episodically erode the dune and subsequent aeolian accretion. Similarly, v (m/yr) represents the natural dune migration rate via aeolian processes. To model berm evolution, we define a background erosion rate E (m/yr), which can be associated with either Bruun-like profile response to sea-level rise and/or sediment loss via gradients in alongshore sediment transport. Anthropogenic influences are included as both Q_{NH} ($m^3/m/yr$), the average sediment renourishment rate to the dune (occurring over multiple episodes) and the average sediment renourishment flux to the berm Q_{NW} ($m^3/m/yr$). Combined, we can then compute the change in dune height as follows:

$$\frac{dH}{dt} = \frac{Q_{NH} - Q_E}{p \cdot H} \tag{1.1}$$

where $p=1/\psi_S + 1/\psi_B$ is a dune shape factor. Equation (1.1) captures the concept that renourishment tends to increase dune height, whereas dune erosion or scarping tends to reduce it. In the particular scenario of a natural dune (i.e., $Q_{NH} = 0$) with sufficient sediment supply of wind-driven transport with respect to the rate of wave-driven erosion (i.e., $Q_E < 0$), this formulation implies that the dune can grow indefinitely. Although wind-driven processes are not modeled explicitly, this scenario of indefinite dune growth is consistent with work by Davidson-Arnott et al. (2018). In contrast, Durán and Moore (2013) find a steady state dune configuration based on bio-physical feedbacks. Our focus in this manuscript, however, is on regions where dunes are constructed when wave-driven erosion exceeds wind-driven sediment supply (i.e., $Q_E > 0$) and renourishment is required to maintain dune volume (i.e., $Q_{NH} > 0$). In the second governing equation, we compute the change in shoreline location as follows:

$$\frac{dx_S}{dt} = E - \frac{Q_{NW}}{D_T} - \frac{Q_E}{D_T} \tag{1.2}$$

As stated by Equation (1.2), beach renourishment and sediment flux from the dune to the shoreface lead to seaward shoreline expansion, whereas the background erosion rate generally results in net shoreline retreat (i.e., $E > 0$). In the third and last governing equation, the change in dune toe location is computed as follows:

$$\frac{dx_T}{dt} = \frac{Q_E}{H} + v - \frac{Q_{NH}}{H} \tag{1.3}$$

Dune erosion and migration lead to landward movement of the dune toe, whereas anthropogenic sediment renourishment moves the dune toe seawards.

The approach presented here, and described by Equations (1.1) - (1.3), is catered to decadal averages and therefore does not account for short-term processes such as single storm events. This simplification allows us to focus on the long-term coupling between berm and dune dynamics and renourishment decisions. We recognize, however, that changes in dune height and ocean shoreline and dune toe locations are a function of a number processes occurring across a wide range of spatial and temporal scales (Brodie et al. 2019, Cohn et al. 2019), and event-scale responses could also affect the interplay between renourishment decisions and changes in the berm-dune geometry. Combining Equations (1.2) and (1.3), we can describe the dynamics of the beach width W (where $W = x_T$-x_S) as follows:

$$\frac{dW}{dt} = \frac{Q_E}{H} + v - \frac{Q_{NH}}{H} - E + \frac{Q_{NW}}{D_T} + \frac{Q_E}{D_T} \tag{1.4}$$

Decreasing beach width W over time will motivate a community to consider undertaking beach and dune nourishment in the years following the initial construction of the berm-dune system; this scenario is consistent with the situation faced by many communities located on sandy coastlines around the world (Leonard et al. 1990; Nordstrom 1994; Nordstrom and Jackson 2018; Beuzen et al. 2019; Gao et al. 2020). Again, here we only consider scenarios in which the background erosion rate exceeds the rate of dune migration (i.e., $E > v$), a common scenario faces by many coastal communities (Burroughs and Tebbens 2008; Richter et al. 2013; Cohn et al. 2019; Héquette et al. 2019; Davidson et al. 2020).

1.2.2 Representative Property Owner's Optimal Response to Shoreline Retreat and Dune Erosion

Following previous efforts that focused primarily on the coupled dynamics of developed shorelines but do not consider dune interactions (Slott et al. 2008; Lazarus et al. 2011; McNamara et al. 2011; Gopalakrishnan et al. 2011; Jin et al. 2013; Gopalakrishnan et al. 2016), we assume the average property owner within a beachfront community maximizes the sum of their future property's annual rental values less renourishment costs over an infinite planning horizon subject to the berm-dune dynamics described in Equations (1.1) to (1.4):

$$\underset{Q_{NW},Q_{NH}}{Max} \int_0^\infty e^{-\delta t} \Big(B\big(W(t), H(t)\big) - C(t)\Big) \cdot dt \tag{1.5}$$

where δ is a discount rate (time preference), B is an economic benefit measured as the yearly rental value of coastal property per meter of alongshore beach, and C is the renourishment cost per meter of alongshore beach. The "rental value" does not imply that all properties are within the rental market, rather this represents the annualized replacement value for other uses of the property.

Empirical research has shown that the benefits *B* can be modeled as a function of aspects of the berm-dune geometry, particularly beach width (Pompe and Rinehart 1994; Gopalakrishnan et al. 2011) or dune height (Eberbach and Hoagland 2011; Dundas 2017). These previous studies demonstrate a positive relationship exists between property values and beach width or height.[1] Therefore, the benefit to a yearly rental value of coastal property per meter of alongshore beach *B(t)* is specified as:

$$B(t) = \alpha \cdot \left(\frac{W}{W_\alpha}\right)^\beta \cdot \left(\frac{H}{H_\alpha}\right)^\theta \quad (1.6)$$

where α represents a community's annualized baseline rental value (attributable to all structural, neighborhood, and environmental characteristics exclusive of beach width and dune height) per year and meter of alongshore beach. β is the elasticity (or percentage change) of annual rental value with respect to beach width, θ is the elasticity of rental value with respect to dune height, and H_α and W_α are baseline reference values for dune height and beach width. We explicitly normalize the width and height terms in Equation (1.6) to allow α to have units of *$/year/m* as the exponents in this equation are fractional.

Equation (1.6) assumes that the property's annual rental value increases with increases in beach width and dune height, where a positive θ is reflective of the beachfront community's preference for coastal protection over ocean views. The greater the θ-value, the greater a

[1] The benefit function does not incorporate other changes in environmental condition or individual welfare, such as effects of renourishment on the local ecosystem, which could play a significant role in some contexts (Wolner et al. 2013; Figlus et al. 2018). Furthermore, this simplified relationship does not account for the empirically derived critical maximum beach width beyond which benefits decline (Gopalakrishnan et al., 2011). This critical width does not affect our results as our scenarios consider beaches facing constant erosion and our optimization results in beach widths smaller than suggested critical widths.

community values protection in general, and vice-versa. However, when a beachfront community prefers ocean views over protection, or outright opposes the mitigation projects, this would be represented by negative θ-values, although it remains unclear what the constraints would be on negative θ-values (Moreover, the model presented here does not investigate negative θ-values). The cost per meter of annual renourishment for the berm-dune system is modeled as:

$$C(t) = \phi_N \cdot (Q_{NW} + Q_{NH}) \tag{1.7}$$

where the parameter ϕ_N (\$/m^3) in Equation (1.7) represents the cost per unit volume of beach renourishment material. The renourishment flux control variables, Q_{NW} and Q_{NH}, are expressed in units of $m^3/m/yr$, or simply m^2/yr, given the idealized cross-sectional profile per meter of alongshore beach (Figure 1.5).

1.2.3 Model Solution

The current value Hamiltonian using Equations (1.1), (1.4), (2.6), and (1.7) can be written as follows:

$$J = \alpha \cdot \left(\frac{W}{W_\alpha}\right)^\beta \cdot \left(\frac{H}{H_\alpha}\right)^\theta - \phi_N \cdot (Q_{NW} + Q_{NH}) + \lambda_{NW} \cdot (\frac{Q_E}{H} + v - \frac{Q_{NH}}{H} - E + \frac{Q_{NW}}{D_T} + \frac{Q_E}{D_T}) + \lambda_{NH} \cdot \left(\frac{Q_{NH} - Q_E}{p \cdot H}\right) \tag{1.8}$$

where λ_{NW} is the shadow value associated with a change in the beach width and λ_{NH} is the shadow value associated with a change in dune height. Applying the Pontryagin's Maximum Principle (Kamien and Schwartz 1981), necessary conditions for optimal renourishment imply $\partial J/\partial Q_{NW} = 0$ and $\partial J/\partial Q_{NH} = 0$, resulting in the following first-order conditions:

$$\lambda_{NW} = \phi_N \cdot D_T \tag{1.9}$$

$$\lambda_{NH} = p \cdot \phi_N \cdot (D_T + H) \tag{1.10}$$

Additionally, the following adjoint equations also need to be satisfied:

$$\frac{\partial J}{\partial W} + \dot{\lambda}_{NW} - \delta \lambda_{NW} = 0 \tag{1.11}$$

$$\frac{\partial J}{\partial H} + \dot{\lambda}_{NH} - \delta \lambda_{NH} = 0 \quad (1.12)$$

Solving for interior solutions under steady state (i.e., $dW/dt = dH/dt = \dot{\lambda}_{NW} = \dot{\lambda}_{NH} = 0$), using Equations (1.8) through (1.12), the optimal beach width W^* and dune height H^* can be solved for as follows:

$$\left[\frac{1}{\beta\alpha} \cdot \left(\frac{H^*}{H_\alpha}\right)^{-\theta} \cdot W_\alpha \cdot \delta \cdot \phi_N \cdot D_T\right]^{\frac{\beta}{\beta-1}} \cdot \frac{\theta\alpha}{H_\alpha} \cdot \left(\frac{H^*}{H_\alpha}\right)^{-\theta} = \delta \cdot p \cdot \phi_N \cdot (D_T + H^*) \quad (1.13)$$

$$W^* = W_\alpha \cdot \left[\frac{1}{\beta \cdot \alpha} \cdot \left(\frac{H^*}{H_\alpha}\right)^{-\theta} \cdot W_\alpha \cdot \delta \cdot \phi_N \cdot D_T\right]^{\frac{1}{\beta-1}} \quad (1.14)$$

We first calculate H^* using the nonlinear equation solver *fsolve* in MatLab™. We then compute W^* with the calculated value for H^*.

1.3 Input Parameter Values

The solution of Equations (1.13) and (1.14) requires both geologic and economic parameters, discussed further below. In short, we base most of the geomorphic parameters on FEMA's "540-Rule" dune construction design and representative values for the New Jersey coast (Table 1.1). The economic parameters were obtained from a review of the literature and local real estate data (Table 1.2).

Table 1.1 - Geomorphic parameters

Symbol	Symbol Name	Value	Units	Reference
W_{max}	"540-Rule" Beach Width	38	*m*	USACE 2014
W_α	Baseline Beach Width (2016)	38	*m*	Google Earth Pro
H_{max}	"540-Rule" Dune Height	7	*m*	USACE 2014
H_α	Baseline Dune Height (2016)	4	*m*	SWFL
D_T	Shoreface Depth of Closure	9	*m*	USACE 1999; Ortiz & Ashton 2016
Ψ_S	Dune Foreslope	1V:5H	-	USACE 2014
Ψ_B	Dune Backslope	1V:10H	-	USACE 2014

Table 1.2 – Economic parameters

Symbol	Symbol Name	Range	Reference

δ	Discount Rate	6.9%	USACE, 1999 and 2014
α	Annual average beachfront property rental value per meter alongshore (beachfront lengths average ~25m)	\$0 -\$4K \$/yr/m	Ocean County Taxation Data 2017
ϕ_N	Yearly renourishment cost per meter alongshore	\$4.2/m^3- \$13.1/m^3 \$/yr/m	Valverde et al. 1999; Hoagland et al. 2012; USACE 2014; Beavers et al. 2016
β	Hedonic Value of *W*	0.50	Gopalakrishnan et al. 2011
θ	Hedonic Value range of *H*	0.001-0.3	θ-value estimations (Table 3)

1.3.1 Geomorphic Parameters

The FEMA "540-Rule" design (Figure 1.2) includes a dune with a seaward-facing sand reservoir of 540ft^2 (~50m^2) in the cross-shore. The sand reservoir must be located above the 100-year still water flood level (SWFL) with dune height H_{max} ~ 7m and baseline height H_α ~ 3m (consistent with the 100 year SWFL) and adjoined by a 125' (~38m) berm, as illustrated in Figure 1.5 and presented in Table 1.1.

1.3.2 Economic Parameters

Aggregating beachfront property data for entire beachfront communities from 2015 to 2019 (Figure 1.6), we obtained a first-order estimate of the elasticity for dune height θ for three municipalities within Long Beach Island, NJ (Figure 1.4). Although dune construction took place in the spring of 2016 for the three beachfront communities, its effect on property values was not uniform across towns. Both Beach Haven and Ship Bottom experienced substantial increases in property values between 2016 and 2017, whereas Long Beach Township, whose residents generally have been opposed to dune construction (Insurance Journal 2013; Zernike 2013; Schapiro 2015; Spoto 2013), experienced only a small increase in property value.

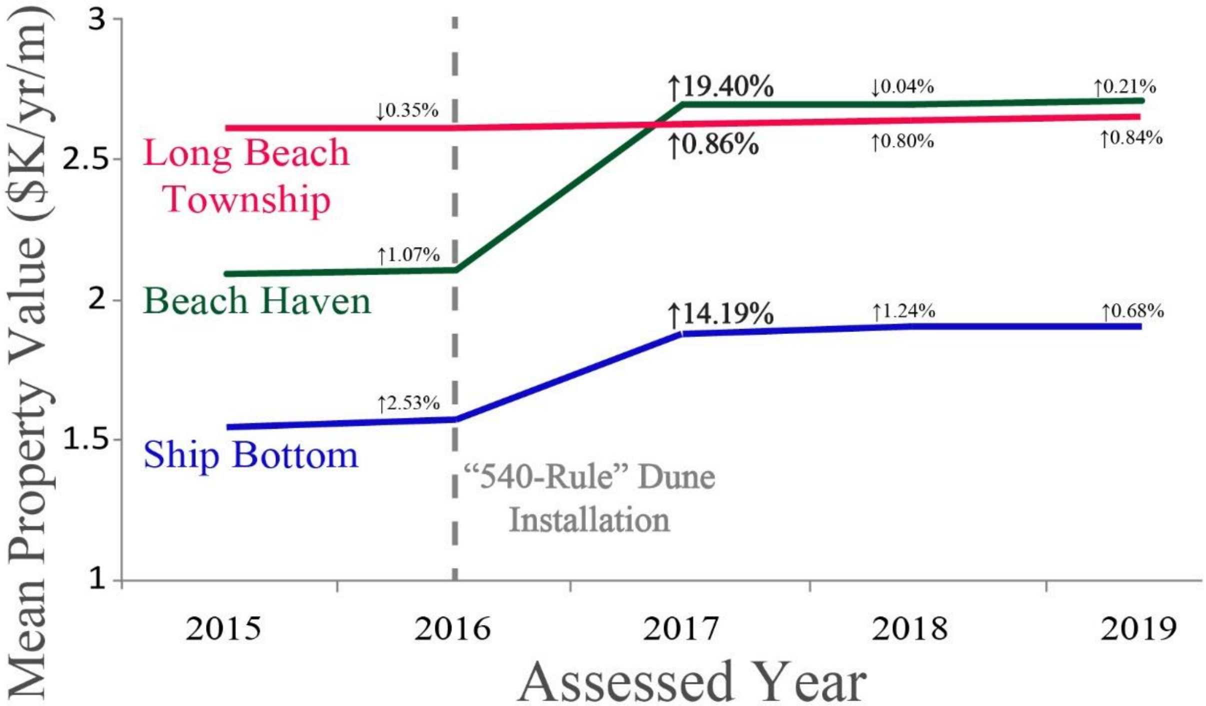

Figure 1.6 – Aggregate beachfront property value trends for 2015-2019, following dune installations in 2016 (Ocean County Taxation Database).

Using Google Earth, the beach widths for all three communities in spring 2016 (prior to berm-dune construction) were found to be within the range of 35-40m, the same range as found in 2017 after berm-dune construction. In other words, the beach profile was extended seaward to make room for the engineered dune without changing the beach width. Therefore, the derivative of the benefit function (Equation (1.6)) can be taken with respect only to H, and the change in benefit ΔB with the change in dune height (H_{max}-H_{α}) between 2016 and 2017 can be measured as follows:

$$\Delta B = \alpha \cdot \theta \cdot (H_{max} - H_{\alpha}) \cdot \left(\frac{1}{H_{\alpha}}\right) \cdot \left(\frac{H_{max}-H_{\alpha}}{H_{\alpha}}\right)^{\theta-1} \cdot \left(\frac{W_{max}}{W_{\alpha}}\right)^{\beta} \tag{1.15}$$

where α is the average beachfront rental value per meter alongshore for each community in 2017 (Table 1.3). The ratio $(W_{max}/W_{\alpha})^{\beta}$ goes to 1, given our observations of W_{α} and W_{max}. Values of θ were found to be within the range 0.01-0.26 (Table 1.3), suggesting all beachfront communities in this sample value protection over ocean views. However, this value is close to zero for Long Beach Township, suggesting that protection and views are approximately equally valued.

Table 1.3 - θ-value estimations from Equation (1.15)

Beachfront Community	α (2017 values)	ΔB (from 2016-2017)	θ-Value
Ship Bottom	α = \$1,825/yr/m	ΔB = \$259/yr/m	0.26
Long Beach Township	α = \$2,670/yr/m	ΔB= \$32/yr/m	0.01
Beach Haven	α = \$2,701/yr/m	ΔB= \$524/yr/m	0.17

1.4 Long Term Feasibility of Coastal Dune Maintenance

Using the steady state solutions described by Equations (1.13) and (1.14) we then compute the conditions under which coastal communities would be willing to continue to maintain their “540-Rule” berm-dunes in the future (i.e., the benefits of continued berm nourishment exceed the maintenance cost). This allows us to compute the optimal dune height H^* as a function of each beachfront community’s average yearly rental value α per meter of alongshore beach and the height elasticity θ (Figure 1.7). A range of positive values for θ were based on the estimates included in Table 1.3, and a range of values for α were based on publicly available beachfront rental values in New Jersey (Table 1.2).

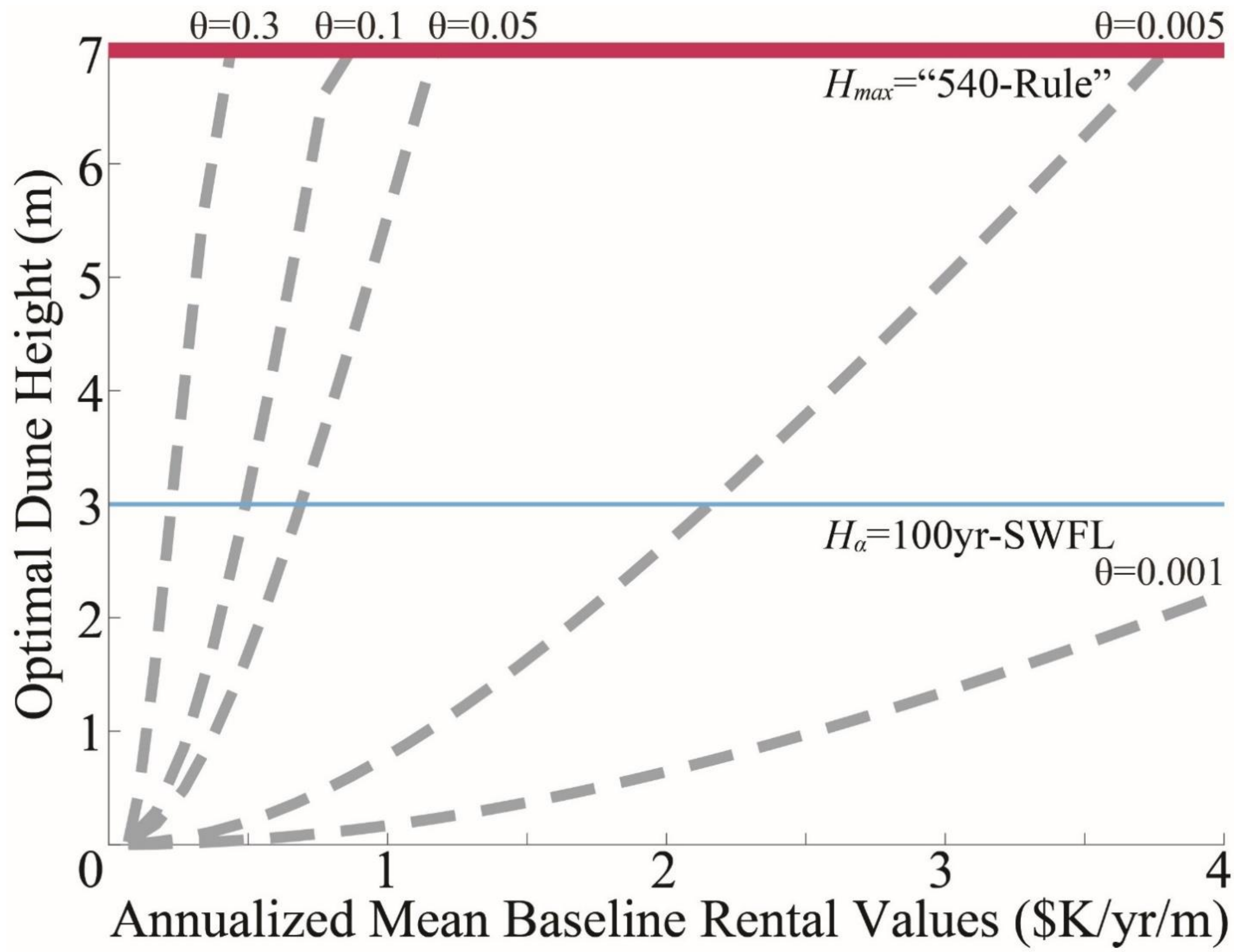

Figure 1.7 – Optimal dune height H* for an annualized beachfront property value, based on a positive range of θ-values.

Beachfront communities with high annual rental values were found to be more economically capable of maintaining the full-size, more costly "540-Rule" dunes (e.g., a large H^* = 7m) than those with low rental values. For many scenarios, maintaining a dune height smaller than that prescribed by the "540-Rule" is considered to be economically optimal, particularly in communities that value views and protection similarly. Further, the optimal dune height was found to be sensitive to changes in the height elasticity θ. For a range of θ-values reflecting preferences that are more in favor of coastal protection over ocean views, even communities with low to medium annual rental values were capable of maintaining the "540-Rule" berm-dune. In contrast, as the importance of ocean views increases relative to coastal protection, all beachfront communities, regardless of their annual rental values, would be unwilling or incapable of maintaining the berm-dunes.

The role of the representative beachfront community's perception towards engineered dune installation was investigated further by depicting the optimal dune height as a function of not only the annualized rental value per meter of alongshore beach α, but also the renourishment costs ϕ_N (Figure 1.8). Both α and ϕ_N were estimated for five New Jersey beachfront communities, including the three beachfront communities from Long Beach Island, all of which received "540-Rule" dunes in 2016, and two additional New Jersey beachfront communities where "540-Rule" dunes were in the process of being installed in the fall of 2019 (i.e., Bay Head α = \$3,658/yr/m and Mantoloking α = \$3,057/yr/m); both of which were opposed to installations on the record (Mikle 2017). For comparative changes in annual rental values per meter of alongshore beach α, 2017 values were used in the comparison.

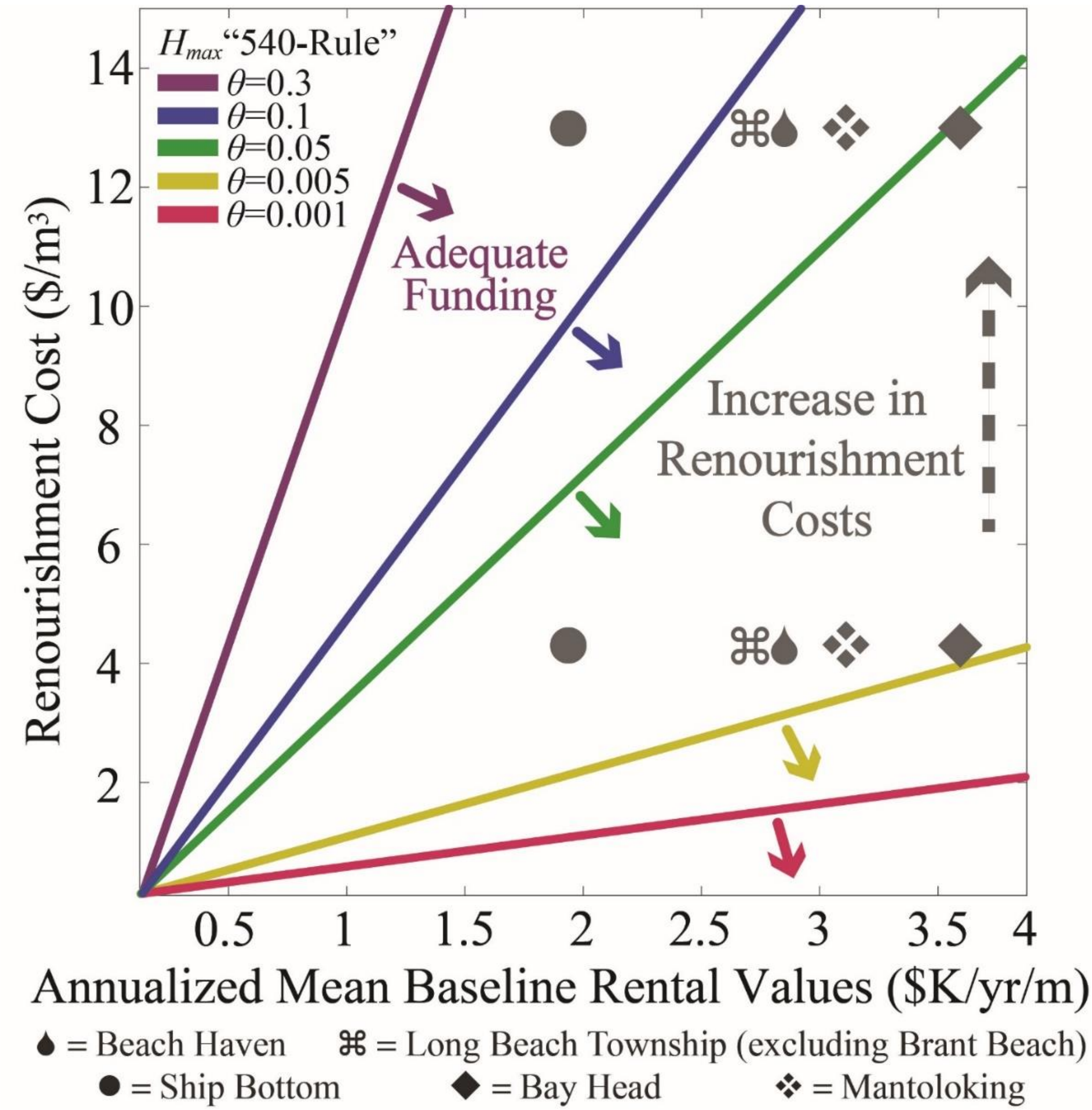

Figure 1.8 - Optimal dune height H* as a function of different variable renourishment costs of ϕN=\$4.2/m^3 and ϕN=\$13.1/m^3, and annualized baseline rental values α for High θ-values (θ=0.3), Intermediate θ-values (θ=0.1, θ=0.05, θ=0.005), and Low θ-values (θ=0.001)

As annual rental values differed substantially across the five communities, we predict different capabilities for each community to maintain their berm-dunes in the future (Figure 1.8). For high to intermediate height elasticities (e.g., $\theta = 0.3$, $\theta = 0.1$, $\theta = 0.05$) and low costs of renourishment (e.g., $\phi_N = \$4.2/m^3$), all communities in this study would maintain engineered berm-dunes up to the "540-Rule" dune height H_{max}. In contrast, for low θ-values (e.g., $\theta = 0.005$ and $\theta = 0.001$), none of the coastal communities would maintain the engineered berm-dunes.

The results are also sensitive to increases in the costs of renourishment. For a higher cost scenario $\phi_N = \$13.1/\text{m}^3$, which corresponds to the 2016 annual renourishment costs seen in Ocean City, NJ (Beavers et al. 2016), the number of communities that are capable of maintaining engineered berm-dunes up to H_{max} decreases. A high θ-value (e.g., $\theta = 0.3$) is the only scenario where all communities can still economically justify adequate funding for future renourishment. For intermediate values (e.g., $\theta = 0.1$ and $\theta = 0.05$), the community with the lowest wealth (i.e., Ship Bottom) cannot prioritize long-term dune maintenance, whereas the wealthiest communities (i.e., Bay Head) can maintain adequate funding.

The modeling framework can also be used to consider the scale of subsidies needed for individual beachfront communities to justify maintenance of engineered dunes, which can be interpreted as the amount of a community's budgetary shortfall in reference to the local cost-share. The current New Jersey cost-share is based on the Sandy Recovery Improvement Act (113th Congress 2013), where the agreement requires local municipalities to contribute 12.5% of the total costs of maintaining a berm-dune. If certain communities do not choose to prioritize their local cost share, the state may have to intervene, spending additional funds. Shortfalls are depicted as a function of each beachfront community's values of annual rental α, and height elasticity from our first-order θ-estimations (Figure 1.9; Table 1.3). Locally feasible renourishment contributions ϕ_{N_θ} (\$/m^3), based individually on each community's θ-estimation, were calculated from the steady-state solution presented in Equations (1.13) and (1.14) as follows:

$$\phi_{N_\theta} = \frac{\alpha \cdot \theta \cdot C_1 \cdot \left(\frac{C_2}{\theta \cdot C_1}\right)^{\beta}}{C_2} \quad (1.16)$$

where

$$C_1 = \left(\frac{\left(\frac{H}{H_\alpha}\right)^{-\theta} \cdot W_\alpha \cdot \delta \cdot D_T}{\beta}\right)^{\frac{\beta}{\beta-1}} \cdot H^{\theta-1} \cdot H_\alpha{}^{-\theta} \tag{1.17}$$

$$C_2 = \delta \cdot p \cdot D_T + \delta \cdot p \cdot H \tag{1.18}$$

The current variable renourishment cost $\phi_{N_{nj}}$ was used to define the budgetary shortfall *SF* percentage as follows:

$$SF = \frac{\phi_{N_{nj}} - \phi_{N_\theta}}{\phi_{N_{nj}}} \cdot 100\% \tag{1.19}$$

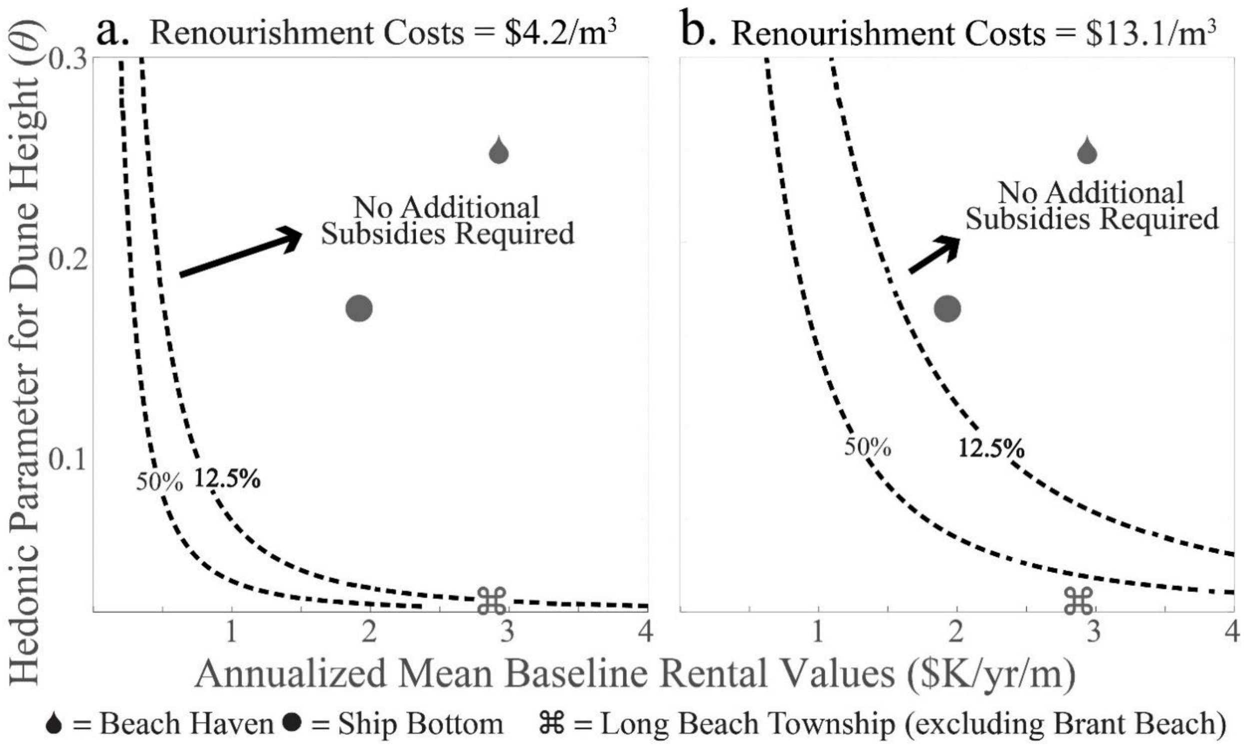

Figure 1.9 - Municipal government "budget shortfalls" requiring external funds (subsidies) to maintain engineered dunes under costs of a. $\phi_{N_{nj}}$=\$4.2/m^3 and b. $\phi_{N_{nj}}$=\$13.1/m^3 scenarios for Long Beach Island, NJ beachfront properties, with θ-values obtained in Table 1.3.

With a low height elasticity (e.g., θ = 0.01), Long Beach Township is the only community where it would be tough to prioritize their berm-dunes with a renourishment cost of $\phi_{N_{nj}} = \$4.2/\text{m}^3$. In contrast, Ship Bottom has the adequate funds to maintain dunes in the foreseeable future due to its relatively high elasticity (i.e., θ = 0.17), despite being the community with the lowest annual rental values. If average sand costs in New Jersey were to rise in the future up to Ocean City, NJ's value $\phi_{N_{nj}} = \$13.1/\mathrm{m}^3$, both Ship Bottom and Beach Haven (i.e., θ = 0.26) would be able to prioritize maintaining a "540-Rule" berm-dune in the long term, although Ship Bottom would be on the brink given its small community size, such that a slight reduction in Ship Bottom's property value or increase in geologic stressors (i.e., background erosion rates) could result in a different optimal decision.

1.5 Discussion and Conclusions

In this paper, we present a coupled geo-economic modeling framework to analyze scenarios under which beachfront communities would be capable of maintaining engineered berm-dune systems in the future. A community's capability to maintain an engineered berm-dune is sensitive to the elasticity of a representative beachfront property owner's annual rental value with respect to dune height, a phenomenon that captures the relative preferences—based upon real estate market outcomes—for coastal protection versus ocean views. Modeling results highlighted the need to focus on the interplay between dune geometries and property values, where future management decisions would be influenced by measures of the implicit prices of local environmental mitigation projects. When beachfront communities exhibited relatively large height elasticities θ (Table 1.3), their property values benefited from the coastal protection provided by engineered berm-dunes (Figure 1.6). In general, these beachfront communities (e.g., Ship Bottom and Beach Haven) would be capable of maintaining the proximate berm-dune over an extended period. In contrast, when beachfront communities exhibited a low positive θ, their property values did not benefit measurably from the proximate berm-dunes due to the narrow difference in protection value versus loss of ocean views (i.e., the dunes were so high that views were partially or wholly blocked). Communities that value views would less likely be able to provide the adequate funds to maintain protective berm-dunes over an extended period because the costs of renourishment would not be seen to fully offset the benefits of coastal protection, a similar scenario discussed in the news article by Moore (2016).

Among the three beachfront communities we reference on Long Beach Island, NJ, both higher beachfront property values and lower renourishment costs were found to increase the likelihood that property owners would be able to continue maintaining engineered “540-Rule” dunes. In reality, however, New Jersey beachfront communities with high-valued properties (i.e., Long Beach Township) publicly expressed opposition to the construction of engineered dunes (Insurance Journal 2013; Zernike 2013; Schapiro 2015). Importantly, given a community’s value for protection being dwarfed by their preference for ocean views, as revealed through local real estate transactions, they would be incapable of maintaining engineered dunes in the future. This position could either disrupt or completely block the implementation and maintenance of regional renourishment projects, leading to catastrophic community or statewide outcomes should major storm events result in significant flooding, local property damages, and loss of tourism, the latter representing a major economic driver in the State of New Jersey (Cooper et al. 2005; Lathrop et al. 2007; Marcus 2017).

In order for New Jersey to armor the shoreline uniformly with FEMA “540-Rule” dunes, easement agreements were sought from beachfront property owners, allowing the state to “take” private property up to the mean high tide line. These agreements comprised legal transfers of land from private to public ownership. Without these agreements, property value heterogeneities across beachfront communities could have resulted in a nonuniformly engineered shoreline, where some communities would be protected by dunes and some not. Even with these land-transfer agreements in place, coastal communities with relatively high annual rental values still might prefer ocean views to coastal protection, thereby threatening the future continuity of the engineered berm-dune system along the coast. To avoid damages from coastal storms in the future, the state might need to consider providing financial assistance (i.e., “subsidize”) those communities with beachfront properties that have relatively high annual rental values in order to persuade them to continue maintaining their proximate dune-berms.

The geo-economic model employed here does not account for the effect of individual events and differences in risk perceptions among the residents of coastal communities, which could also preclude future renourishment projects. When coastal protections are put in place and shown to be effective in the face of storm hazards community preferences tend to favor the maintenance of coastal protection (Kriesel et al. 2000; Gravens et al. 2007; Eckel et al. 2009; Turner 2012; Cameron and Shah 2015; Leichenko et al. 2015; Dundas 2017). On the other hand, if a hiatus (e.g., a decadal scale lull) in the intensity and frequency of local storm impacts were to occur, community preferences might begin to shift away from protection in favor of ocean views (Leichenko et al. 2014). To account for these effects, the geo-economic framework will be extended to account for temporal changes in the frequency and the magnitude of storms, and the height elasticity θ will be modeled as a dynamic parameter, shifting with a lag in response to changes in climate and storm regimes. The possibility of shifting community-level berm-dune height elasticities and their impacts on coastal protection is particularly important given that coastal storms are expected to increase in intensity and frequency (Emanuel 2010; Emanuel 2013; Kirshen et al. 2020).

CHAPTER 2: UNDERSTANDING THE HEDONIC RELATIONSHIP BETWEEN ENGINEERED DUNE CONSTRUCTION AND COASTAL PROPERTY VALUES

2.0 Summary

In the years following Hurricane Sandy, the State of New Jersey constructed large-scale engineered berm-dune structures to mitigate future storm-related damages to residential properties and the state's coastal tourism industry. As federal and state contributions towards coastal protection potentially decline, it is unclear whether local beachfront communities would be able to financially contribute towards their maintenance in the long-term. Therefore, estimating the net benefits the average beachfront stakeholder receives from this protection strategy, versus their future costs of renourishment, is important information for beachfront communities. This provides them with their abilities to maintaining an adequate coastal protection strategy (i.e., engineered dune) in the long-term. This study examines the relationship between dune construction and the relevant benefits gained by the protection provide to local stakeholders. In Long Beach Island, New Jersey some beachfront communities experienced a sudden increase in property values immediately following the installation of such berm-dunes in 2017. To uncover whether dune construction played a key role in this response, we employ a hedonic pricing model to estimate the variations in property values in response to dune implementation and other property characteristics. Our results expose the marginal price elasticity (or percentage change) of dune construction increased property values by 15.7% (Ship Bottom), 1.3% (Long Beach Township), and 20.7% (Beach Haven), respectively. The communities with larger marginal elasticity values accumulated a substantial communal benefit between the two years, enough that is suitable to offset the potentially increasing costs of renourishment episodes in the future. In addition, we include components of stakeholder risk-perception. We find that new property construction following dune installation reveals a change in various structural characteristics (e.g., piling foundations, increasing story height, more beds

and baths, more weather-resistant designs, etc.). The emergence of these structural changes exposes the value individual stakeholders are placing on becoming more resilient.

2.1 Introduction

In the past few decades, along the mid-Atlantic coastline, mitigation strategies and responses to potential future storm surge impacts have adapted to meet an accelerating rate of natural change to the shoreline position and geometry (Titus et al. 1991; Yohe et al. 1995; Yohe and Schlesinger 1998; Valverde et al. 1999; Psuty and Ofiara 2002; Landry et al. 2003; Titus 2009; Lazarus et al. 2011; Hapke et al. 2013, Fallon et al. 2017; Beasley and Dundas 2018). These changes are driven by the natural geomorphic responses of erosion due to increasing rates of anthropogenic-induced sea-level rise (Vermeer and Rahmstorf 2009; Engelhart and Horton 2012; Kopp et al. 2019), combined with the exacerbation of storm frequency and intensity (Emanuel 2010; Emanuel 2013; Kirshen et al. 2020). Furthermore, human development-planning along these vulnerable landscapes has traditionally followed resiliency projects that add a sense of protection (Titus et al. 1991; Valverde et al. 1999; Psuty and Ofiara 2002; Hapke et al. 2013; Beasley and Dundas 2018, Gault 2019). The fundamental reasoning behind these management decisions and incessant policy measures amongst developed beachfront communities is to continue the generation of future benefits (i.e., tax revenue and recreational benefits), with a reduction in potential damage costs in mind (USACE 1999, Parsons and Powell 2001, Hoagland et al. 2012, USACE 2014, FEMA NFIP 2020). Whereas, the cost of maintaining the shoreline in order to keep up with sea-level rise is merely a fraction of that return.

Following the impacts of Hurricane Sandy in 2012, the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program's (NFIP) top protective strategy from storm-surge impacts, termed the FEMA "540-Rule" dune design, was adopted statewide along

New Jersey's 127-mile shoreline (Figures 1.1 and 1.2). The "540-Rule" dune structures were built to withstand the impacts of a 100-year storm surge and still water flood level (SWFL). The FEMA design was a distinctive selection, in the sense that when they were built up to six years prior to Hurricane Sandy within three Long Beach Island (LBI), NJ beachfront communities (e.g., Surf City, Harvey Cedars, and a sub-sectional community of Long Beach Township, Brant Beach), they demonstrated adequate protection. Post-Hurricane Sandy in the spring of 2016, the USACE completed filling in the gaps along most of the LBI, NJ coastline, where "540-Rule" dunes did not yet exist: Ship Bottom, the majority of Long Beach Township, and Beach Haven (Figure 1.4). These three LBI, NJ communities with newly installed dunes will act as our main study sites. As with most of New Jersey's new protective strategy, initial project funding came entirely from the U.S. Congress' Sandy Recovery Improvement Act of 2013 (113^{th} Congress 2013). Moving forward in the next 50 years, the 113^{th} Congress also agreed to invest in a 50% cost-share for up to seven future renourishment projects, while the State of New Jersey would subsidize 37.5% of the remainder, leaving the local communities responsible for the remaining 12.5%.

What is unclear, however, is the long-term financial stability of these beachfront communities to maintain "540-Rule" dunes. Kolodin et al. (2021 *accepted for publication*) used a hedonic pricing estimation approach to gain insight into the maximum addition of property value gained by the average stakeholder from a beachfront community when an engineered dune was installed along their beaches. Similar exploratory models that examine the "geo-economic" relationships between coastal protection strategies (i.e., beach renourishment) and stakeholder property values have been an emerging topic of conversation (Parson and Powell 2001, Gopalakrishnan et al. 2011, Jin et al. 2015, Fallon et al. 2017), but only few have considered the measure of value with the installation of engineered dunes (Eberbach and Hoagland 2012, Dundas 2017). Kolodin et al.'s (2021 *accepted for publication*) findings reveal the differences that exists among communities in favor of this protection strategy, versus those with stakeholders who were verbally opposed to their installation. Those stakeholder's opposed to these measures argued that the tall dune geometry would block ocean views, potentially leading towards a reduction in property value. In fact, regardless of dune installation, all communities in the study demonstrated the protection gained from engineered dunes outweighed the ancillary costs (i.e., losses in ocean views).

There will certainly be unforeseen challenges that arise to the morphodynamic and micro-economies as coastal storms intensify with more frequency and sea-level rise accelerates (Emanuel 2010; Emanuel 2013; Kirshen et al. 2020). The goals of this study are to examine these geo-economic relationships in more detail. We take into account not just the installation of engineered "540-Rule" dunes, but also, the stakeholder adjustments taking place towards building homes more resiliently along these sensitive landscapes. To do this, we employ a hedonic analysis that reveals the true marginal price elasticity (or percentage change) that dune construction contributes to gains (or losses) on the average stakeholder's property value.

2.2 Background

The recent engineered berm-dune projects have fashioned a single geometric shoreline from the southernmost portion of Beach Haven to Long Beach Township's Division D. For clarification, Long Beach Township includes a swath of sub-sectional communities (Figure 2.1), which are contained within the entirety of the 18-mile stretch of coastline (i.e. Divisions A-E). Several sub-sections that are included, but were passed on having "540-Rule" dunes installed in 2016, are found in the most northeastern section of Division D and the whole of Division E. The decision to ultimately skip this portion of the island was, in part, due to the existing presence of adequate natural foredune systems. The singular sub-community of Long Beach Township not included in our study is the sub-sectional community Brant Beach, found in the northern section of Division B. As previously mentioned, Brant Beach was a community that received FEMA "540-Rule" dunes just prior to Hurricane Sandy in 2012, along with Surf City and Harvey Cedars.

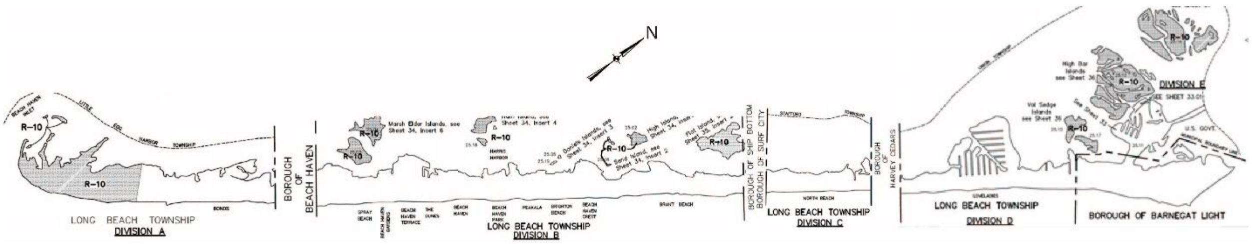

Figure 2.1 - Long Beach Township sub-sectional zoning map (Long Beach Township 2011), with more detailed information for separate Divisions A-E (Appendix Figure A.1)

The USACE's 2014 Feasibility Report was based on a 20-mile long "Barnegat Inlet to Little Egg Inlet" project, encompassing the full alongshore length of LBI, with the intention of fortifying the adjacent developed landscape with large-scale engineered berm-dune systems in order to mitigate future storm surge impacts (USACE 2014). The fundamental justification for the project was that the costs were less than the benefits received, due to a reduction in storm surge impacts (Neumann et al. 2010, Bin et al. 2011, Gopalakrishnan et al. 2011). A more detailed explanation suggests that the generation of benefits, minus the damage costs, over a longer time horizon, should significantly outweigh the benefits over a shorter time horizon, in the absence of a project (Graven et al. 2007); simply known as "the total damage reduction benefits" (Whitehead et al. 2006, USACE 2014). The feasibility report continues to explain how total project costs, and future episodic renourishment costs themselves become insignificant over a longer time horizon, especially when New Jersey's shore-tourism industry generates $44.1 billion in annual revenues (Marcus, March 2017).

2.2.1 Stakeholder Response to FEMA "540-Rule" Dune Construction in LBI, NJ

The current mitigation project within LBI, NJ focuses on a long-term fixation of the shoreline position and storm-surge protection from the engineered dune, ensuring continued economic growth for both real estate and recreational purposes. In reality, the tangible benefits received from mitigation project costs are only realized once storm impacts are truly alleviated. However, the protective value gained by "540-Rule" dunes may vary among different local beachfront municipalities, potentially leaving vulnerable gaps alongshore. That is, if certain communities do not have a need to, or simply cannot afford to contribute to future renourishment episodes, uncoordinated efforts could inhibit the mitigation efficacy along the coast. Just after the announcement of construction and prior to installation in 2016, a handful of LBI, NJ stakeholders expressed opposition to these measures; specifically, beachfront homeowners in various sub-communities within Long Beach Township's Divisions B and D (Allentoff May 2013). As most stakeholders were still reeling from the emotional and financial tolls the storm created in 2012 (Halpin 2013), the small collection of beachfront homeowners saw these projects as a detriment to their properties' future market value. Their main arguments were that private real estate to the berm's high-tide line was being seized (via easement amendments) while the engineered dune structures would conceivably obstruct ocean views, thus depreciating beachfront property value (Anon. 2013; Zernike 2013; Spoto 2013; Schapiro 2015). To understand the immediate aftermath and localized economic impacts these mitigation projects had on local communities, prior to their intended usage during a major storm, is key to understanding the relationship at play, or how and when tangible benefits are received before future events occur.

2.3 Methods: A Hedonic Pricing Model (HPM) for FEMA "540-Rule" Dune Construction

Formerly, the hedonic relationship was first used in Brown and Pollakowski (1977) to identify the benefit a particular environmental characteristic has on the local economy. By compiling real estate data from single-family homes, previous studies were able to foster methods for determining the marginal implicit price (MIP) a stakeholder's property value benefits from following the installation of an environmental attribute, also known as a hedonic pricing model (HPM) (Smith 1985, Cummings et al. 1986, Mitchell and Carson 1987, Silberman and Klock 1988, Freeman 1993). Freeman's (1993) HPM framework specifies that a property's market value *PV* is a function of the three independent variable classifications: structural *S*, neighborhood *N*, and environmental *E* (Equation 2.1). When the function's equation expands into an estimation of the benefit received, each independent variable's significance, or hedonic value, is embedded as an exponent for each variable. For instance, Kolodin et al. (2021 *accepted for publication*) measured the benefit as a function of time *B(t)* when a protective engineered dune H/H_α was added to protect the average property within a beachfront community α (Equation 2.2). The quantitative value presented in the exponent of Equation (2.2) θ measures the implied asset value or the elasticity margin that a stakeholder is willing to pay for the environmental characteristic, like adding a protective dune (updated from Equation 1.6). The relationship can either be positive (e.g., between 0-1) when it provides additional benefits to the existing property, or negative (between -1-0) when the environmental attribute presents itself as a nuisance to the local community. To better constrain this value, a multi-linear regression analysis is required.

$$PV = f(S, N, E) \tag{2.1}$$

$$B(t) = \alpha \cdot \left(\frac{H}{H_{\alpha}}\right)^{\theta} \quad (2.2)$$

The intuition from Equation (2.2) derives from more recent studies that have applied similar HPM approaches to the former, where the focus is related to understanding the interplay that exists between the coupled natural-human systems of beach erosion and sustainable coastal development (Edwards and Gable 1991, Kriesel et al. 2000, Parson and Powell 2001, Bin et al. 2011, Gopalakrishnan et al. 2011, Au 2011, Hoagland et al. 2012, Eberbach and Hoagland 2012, Jin et al. 2015, Shi 2016, Fallon et al. 2017). For instance, Gopalakrishnan et al.'s (2011) work was able to ascertain the hedonic value North Carolina beachfront stakeholders place on wider beach widths and their endorsement of renourishment episodes. They concluded a highly positive relationship with wider beach widths existed, while favoring future projects. Where Eberbach and Hoagland (2012) also concluded a positive relationship exists between wider beach widths and property value, but rather using a measured variable termed "geo-time," in which the rate of erosion resulted in an average depreciation of beachfront properties along the coastal community of Sandwich, MA. A key variable Eberbach and Hoagland (2012) included in their multi-linear regression analysis was the presence of a recently installed engineered dune, not related to the "540-Rule" design. As a result, a negative hedonic value appeared (e.g., -0.1098), intuitively demonstrating that Sandwich, MA properties, which include adjacent engineered dunes, were negatively influenced by the presence of dune construction, or worth roughly 11% less than an equivalent property without an engineered dune. Building off the intriguing result for dune construction in Eberbach and Hoagland's (2012) framework, Dundas' (2017) used a quasi-hedonic approach with the intention of quantifying the average property's capitalization following engineered dune construction. The author's study site also happened to exist within LBI, NJ, and included the townships with "540-Rule" dunes installed prior to

Hurricane Sandy, as mentioned before (USACE 1999, Dundas 2017). Furthermore, as the findings show a positive capitalization value, or positive net benefit of 3.6% was received by the average homeowner from 2010-2012 (or an average rate of ~$3,000 per household, per year), a study which serves as a key motivation for our research presented in this paper.

Our HPM follows a similar approach to those used in Gopalakrishnan et al. (2011), Eberbach and Hoagland (2011), and Fallon et al. (2017), which quantify the impact-value human actions at the coastline (e.g., beach renourishment) have on local communities. Here, we focus on the hedonic value a "540-Rule" dune provides as protection for a local community ω, and more importantly, the specific marginal price elasticity that dune construction places on an average local property. In our study, when ω-values are in the positive range, it is interpreted that the average homeowner values protection from dune construction, over the potentially ancillary costs of losses in ocean views and private property. The opposite is true when our ω-value is negative, wherein the protection gained from the dune generates a decrease in benefits due to higher ancillary costs.

We use a HPM equation, as described in Equation (2.3), to quantify the benefit received from a single-family residential coastal property in community j (PV_j), as a function of an average property's various structural characteristics for variables (X_j), and the presence of a "540-Rule" dune D_j. For simplicity, we disregard neighborhood characteristics in our model, considering our study sites are skewed towards secondary homeowners (~84% - Table 2.1), while the local shopping attractions are spatially distributed evenly along the same main road that runs north to south through all of the LBI, NJ communities. These findings indicates vast unimportance or reasonably similar prerequisites from the stakeholders in this study preferring municipal amenities overall.

We start with the following HPM equation:

$$\ln(PV_j) = \alpha_{0_j} + \sum_{j=1}^{j=3} \alpha_{1_j} X_j + \sum_{j=1}^{j=3} \alpha_{2_j} D_j + \sum_{j=1}^{j=3} \varepsilon_j \quad (2.3)$$

where PV_j is the assessed value of a property in location j, and α_{1_j} represent the vectors of housing structural characteristic parameters to be estimated in each general category. For our vector related to dune construction α_{2_j}, we can run our regression for the entire set of communities to ensure that the dataset has a sufficient number of observations, while maintaining the values that represent the entire project. To do this, we subjectively chose *SB* as the baseline vector α_{2_1} defining their "540-Rule" dune dummy variable as D_1. Additionally, the vectors for our adjacent communities *LBT* α_{2_2} and *BH* α_{2_3}, each contain their representative "540-Rule" dune dummy variable D_2 and D_3, respectively. The resulting vectors for adjacent communities are then added to the reference vector, $\alpha_{2_1} + \alpha_{2_2}$ and $\alpha_{2_1} + \alpha_{2_3}$, revealing our true dune variable coefficients ω_j for a community j (where $\alpha_{2_1} = \alpha_{2_1}$), or the marginal elasticity[2].

Table 2.1 shows a detailed list of variables included in the model, along with their statistical forms and descriptive statistics. Included are three continuous variables in their natural log form, four continuous variables with their whole values, and eighteen dummy variables, including the unique dummy variable for "540-Rule" dune construction ω. The full data set of residential properties within all three communities (Ship Bottom *SB*, Long Beach Township *LBT*, and Beach Haven *BH*) consists of 11,836 properties. The data was trimmed to 7,878 properties (*SB*=1,325; *LBT*=5,312; *BH*=1,241) with an emphasis on isolating single-family residences,

[2] The marginal elasticity used in this hedonic regression model treats the heterogeneous attribute of dune construction separately, by estimating the elastic percentage value that the presence of a dune has on property values when the semi-log form. Since a dummy variable is used for the presence of a "540-Rule" dune, the resulting coefficients equal the true elasticity value ω_j for a particular community j. Similar quality control standard approaches are used by the Appraisal Foundation via the Uniform Standards of Professional Appraisal Practices (The Appraisal Foundation's Appraisal Standards Board 2021).

while eliminating those properties with multiple points of missing data. Additionally, we eliminate the specific properties in *LBT* with either pre-existing "540-Rule" dunes installed or those areas containing natural dunes with adequate protection (e.g. Brant Beach and *LBT* properties to the north of Section D that did not necessitate dune installation) (USACE 2014; Dundas 2017). Most importantly, we trimmed properties to include only those built in 2016 and before, providing our dataset a full representation of the two-year interval period between dune construction. This is not to say the data was fully complete. Thus, for the variables with some missing data, we substituted the *NA* values with the variable's mean for our continuous variables in the natural log form, while substituting the median for whole number continuous variables, including our dummy variables. For more information about this data table and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

Traditionally, HPMs are designed to discretely examine how external environmental characteristics affect the market value response for residential properties. Here, property values experience a private equity gain from these environmental projects, transitioning into an important revenue generation component, not just for the property owners, but for the tax revenue of local, state, and federal governments. Therefore, direct sales, via a deed transfer, provide these tangible values. Inopportunely, of our 7,878 properties, only ~62% contain complete sale prices, where the remainder are dominated by properties that contained minimal deed transfers (≤$100), a minimum requirement of New Jersey state law. In lieu of these missing values, another way to discretely measure the property value response to environmental project impacts is to apply the assessment values as the response instead. To make this practical, we first examine if a relationship exists between sale prices and assessment values from the following year (Kriesel et al. 2000, Fallon et al. 2017). The authors in Fallon et al. (2017) explain how property assessments generally depend on localized tax assessor algorithms, taking into account “sales and value data from the previous year.” Therefore, we take the available property data that included both assessment values and sales data for the years prior, utilizing a threshold difference of 50%, for the timespan (i.e. 2015-2019). As a result, a high correlation appears to exist, where the sales price is estimated to increase at a rate of 93%, or \$0.93 ± \$0.01 for every dollar increase in assessed value ($p<<<0.001$, $R^2 = 0.86$).

The housing attribute and assessment data for the three communities was compiled from Ocean County, NJ’s open-source real estate sr1a database. In our database, all properties were duplicated to include assessed values for both 2016 and 2017, years representing the absence and presence of a “540-Rule” dune, respectively. For simplicity, we assume most all housing attributes to remain the same throughout. Our model’s dummy variables include several specific property details. For instance, whether properties are the primary (“0”) or secondary homes (“1”) of owners, as well as the structural components of the property’s foundation, either a concrete foundation (“0”) or piling foundation (“1”). Furthermore, our remaining dummy variables relative to interior and exterior “attached” attributes are determined by their existence within a property, NO (“0”) or YES (“1”). Since we are aware that “540-Rule” dune construction was completed in the spring of 2016, we designate the presence of a new “540-Rule” dune in 2017 as “1.” Whereas, in the year prior to dune installation in 2016, the property receives a “0.” Therefore, in order for our analysis to generate meaningful results regarding how dune installation truly affects property values, we incorporate the same property twice in our data, with their represented dependent variable for net property values in both 2016 and 2017. In principle, we assume all of our independent variables have a positive influence on the coastal property value. For more information about this data table and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

Table 2.1 - Independent variables with noted statistical form

Variable	Units	Statistical Form	Minimum	Mean	Median	Maximum	s.d.
Response (n=7,878)							
Assessed Value 2016	\$2016		137,200	866,788	748,900	4,994,900	502,287
Assessed Value 2016 (natural log)			11.83	13.55	13.53	15.42	0.47
Assessed Value 2017	\$2017		152,800	921,334	801,900	4,994,900	516,762
Assessed Value 2017 (natural log)			11.94	13.62	13.59	15.42	0.45
Housing Attributes α_n							
General Characteristics							
Year Built	yr	CONTINUOUS(ln)	1920	1977	1979	2016	25
Lot Size	ft^2	CONTINUOUS(ln)	338	6,493	5,000	85,000	5,067
Finished area	ft^2	CONTINUOUS(ln)	120	1,980	1,858	9,526	869
Total Rooms	rooms	CONTINUOUS	1	7.30	7	17	1.67
Beds	rooms	CONTINUOUS	1	3.94	4	12	1.04
Baths	rooms	CONTINUOUS	1	2.89	3	11	1.30
Secondary Homes		0 = Primary, 1 = Secondary	0	0.84	1	1	0.37
Structural Characteristics							
Story Height	floors	CONTINUOUS	1	1.79	2	3.5	0.45
Piling Foundation		0 = Concrete, 1 = Piling	0	0.52	1	1	0.50
Contemporary Roof		0 = NO, 1 = YES	0	0.16	0	1	0.36
Contemporary Design		0 = NO, 1 = YES	0	0.46	0	1	0.50
Wood Exterior		0 = NO, 1 = YES	0	0.33	0	1	0.47
Aluminum Exterior		0 = NO, 1 = YES	0	0.57	1	1	0.50
Housing Attributes							
Electric Heating		0 = NO, 1 = YES	0	0.16	0	1	0.36
Fireplace Attached		0 = NO, 1 = YES	0	0.54	1	1	0.50
HVAC Installed		0 = NO, 1 = YES	0	0.76	1	1	0.42
Patio Attached		0 = NO, 1 = YES	0	0.04	0	1	0.20
Deck Attached		0 = NO, 1 = YES	0	0.60	1	1	0.49
Porch Attached		0 = NO, 1 = YES	0	0.58	1	1	0.49
Garage Attached		0 = NO, 1 = YES	0	0.38	0	1	0.48
Pool Attached		0 = NO, 1 = YES	0	0.11	0	1	0.31
Shed Attached		0 = NO, 1 = YES	0	0.25	0	1	0.43
Hot Tub Attached		0 = NO, 1 = YES	0	0.11	0	1	0.31
Environmental ω							
"540-Rule" Dune		0 = NO, 1 = YES	0	0.50	0	1	0.50

2.4 HPM Results for FEMA "540-Rule" Dune Construction

We further explore the relationship that exists between Kolodin et al.'s (2021 *accepted for publication*) theoretical θ-values for "540-Rule" dune construction (Appendix Tables A.1 and A.2) and our HPM's dune coefficients for specific municipalities ω_j, represented in Equation (2.6). Considering the 2016 project was funded on a regional scale, we use an HPM approach that includes all available data, showing the percentage response "540-Rule" dunes have on the average property, per municipality, and in relation to the average property's characteristics project-wide. To do this, we set up the following matrix for our unique 2017 "540-Rule" dune dummy variable (Table 2.2), using *SB* arbitrarily as the reference value for the linear regression model α_{2_1}, while *LBT* and *BH* are vectors α_{3_2} and α_{3_3}, respectively. Thus, the dune coefficient values for *LBT* and *BH* will appear as values in reference to *SB*: $\omega_{SB} = \alpha_{2_1}$, $\omega_{LBT} = \alpha_{2_1} + \alpha_{2_2}$, and $\omega_{BH} = \alpha_{2_1} + \alpha_{2_3}$. We run our model using the semi-log, so to gain insight into the elasticity factor, or marginal implicit value our "540-Rule" dune variable embodies among the average property value in community *j*. Our linear regression results for our matrix are shown in Table 2.3.

Table 2.2 - Homogenous matrix of dummy variables for "540-Rule" dunes

	New "540-Rule" dune (*SB*)	*BH* "540-Rule" dune	*LBT* "540-Rule" dune
2016 (BH)	0	1	0
2017 (BH)	1	1	0
2016 (LBT)	0	0	1
2017 (LBT)	1	0	1
2016 (SB)	0	0	0
2017 (SB)	1	0	0

Table 2.3 - Results of HPM regression for a homogenous matrix (SB reference community)

Variable	Coefficient values (w/ Significance)	Std. Error
Housing Attributes α_{1_j}		
Year Built (ln)	0.1751	0.2393
Lot Size (SqFt) (ln)	0.3491***	0.0048
Finished area (SqFt) (ln)	0.2451***	0.0098
Total Rooms	0.0032	0.0023
Story Height	0.0190**	0.0059
Beds	-0.0062*	0.0031
Baths	0.0676***	0.0027
Secondary Homes	0.0514***	0.0051
Piling Foundation	0.0246***	0.0060
Basement	0.0443***	0.0050
Contemporary Roof	0.0208***	0.0059
Contemporary Design	0.0940***	0.0057
Wood Exterior	0.0194	0.0137
Asbestos Exterior	-0.0310*	0.0145
Aluminum Exterior	-0.0300*	0.0136
Electric Heating	-0.0162**	0.0056
Fireplace Attached	0.0371***	0.0040
HVAC Installed	0.0040	0.0053

Patio Attached	-0.0019	0.0092
Deck Attached	-0.0038	0.0042
Porch Attached	-0.0040	0.0043
Garage Attached	0.0054	0.0045
Pool Attached	-0.0142*	0.0066
Shed Attached	0.0081	0.0049
Hot Tub Attached	0.0574***	0.0066
Environmental ω_j		
"540-Rule" dune *SB*	0.1572***	0.0089
"540-Rule" dune *LBT*	0.0134***	0.0100
"540-Rule" dune *BH*	0.2071***	0.0128

R^2-value = 0.752 Model Significance = p-value < 0.001

We enhance our HPM results using the white-estimator; a more robust modeling approach to check for heteroscedasticity (Appendix Table A.3). By doing this, our R^2-value (0.753) and standard deviations slightly increase, without changes to our variable significances and coefficient values.

Table 3 reveals the coefficients for each community that represent the protection gained from the installation of "540-Rule" dunes, quantified as ω-values. We can also express our ω-values as percentages average municipal stakeholders are willing to pay for "540-Rule" dunes, or the marginal implicit value a protective dune provides for an average property within that community j. For instance, *LBT* clearly demonstrates the lowest percentage value that engineered dunes place on their property's market value (1.34%), yet they maintain a positive relationship nonetheless, where the protection from dune construction is valued greater than the ancillary costs of losses in ocean views and private property. In comparison, the marginal WTP in *SB* (15.72%) and *BH* (20.71%) are much higher, showing a significantly greater positive value toward protection strategies (i.e., dune construction). In addition to each township's hedonic values for "540-Rule" dune construction, we ran a similar linear regression analysis for the entire renourishment project's population, revealing an overall average WTP of 6.82% (R^2-value=0.721, p-value<0.001) by an average stakeholder residing within *SB*, *LBT*, and *BH* (Appendix Table A.4).

2.4.1 Comparing the HPM and Simple HPM Estimation Approach

For our analysis in this paper, we use a similar HPM framework for LBI, NJ, effectively constraining the marginal willingness to pay by a beachfront community for the added protection a “540-Rule” dune provides, captured in the response it has on the average stakeholder’s property value. Considering the fact that LBI, NJ had just recently endured devastating impacts from storm-surge damages, we hypothesize that the average property’s capitalization rate will be larger than the values revealed in Dundas (2017); a proxy of a larger sense of risk-aversion. Furthermore, Kolodin et al. (2021 *accepted for publication*) uses an approximation approach, or θ-estimation (Equation (2.4)) in reference to Equation (2.2). This results in an upper-limit hedonic value, which is solely attributed to the protection value gained by the average property owner in a particular beachfront community from installing a “540-Rule” dune in 2017 (Figure 1.6), rather than incorporating changes within α variables (Appendix 1A).

$$\Delta B = \alpha \cdot \theta \cdot (H_{max} - H_{\alpha}) \cdot \left(\frac{1}{H_{\alpha}}\right) \cdot \left(\frac{H_{max} - H_{\alpha}}{H_{\alpha}}\right)^{\theta - 1} \tag{2.4}$$

We constrain the theoretical model’s θ-values to generate true WTP values using a HPM. Incorporating a more thorough expansion of the housing characteristic variable inputs α from Equation (2.2), allows our model to provide a more detailed result for the HPM coefficient that pertains to the average stakeholder’s discrete willingness to pay (WTP) for dune construction, which we change to ω. The alternative variable of our HPM coefficient value for dune construction ω bears in mind the slight differences that exist between this modeling approach and our original θ-estimations in (Appendix Table A.2). If we assume our theoretical benefit function (Equation (2.2)) exists in the natural log – natural log form (Equation (2.5)), our “540-Rule” dune variable in both the theoretical form and HPM approach should result in a similar coefficient value (Equation (2.6)). The in reference to our HPM Equation (2.3), the coefficient value for an engineered dune *New540Dune* is calculated as a dummy variable within a linear regression. Again, this is what ultimately determines the marginal price elasticity (University of Minnesota Libraries Publishing 2011), or the measurement of percentage change a dune has on the property value responses in 2017, the year following "540-Rule" dune installation in LBI, NJ.

$$lnPV = ln(\alpha) + \theta \cdot ln\left(\frac{H_{max}}{H_{\alpha}}\right) \quad (2.5)$$

$$\omega(New540Dune) \sim \theta \cdot ln\left(\frac{H_{max}}{H_{\alpha}}\right) \quad (2.6)$$

Therefore, aggregate property value trends presented in Figure 4 and our first-order estimations from Appendix Table A.2 demonstrate that our first-order estimations are an easy way to evaluate a beachfront community's perceived value towards a mitigation project, such as dune construction.

2.5 Measuring Community Resiliency: Insights from our Descriptive Statistics

Along with our findings related to the protective value communities place on "540-Rule" dune, our data contains a variety of significant α variables related to the way beachfront community stakeholders have responded to the implementation of these dunes in following years. In general, the housing construction response of new stakeholder properties following dune installation can reveal a shift in community resiliency, as risk and vulnerability is reduced (Gaul 2019). To do this with our dataset, we compare our regression's dataset for all properties in *SB*, *LBT*, and *BH* built in 2016 and prior to the dataset for properties built in 2017 to 2020. We separate the descriptive statistics into two comparative tables for *Long Beach Township* and combined *Ship Bottom* and *Beach Haven* (Tables 2.4 and 2.5), while the tables each display both the mean and median values for the data set. Furthermore, the α variables are split into three subcategories: *General housing characteristics*, *Structural characteristics,* and the presence of attached and detached *Housing attributes* (Table 2.1).

General housing characteristics that changed since dune construction reveal houses amongst all communities are becoming more expensive, along with the addition of 1 to 2 additional rooms (*Beds* and/or *Baths*) on average. Interestingly, while data for *SB* and *BH* show a decrease in an average property's lot size, while their finished area is becoming larger. In contrast, *LBT*'s lot size is increasing and their finished area on average is decreasing. This inverse relationship may be the result of the differences between the value each set of communities place on dune protection; the greater the perceived protection value (a reduction in risk and vulnerability), the more willing stakeholders are to invest in development with higher price tags (Lazarus et al. 2021).

The structural components for newly constructed properties more clearly demonstrate the interplay between stakeholder responses to valued dune protection and the reformed policies of the municipality following dune installation. For instance, houses across the board are becoming taller in terms of structural floors (Figures 2.2a and 2.2b). This increase in elevation is most likely associated with New Jersey's new Base Flood Elevation (BFE) 12ft +NAVD (FEMA 2013, CCC 2013, Jones et al. 2016), which could also be a positive correlation associated with the structural foundations that use pilings. In *LBT*, all 221 newly constructed properties include pilings, rather than concrete or stone like foundations. The generalized trend of building a new home with pilings as the main structural component could be due to the importance of having a home that will withstand future flooding and storm-surge impacts (Jones 2001), or simply a proxy of new building code enforcements. Moreover, available zoning information shows how all three communities' codes for maximum height restrictions were raised, following the impacts of Hurricane Sandy in 2012 (ecode360: §212-9, §205-10, §16.20.010P, and §16.60.010). In addition, another change seen in the dataset is that in all three communities' houses are being built with a contemporary design and opting for aluminum siding outside on the exterior of the houses, rather than wood (right-side vs left-side house, Figure 2.2b). Aluminum siding is a typical choice with contemporary designs, but could also be interpreted as a long-term sustainable approach towards limiting deterioration from specific chemical and physical weathering processes witnessed along these mid-Atlantic coastlines. In fact, what determines the local real estate market's value of a contemporary fashioned home versus a modern/traditional one is entirely myopic (Hanson 2018).

The attached and detached attributes are also changing, most likely related to the changes occurring structurally. As houses are being raised above the new 100-year SWFL they are eliminating attached ground-floor extensions from the property (e.g., patios and decks), and installing perched extensions such as porches. One structural feature that has become a popular building component in recent years along LBI, NJ is the construction of roof porches (Figure 2.2c), which could be a direct correlation to loss in ocean views. As more accommodation space has become available at ground level with houses being raised in all three communities, more pools and sheds are being installed. The addition of pools could be what is causing *LBT*'s overall net values to increase, while finished areas are decreasing.

None-the-less, it appears that newly constructed properties in all three townships are building with more resiliency towards the future. In addition to this, the overall sense of protection from dune construction is promoting a greater sense of security and newly constructed properties are being built with a greater value, raising the long-term social vulnerability index.

For more information about this data table and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

a.  b.  c. 

Figure 2.2a-2.2c - Properties in LBI, NJ built after 2016 (Photo Credit: a. Nathan Colmer, b. and c. Ball and Albanese)

Table 2.4 - Descriptive statistics for variables ≤2016 n=6,590 and ≥2017 n=221

Long Beach Township MEAN/MEDIAN	**Mean ≤2016**	**Med ≤2016**	**Mean ≥2017**	**Med ≥2017**
Net Values	981,545	843,300	1,409,143	1,164,800
General Characteristics				
Year Built	1979	1981	2018	2017
Lot Size	7,864	5,580	8,271	6,000
Finished area	2,123	2,123	1,887	1,839
Total Rooms	7.46	7	9.17	9
Beds	4.01	4	4.87	5
Baths	3.01	3	4.86	4
Secondary Homes	0.84	1	0.83	1
Structural Characteristics				
Story Height	1.79	2	2.12	2
Piling Foundation	0.62	1	1.00	1
Basement	0.49	0	0.77	1
Contemporary Design	0.51	1	0.92	1
Wood Exterior	0.36	0	0.17	0
Aluminum Exterior	0.54	1	0.81	1
Housing Attributes				
HVAC Installed	0.78	1	1.00	1
Patio Attached	0.01	0	NA	0
Deck Attached	0.36	0	0.04	0
Porch Attached	0.42	0	0.81	1
Garage Attached	0.24	0	0.17	0
Pool Attached	0.13	0	0.34	0
Shed Attached	0.29	0	0.81	1

Table 2.5 - Descriptive statistics for variables ≤2016 n=3,500 and ≥2017 n=127

Beach Haven & Ship Bottom MEAN/MEDIAN	**Mean ≤2016**	**Med ≤2016**	**Mean ≥2017**	**Med ≥2017**
Net Values	744,383	671,250	1,124,391	1,008,400
General Characteristics				
Year Built	1972	1974	2018	2018
Lot Size	12,701	5,250	8,058	5,000
Finished area	1,750	1,696	2,471	2,498
Total Rooms	6.53	6	8.02	8
Beds	3.50	3	4.21	4

Baths	2.55	2	4.00	4
Secondary Homes	0.83	1	0.82	1
Structural Characteristics				
Story Height	1.73	2	1.99	2
Piling Foundation	0.33	0	0.90	1
Basement	0.24	0	0.61	1
Contemporary Design	0.27	0	0.38	0
Wood Exterior	0.31	0	0.11	0
Aluminum Exterior	0.57	1	0.84	1
Housing Attributes				
HVAC Installed	0.71	1	0.95	1
Patio Attached	0.03	0	0.00	0
Deck Attached	0.36	0	0.12	0
Porch Attached	0.29	0	0.43	0
Garage Attached	0.34	0	0.46	0
Pool Attached	0.05	0	0.18	0
Shed Attached	0.13	0	0.29	0

2.6 Long-Term Effects on Stakeholders from Dune Construction

In order to assess the abilities of coastal communities to maintain engineered dunes in the long-term, we compute the Net Present Value *NPV* following dune construction by taking the ω-values and applying them as elasticity values pertaining to the total community wealth. To do this, we discount the total string of annualized benefits received in year 2017 minus the discrete costs, discounted over the project's time horizon (i.e., 50 years) (Equation (2.7)). We can express the percentage values, or ω-values, as a measure of the marginal implicit price an average homeowner receives on their property value throughout the 50 years. Simply, we can calculate the *NPV* (Equation (2.8)) as a total string of benefits received by an average stakeholder from the protection a "540-Rule" dune provides as a function of the community's cumulative property value PV_{total_j}, by the community's marginal willingness to pay for adequate dune protection ω_j. The sum of our discounted costs is a function of the total nourishment costs required to maintain the shoreline geometry, including the cumulative sediment costs ϕ_N (\$/m^3), total nourishment volume demands V_{N_j} (m^3) for a community j, and total number of nourishment episodes E_N over the 50-year time horizon T, including the local cost-share percentage of contribution for the entire project CS_N. Our benefit-cost parameters shown in Table 7 are based upon the 2017 assessed values and the average costs of the initial construction project.

$$NPV_j = \sum_{t=0}^{t=T} \frac{Benefits - Costs}{(1+\delta)^T} \quad (2.7)$$

$$NPV_j = PV_{total_j} \cdot \omega_j - \sum_{t=0}^{t=50} \frac{\phi_N \cdot \frac{V_{N\,j} \cdot E_N}{T} \cdot CS_N}{(1+\delta)^t} \quad (2.8)$$

Table 2.6 - Benefit-Cost Input parameters

Symbol	Symbol Name	Value	Reference
PV_{total_j}	Cumulative Assessed Value of community *j*	~\$0.88B - ~\$5.16B	Ocean County Sr1a Data
ω_j	Total WTP for a “540-Rule” dune of a beachfront community *j*	1.34% - 20.71%	Table 3 results
ϕ_N	Variable and Fixed 2016 Sediment Costs (\$/m^3)	\$22.06/m^3 (adjusted for 2018)	ASBPA APTIM National Beach Nourishment Database
$V_{N\,j}$	Estimated Nourishment Volume Demand (m^3) for beachfront community *j*	1,529,110m^3 (by ratio per community, per distance alongshore for the entire project length)	USACE 2014, Weeks Marine, Google Earth Pro
E_N	Estimated Number of Nourishment Episodes	7	Sandy Recovery Improvement Act, 2013 (113th US Congress)
CS_N	Renourishment Local Cost-Share	12.5%	Sandy Recovery Improvement Act, 2013 (113th US Congress)
T	Project Lifetime Horizon	50 years	USACE 2014
δ	Discount Rate	~7%	USACE 2014

As a result, if our input parameters in Table 7 were to remain stable throughout the project’s 50-year time horizon, the typical stakeholder within the entire project would collect a yearly average NPV on their property (p) of \$1,160/yr/p: *SB* = \$2,075/yr/p, *LBT* = \$250/yr/p, and *BH* = \$4,050/yr/p, respectively. We can link these results harmoniously with Kolodin et al.’s (2021 *accepted for publication*) study pertaining to a property’s *NPV*, per meter of alongshore beach (\$/y/m): *Project-Wide* ≈ \$500/yr/m, *SB* ≈ \$1,275/yr/m, *LBT* ≈ \$100/yr/m, and *BH* ≈ \$1,650/yr/m, respectively. These values are expressed as a collective social benefit for the community, even as property transfers may occur throughout the project’s lifetime.

Our results from Equation (2.8) demonstrate specifically how ω-values play a crucial role in maintaining highly positive *NPV*s in the future, while current property values can only sustain these positive values until a cost-volume threshold is reached. We can use this modeling tool to explain potential outcomes for a wider range of communities, based on their anticipated fluctuations in future assessments of property values. Where ω-values are not yet well understood for communities with newly installed “540-Rule” dunes, we can explore how the *NPV* of a community is affected by changes in both renourishment costs ϕ_N and ω-values at the lower end of the spectrum. For reference, a study by McNamara et al. (2015) considered the possibility for renourishment costs to double, and potentially quadruple, as locally available sediment resources become more limited. Furthermore, we explore these outcomes for two geomorphic conditions by using a set of applicable mock-values for the economic parameters in Table 4, where V_N=60m^3/m and V_N=300m^3/m (Figure 2.3)[3].

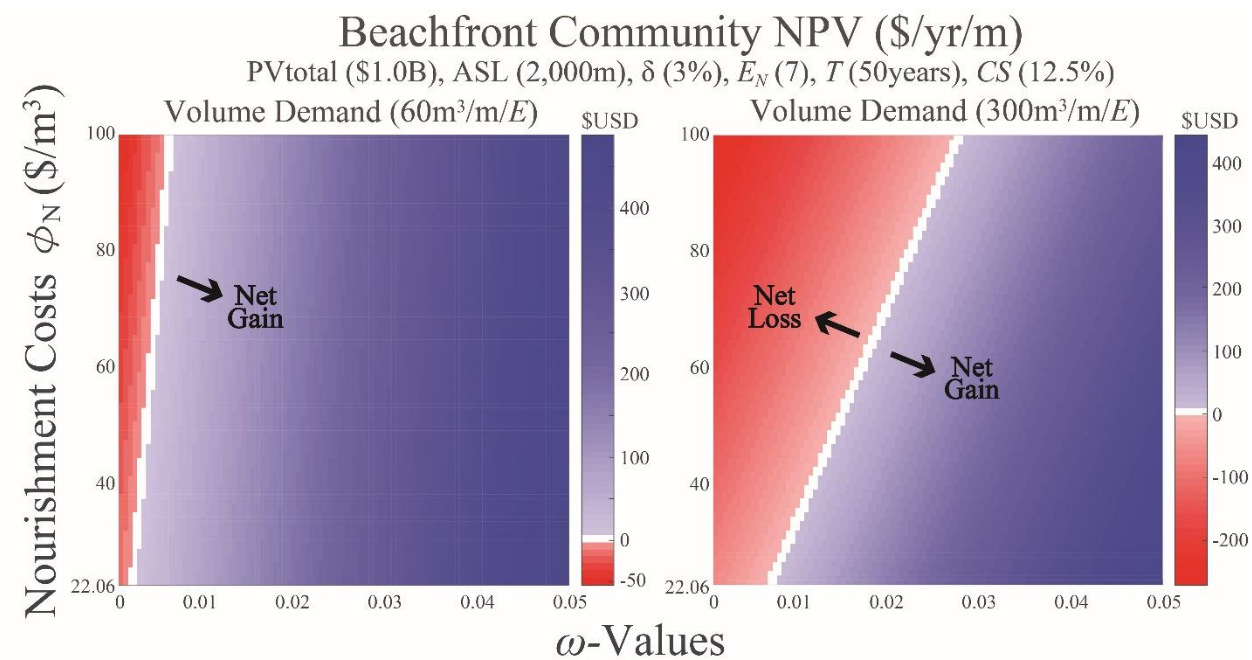

Figure 2.3 - Beachfront community stakeholder’s average NPV ($/yr/m) for a mock-community, with changes in nourishment costs ($/m3) and overall value towards protection ω, over the project’s 50-year time horizon.

2.7 Conclusions

[3] The changing parameters used in Figure 2.3 represent a scenario where volume demands V_N for seven future nourishment events range from the USACE 2014 feasibility report estimations (V_N=60m^3/m/E_N) to an upper limit roughly calculated when assuming the entire dune was destroyed during an overwash event (V_N=300m^3/m/E_N).

This paper helps demonstrate the relationship between local beachfront property values and the added protection a constructed FEMA "540-Rule" dune offers to the local community. Our model results also strengthen the connection between our first-order θ-value estimations (Appendix Table A.2) and our constrained ω-values (Table 2.3), validating the effectiveness of a back-of-the-envelope approach to estimate unknown hedonic values favoring protection. The measured WTP by the average stakeholder can significantly improve the net benefit received throughout the project's lifetime.

Using a quantified range of ω-values found within our multilinear regression analysis, we can show in Figure 2.3 how potential increases in sediment costs and volume demands alongshore will force communities with lowered benefits (driven by smaller ω-values) to experience net losses throughout the lifetime of this 50-year project. Furthermore, if some adjacent communities behave more myopic than hyperopic, the collective results would fall beneath the feasibility realm of sustaining a positive net benefit as costs and volume demands increase over time. This effect was evident in our study when *LBT* did not value the protection offered by dune construction compared to their neighbors *SB* and *BH*.

The evolution of housing characteristics described in Tables 2.4 and 2.5 expose how the three adjacent LBI, NJ communities are placing an emphasis on the way risk and vulnerability are becoming an important component amongst stakeholders. Although, it is still unknown the exact causes of this, shifting local policies may be the direct culprit for these shifting behaviors observed after dune construction in 2017. As similar coastal communities continue to endure larger-scale and more frequent storm events, we may see an increasing transfer of residents from primary homeowners to more secondary homeowners with less whole-equity to lose. This behavior may prompt a more myopic response in the long-term, potentially affecting the discount rate at the local level. Coastal community management will continue to adapt to the ever-changing environmental pressures, ultimately, until the last-resort option of managed retreat becomes an inevitable factor.

While the model can quantify a community's long-term feasibility to maintain a positive net benefit, there still exists a wide selection of unknown variables, specifically how a community will respond to a changing environment. With increasing storm intensity and frequency, communities may act heavily in favor of maintaining their protective dune structures, regardless of their current status (Kriesel et al. 2000; Gravens et al. 2007; Eckel et al. 2009; Turner 2012; Cameron and Shah 2015; Leichenko et al. 2015; Dundas 2017, Kolodin et al. 2021 *accepted for publication*), prompting a systematic increase in their ω-value. Whereas, given circumstances in which a decadal scale lull in storm activity occurs, ω-values may instead decrease. These behaviors are nearly impossible to predict. Therefore, it is imperative to monitor the cost-side of our *NPV* Equation (2.8). For instance, if a particular beachfront community can monitor their local rate of erosion, along with knowing their fully available offshore resource stock, they can back-calculate the required capital growth needed to maintain a positive *NPV*, similar to the approach used for our θ-estimations (Equation (2.3)). Armed with this critical information, managers may choose how to address their shifting needs to raise future budgets, either via a municipal tax increase, or through a property value-readjustment approach seen in this paper, where tax assessors of *Ship Bottom* and *Beach Haven* raised the assessed property values following the installation of a protective dune. Additionally, facilitating local management with a useful tool to calculate their changing needs in the future will provide a better path towards a more cooperative outlook amongst adjacent beachfront communities. Thus, the development of a graphical user interface, combined with an efficient way for beachfront communities to measure their localized erosion rate in order to maintain positive *NPV*s in the long-term are important subjects for future research.

CHAPTER 3 – A DECISION SUPPORT TOOL TO ASSESS THE FEASIBILITY OF ENGINEERED DUNE CONSTRUCTION AND MAINTENANCE BY COASTAL COMMUNITIES

3.0 Summary

As the rate of sea-level rise, storm frequency, and their related impacts of berm-dune erosion along the Mid-Atlantic region of the United States increase, the potential inabilities for highly-developed beachfront municipalities to acclimate financially to these changes in a timely manner are becoming more evident. A large number of beachfront communities may not be able to keep pace with potential increases in costs associated with these natural external factors of erosion, particularly as state and federal funding decreases. This situation may lead towards potential losses in property value as development becomes more easily exposed to future storm-surge events. To address the question of whether or not a beachfront community can afford their cost-share of berm-dune renourishment in the future, we develop a decision support tools as a graphical user interface that integrates geologic and economic information with our process-based framework in relation to the tangible municipal budgets (i.e., municipal tax rates) for a particular community. Due to uncertainty of future rates of erosion and sediment volume demands, this may prompt coastal communities to shift their risk-perceptions accordingly, by building towards more resilient future. To further advance our understanding of the morphodynamic system, we can measure a community's rate of berm-dune erosion using high-precision remote sensing techniques (i.e., photogrammetry and LiDAR). Although, this continues to present a challenge when estimating sediment demands over future decades, seasonal monitoring will provide more insight in the system's evolution and provide the graphical user interface an opportunity to refine its results. In addition, we consider a threshold condition based on an engineered dune's geometric design, where a community should renourish their berm-dune system to meet the adequate protection strategies originally in place. Ideally, this information can serve as input values for our decision support tool, helping decision maker's budget optimally for their potential costs and timeframe for the next renourishment event.

3.1 Introduction

Developed coastal communities along the Mid-Atlantic region of North America (USA) face a continuous struggle to adapt their mitigation strategies in response to the increasing threat of sea-level rise combined with intensifying storm activity (Titus et al. 1991; Yohe et al. 1995; Yohe and Schlesinger 1998; Valverde et al. 1999; Psuty and Ofiara 2002; Landry et al. 2003; Titus 2009; Lazarus et al. 2011; Hapke et al. 2013, Fallon et al. 2017; Beasley and Dundas 2018). Following the disastrous effects of storm overwash and inundation from Hurricane Sandy in 2012 (Halpin 2013), the State of New Jersey responded by fortifying their developed beaches with engineered berm-dune structures (Johnston et al. 2014, Kolodin et al. 2021 *accepted for publication*). The goal of adding engineered dune systems (Figures 1.1 and 1.2) is to protect the adjacent private and public infrastructure (e.g., properties, commercial real estate, boardwalks, roads, pipelines, communications, etc.) from future storm events. Initially, the projects were entirely funded from the U.S. 113th Congress's in 2013 (i.e., The Sandy Recovery Improvement Act). However, the challenges facing these beachfront communities is whether they will have enough cumulative budgeting for their 12.5% cost-share portion (Bates 2015; O'Neil 2015) for periodic maintenance (i.e., beach renourishment) in the long-term. Thus, looking to the future, beachfront communities will more likely be unwilling to bear the costs of coastal protection.

Engineered berm-dune systems provide both recreational and protection benefits (Dundas 2017; Marcus 2017, Kolodin et al. 2021 *accepted for publication*), where a continuous stream of benefits from tourism and coastal living are met with a reduction in the potential damage costs related to storm impacts for the community stakeholders (USACE 1999; USACE 2014). Without the proper municipal budget for maintenance, a local beachfront community may fall short in regards to future berm-dune renourishment projects (Kolodin et al. 2021 *accepted for publication*).

In this regard, a simple benefit-cost analysis can calculate a particular beachfront community's net present value *NPV*, based on a number of geomorphic and economic variables. To assist in helping New Jersey managers adapt to the various challenges brought about by shifting natural conditions (Ahn and Ronan 2021) along the state's shoreline (e.g., storm-related impacts, shoreline erosion, inundation, overwash, etc.), a decision support tool that includes both economic and geologic parameters (Figure 3.1) would be a valuable asset to better plan for future coastal risk management strategies (Zanuttigh et al. 2014). Furthermore, the development of a graphical user interface (GUI), based on the variables used in the decision support tool, can provide local, county, and state officials with various options on how to reform their current budgetary status, in reference to a cost-benefit algorithm. For instance, when communities do not appropriately budget for future renourishment events, this can place a greater burden on the state government's long-term ability to allocate adequate funding for those communities in need, especially in the wake of emergencies (Moore 2016).

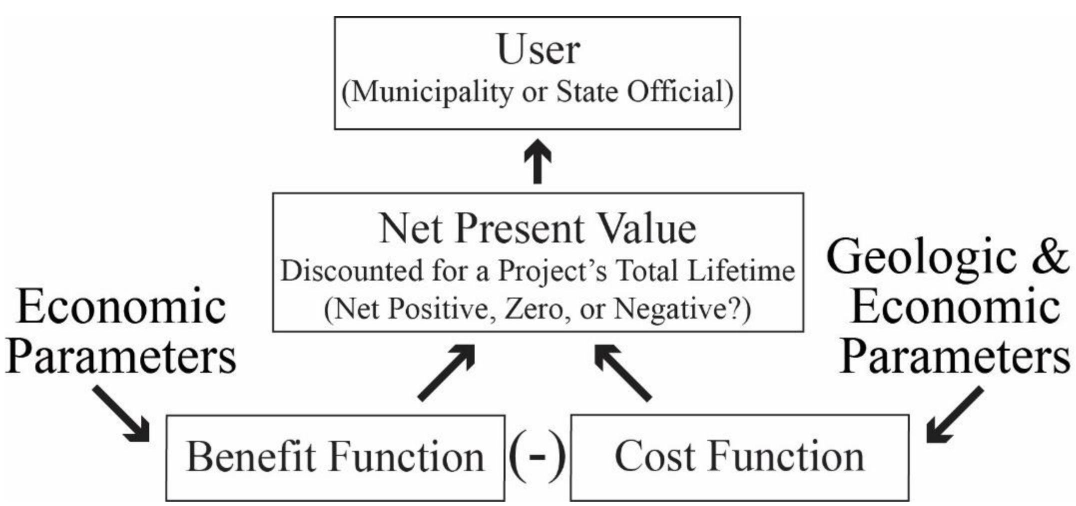

Figure 3.1 - A simple decision support tool for coastal communities based on a cost-benefit analysis.

The objectives of this study develop a multifaceted decision support tool to assist the local and state governments on how to better prepare for future resiliency measures. More specifically, a tool that can inform local and state governments about how to budget for future renourishment episodes. As government officials seek effective strategies to bridge the communication gap between coastal science, policy, and local action, this reinforces the need for a method of cost-benefit analysis is necessary to ensure the protection and longevity of these coastal communities (Kolodin et al. 2021 *accepted for publication*). We use remote sensing tools (i.e., unmanned aircraft systems) to quantify changes to the local sediment volume budgets, including monitoring the berm-dune evolution to inform the local communities when "540-Rule" dunes become compromised. These novel approaches will provide insight for beachfront communities willing to adapt to a changing climate.

3.2 A Decision Support Tool for Municipal Risk-Management Strategies

The parameters used in our decision support tool are associated to the local municipality's economic and geologic conditions (Figure 3.2). In addition, the tool is adapted as a GUI, where decision-makers record the seasonal and storm event-based sediment losses to erosion V_N-values, including additional geologic and economic parameters related to costs. The GUI's algorithm works using a cost-benefit framework as described by Equation (3.1), where storm-related impacts influence changing cost variables, allowing the benefit-side of the function to readjust in order to produce the adequate result, based upon the user's *j* choice. As a result, the algorithm determines the net benefit, loss, or equilibrium at that point in time. For more information about this GUI app and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

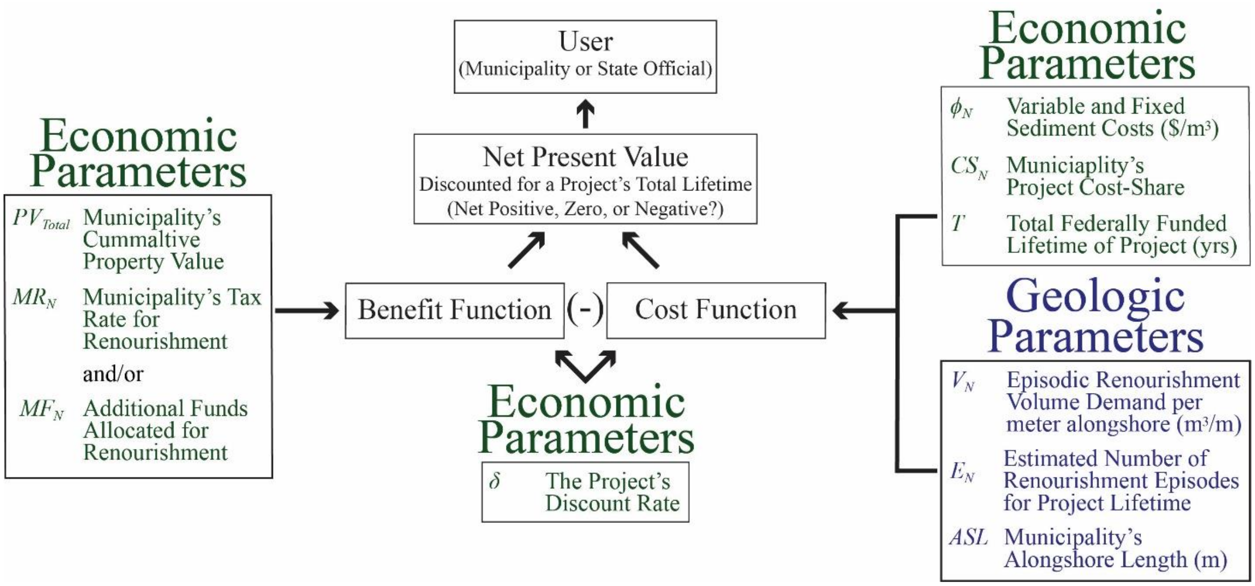

Figure 3.2 - Flow chart of the graphical user interface (GUI) used to produce an optimal risk-management response.

$$NPV_j = \left(\sum_{t=0}^{t=T} \frac{PV_{total_j} \cdot MR_{N_j}}{(1+\delta)^t}\right) - \sum_{t=0}^{t=T} \frac{\phi_N \cdot \frac{V_{N_j} \cdot E_{N_j}}{T} \cdot CS_N}{(1+\delta)^t} \tag{3.1}$$

Typically in New Jersey, beach renourishment events are a result of emergency management measures (Haddad and Pilkey 1998; Psuty and Rohr 2000; Hoagland et al. 2012), ensuring the stabilization of the local economies that rely heavily on beach tourism. Therefore, the GUI will be able to adjust to the average geomorphic volume requirements related to the cumulative impacts of substantial sediment erosion from storm events V_N before the end of the project's federally funded lifetime T.

As Earth's climate is constantly changing, coastal storms are expected to increase in intensity and frequency (Emanuel 2010; Emanuel 2013; Kirshen et al. 2020). In addition, as sea-level rise accelerates, the rates of erosion to the shoreline are bound to increase the demand for sediment volume, including the variable and fixed costs associated with future renourishment episodes. Looking at the past 70 years of renourishment episodes along Long Beach Island (LBI), NJ, the data exhibits increases in sediment costs ϕ_N (\$0.16/m^3/yr) in Figure 3.3, with costs adjusted to 2018 USD. Renourishment demands have also witnessed a drastic change (Figure 3.4), as shoreline geometry in recent decades has added a substantial amount to the overall sediment budget. Additionally, in some places, the shoreline position has extended approximately 30m-40m in the seaward direction since dune construction took place (Figure 3.5), potentially exacerbating the issue of erosion.

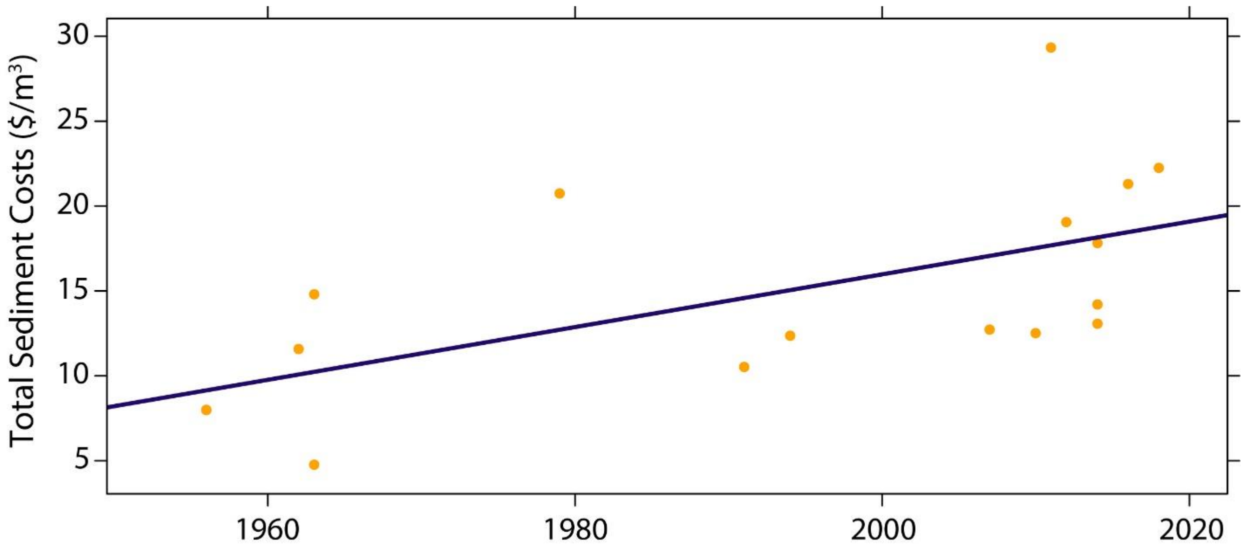

Figure 3.3 - Variable and fixed sediment costs ϕ_N (\$/m^3) over time, adjusted for 2018 dollars (1954-2018), for all of LBI, NJ.

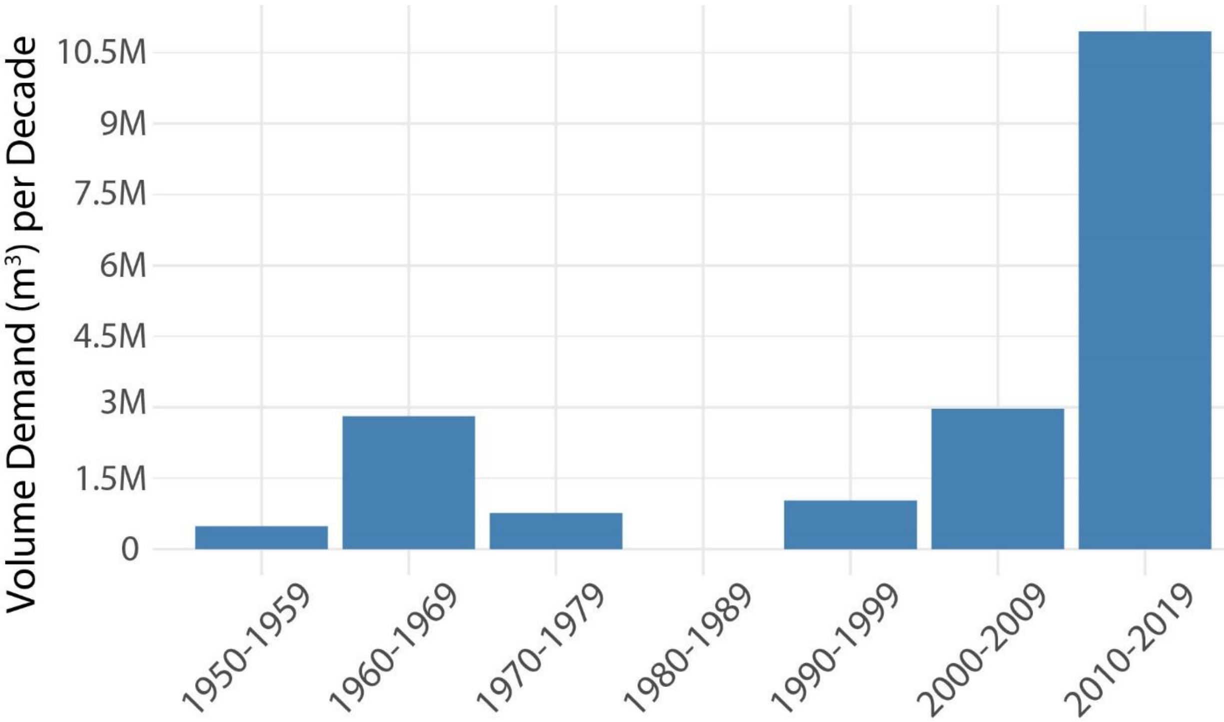

Figure 3.4 - Sediment volume demands V_N (m^3) over time, per decade (1954-2018), for all of LBI, NJ.

Figure 3.5 - Plan view of shoreline extension from 2016 to 2017 (looking north), after "540-Rule" berm-dune installation within Long Beach Township (LBI), NJ (Google Earth Imagery 2021).

Furthermore, as local offshore sediment supplies dwindle, costs could rise to unprecedented levels, considerably impacting a stakeholder's yearly net benefit in the future. According to the USACE's 2014 feasibility report of available dredge material immediately off-shore LBI, NJ, the remaining offshore "borrow" site deemed for dredging beyond 1999 (e.g., D1) did not contain enough material to complete the homogenous 2016 FEMA "540-Rule" project design (Figure 3.6). After a thorough investigation using core analyses of five potential candidate borrow sites, they concluded only one (e.g., D2) was adequate for dredging purposes, just east of the original borrow site. More specifically, the D2 borrow site contained 18.5 million cubic yards (mcy), 4.9mcy of which was needed to complete the initial project, leaving approximately 13.6mcy for future renourishment cycles (USACE 2014). This threshold is below the suitable requirements estimated for the project's 50-year lifetime; i.e., for seven episodes at 2 million cubic yards per episode (e.g., ~1.5 million cubic meters). Therefore, we make the case for how our GUI's geologic and economic parameters are influenced by external factors such as these.

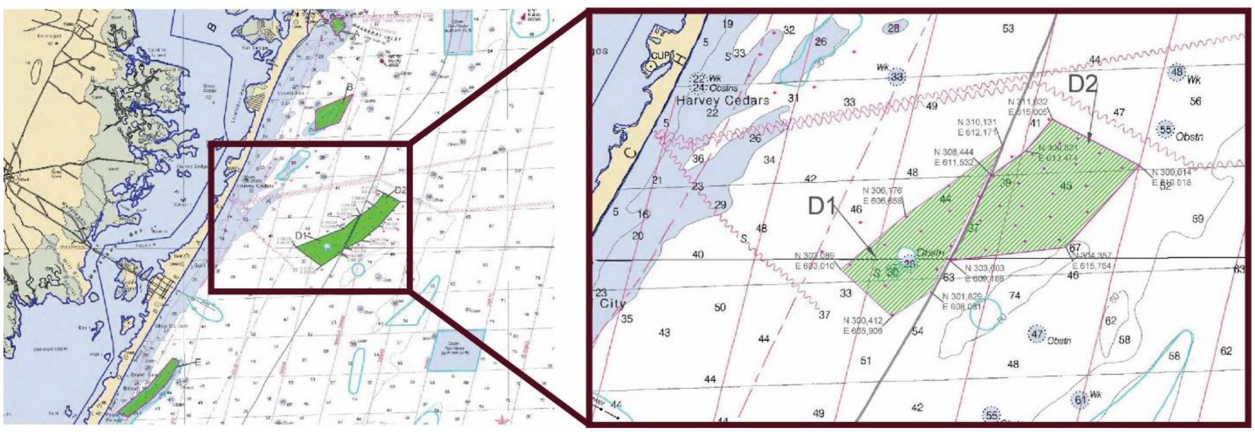

Figure 3.6 - USACE 2014 Feasibility Report showing the location of borrow sites D1 and D2.

3.2.1 Geologic Parameters

The geologic parameters include the community's alongshore distance *ASL*, the time lag between storms associated with renourishment events E_N, and volumetric demands for sediment to recover the losses from erosion V_N (Table 3.1).

Table 3.1 - Geologic parameters introduced in the GUI (Figure 3.2)

Symbol	Symbol Name	Units
V_N	Episodic renourishment volume demand per meter alongshore distance	m^3/m
E_N	Estimated number of renourishment episodes for project lifetime	
ASL	Municipality's alongshore distance	*m*

3.2.2 Economic Parameters

The economic parameters include the benefit, which is a function of the community's total property wealth PV_{Total}, their municipal tax rate associated with beach renourishment MR_N, (if they choose instead) their annual line item budget for beach renourishment MR_F. The cost function includes the cost of a cubic meter of sediment during renourishment episodes ϕ_N, the town's cost-share percentage of the episode CS_N, the time left of the project T, and the associated discount rate δ, which also applies to the benefit function (Table 3.2).

Table 3.2 - Economic parameters introduced in the GUI (Figure 3.2)

Symbol	Symbol Name	Units
PV_{Total}	Municipality's cumulative property value	*$*
MR_N	Municipality's tax rate for renourishment	*%*
MR_F	Municipality's additional funds allocated for renourishment	*$*
ϕ_N	Variable and fixed sediment costs	$\$/m^3$
CS_N	Local cost-share	*%*
T	Total federally funded lifetime of project	*Years*
δ	Discount rate	*%*

In addition, the user can input their current budgeting status in different ways, either using the yearly revenue based on a fraction of the total town's cumulative property wealth related to the renourishment budget $PV_{Total} \bullet MR_N$, or the line-item budgeted annual dollar amount that goes toward beach renourishment MR_F. In this regard, the benefits are adjusted to either meet or outweigh the required future costs, while incorporating a time lag for the average renourishment event E_N (driven by an emergency response to a storm event).

If the GUI's user wants to maintain a positive *NPV*-value, this indicates they currently have enough funding to adequately afford a renourishment event. When the output is negative, the user can simply determine how to reform their budgeting status, by either raising their MR_N-value or MR_F-value accordingly. This method helps the user meet either an equilibrium state or net positive budgeting scenario, depending on how they want to amend their annual audit.

Ultimately, the end user can choose to either budget through an optimistic lens (i.e., maintaining an equilibrium or net positive scenario), pessimistic (i.e., decreasing the budget to allocate money elsewhere), or business as usual (i.e., unchanged budget). These divergent scenarios are related to community preferences when coastal protections are put in place and shown to be effective (Kolodin et al. 2021 *accepted for publication*). In an optimistic scenario, when stakeholders are witness to the adequacy of protection the municipality as a whole would tend to favor future maintenance (Kriesel et al. 2000; Gravens et al. 2007; Eckel et al. 2009; Turner 2012; Cameron and Shah 2015; Leichenko et al. 2015; Dundas 2017). Pessimistically, a lull in storm activity would shift the value towards protection inversely (Leichenko et al. 2014), where cumulative beach renourishment budgets continue to grow and not be used, community managers may favor either reducing future budgets or reallocating the money elsewhere. On the other hand, communities who have yet to experience a single storm event after a new resiliency project was put in place, such as the FEMA “540-Rule” berm-dune design currently being installed along the shorelines of New Jersey (USACE 2014), may not choose any option and continue with their current beach renourishment budgets.

As the number of future storm-related events potentially increase, this will prompt a higher frequency in renourishment events E_{N_j}, additionally increasing the demand of volume required over the project’s lifetime V_{N_j}, ultimately increasing costs. This intuition derives from what we term as stakeholder risk-perception, where the local residents respond to the frequency of storm activity. For instance, if storm frequency and intensities increase in the future, as noted, this will create a situation where the average volume demand V_{N_j} and the frequency of renourishment episodes E_{N_j} increase. This situation further compounds the issue of maintaining adequate protection through time, thus requiring a sufficient response in order to maintain a stable municipal budget.

Among New Jersey beachfront communities, we consider a cause and effect scenario that is common amongst other U.S. mid-Atlantic coastal communities, where the construction of a protection strategy and increasing development proceeds (Gaul 2019). There is evidence that suggests a positive correlation between engineered berm-dune construction and redevelopment occurs (Gaul 2019), including the increase in average property value (Kolodin et al. 2021 *accepted for publication*). Furthermore, continuous redevelopment following a protection project (i.e., engineered berm-dune systems) only escalates the socioeconomic vulnerability from future storms (Lazaraus et al. 2021), so long as these coastal protection strategies are not well-maintained in the future. Therefore, how can municipalities plan their budgets accordingly to maintain protective structures while meeting their growing socio-economic statuses?

3.3 Discussion and Conclusions

3.3.1 Long-Term Effects on Municipality Budgets from Dune Construction

It is evident that the potential economic and geomorphic changes to the shoreline can have major impacts on a municipality's future renourishment budget. Furthermore, as municipal tax assessors gauge the volumetric demands V_N moving forward (a proxy of berm-dune erosion) they may want a better idea of these seasonal and yearly changes, especially in the wake of major storms, so to raise more of the town's overall budget in order to maintain a net zero state or positive condition (i.e., an optimistic scenario). For instance, the municipality's current tax revenue reserved for berm-dune renourishment MR_{N_j} is a ratio of the money budgeted in comparison to the community j's total cumulative property values PV_{total_j}. In essence, our benefit function is the tangible revenue stream that is budgeted for future renourishment costs, where we assume variables remain stable throughout the project's 50-year lifetime; similar to that of the "540-Rule" dune project (Equation (3.1)).

We can consider a representative community with a particular fixed set of parameters from our GUI (Table 3.3). Using these values, we study how the "geo-economic" parameters affect the feasibility of a community's ability to maintain an engineered dune as cost variables ϕ_N and V_N increase (Figure 3.7). Additionally, as a community's MR_N-value increases (0.005%-0.05%) it becomes more feasible for communities to ensure a stable budget in the future, either within an equilibrium net zero state or net positive scenario. For more information about this data table and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

Table 3.3 - Fixed input parameters for a representative beachfront community with "540-Rule" dunes

Symbol	Symbol Name	Value	Units	Reference
PV_{total_j}	Cumulative Assessed Value of community	$1 Billion	*$*	Exploratory
σ	Percentage Change to Benefit (unchanged)	1		Exploratory
ASL	Alongshore Beach Length	2,000	*m*	Google Earth Pro
E_N	Estimated Number of Renourishment Episodes	7	*events*	Sandy Recovery Improvement Act, 2013 (113th US Congress)
CS_N	Renourishment Local Cost-Share	12.5%	*%*	Sandy Recovery Improvement Act, 2013 (113th US Congress)
T	Project Lifetime Horizon	50	*years*	USACE 2014
δ	Discount Rate	3	*%*	Exploratory

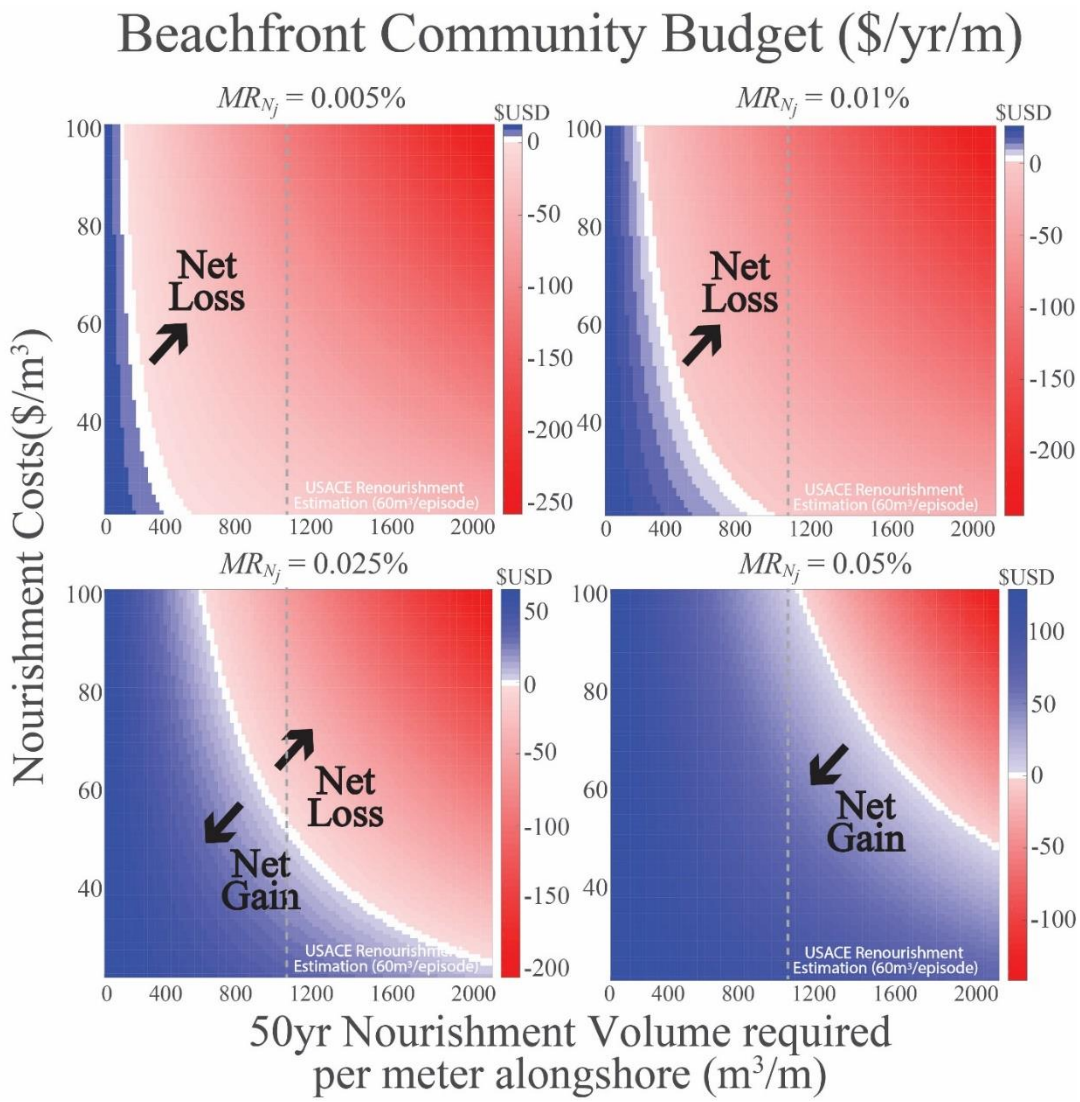

Figure 3.7 - Beachfront community stakeholder's average yearly budget alongshore (*$/yr/m*) for a mock-community with different MR_{N_J}-values (0.005%-0.05%), including changes in renourishment costs ϕ_N (*$/m^3*) and volume demands V_N (*m^3*). Fixed input parameters (Table 3.3).

3.3.2 Measuring Beachfront Community Budgetary Resiliency

Existing policy reforms in the State of New Jersey have not adequately addressed the ever-changing geomorphic conditions currently being witnessed at the shoreline (e.g., background erosion rates), especially at the municipal level where these local changes are not well understood (Hoagland et al. 2012). Furthermore, not having the ample knowledge of the related costs for periodic renourishment projects only compounds the problem. The decision support tool does present various limitations, specifically those geologic parameters where long-term data is not supported (e.g., V_N and E_N). In hindsight, these limitations can be resolved by monitoring these berm-dune systems through time. The use of remote sensing methods, such as lost-cost unmanned aircraft system (UAS) technology attached with various high-resolution sensors, such as RGB and Light Detection and Ranging (LiDAR), can fulfill this task.

Both RGB and LiDAR technology have the abilities to reveal precise topographic elevation *z*-values relative to the shoreface elevation, where we determine which method is the most efficient and effective at the regional scale. For instance, a technique called Structure for Motion (SfM) is able to quantify volumetric changes due to erosion V_N seen along berm-dune systems (Lentz et al. 2017, Brodie et al. 2019, Laporte-Fauret et al. 2019). The ultimate goal for future research is to compare and contrast both methods to effectively reduce our resolution error, or ground sampling distance (GSD). Essentially, our GUI's algorithm can use both the spatial and elevation data to reveal detailed changes to the berm-dune volumes. Furthermore, if local decision-makers were presented quantifiable information about these geomorphic and economic fluctuations, they could use our GUI tool (Figure 3.2) to budget their anticipated municipal funds more appropriately. The added advantage of using UAS technology is the ability of establishing a feasible alongshore monitoring program, specifically a seasonal and storm event-based monitoring one for local communities hit the hardest by erosion.

Our decision support tool, combined with an established monitoring program has the capabilities of providing important detailed information for local community managers. It is important to note that when early in the protection strategy's lifetime, the user does not have to consider how many years in the future they will need to budget for the next natural disaster, where they have to renourish just after. The monitoring program we have proposed in this study merely suggests keeping a watchful eye on the evolution of the dune's frontal crest D_C, in relation to the critical threshold position D_{CT}. Once the D_{CT} point is breached, the dune has effectively lost its adequate protection value, and this is when the accumulated budget acquired in the years before are spent. To further conceptualize how a town would be able to react to a double-whammy situation where two major storms occur back-to-back, and two renourishment events happen in a very short amount of time, the assumption is that future tax revenue generation can make up for any debt accrued during that time. As the rates of the geologic and economic parameters increase, so should the budgets. If the geo-economic rates remain steady, or stall for whatever reason, the budgets should continue to match or exceed the most extreme scenarios previously witnessed in the local area.

Previous research has employed similar high-resolution UAS technology to identify particular berm-dune geometric features such as the shoreline position S, dune toe D_T, and dune crest D_C (Elko et al. 2016, Sturdivant et al. 2017, Doyle and Woodroffe 2018, Laporte-Fauret et al. 2019, Beuzen 2019, Brodie et al. 2019, Smith et al. 2020). For our study, we can add a boundary feature by selecting a particular critical threshold point located on the dune crest D_{CT} (Figure 3.8). The intention of identifying this location can direct a local beachfront community with an engineered dune to consider investing in a berm-dune renourishment project (or E_N in our GUI). To do this, we consider the geomorphic evolution of a "540-Rule" dune's trapezoidal geometry (Figure 1.2), and more specifically, spatially track the 540ft^2 sand reservoir that sits perched on top of the 100-year SWFL. For reference, the top section of the trapezoid extends halfway through the ~30ft dune crest (Figure 3.8). Furthermore, the engineered dune is designed for allowing periodic scarping to the frontal dune toe, until the reservoir becomes compromised (i.e., when the frontal dune crest position exceeds the original halfway mark, or what we can the dune crest critical threshold value D_{CT})[4]. In this regard, we assume the dune's foredune slope will continuously meet a repose position as storm erosion erodes the foredune (USACE 1999, Durán and Moore 2013, Charbonneau and Casper 2018, Hallin et al. 2019, Smith et al. 2020).

Figure 3.8 - Example of a "540-Rule" dune's critical threshold location following a dune scarping event (Bay Head, NJ).

When referring back to the GUI, if a beachfront community chooses to know when they will need to spend their accumulated budgets reserved for berm-dune renourishment, they can use visual observations from UAS point-cloud data to spatially locate the ~15ft critical threshold value of the dune crest D_{CT}. We present an example in Figure 3.9 as a DEM, where the boundary locations of a berm and natural dune (S, D_T, D_C, and D_{CT}) are easily identifiable. To note, Figure 3.9 represents a natural dune system and the natural geometric setting does not represent a

[4] Dewberry and Davis (1985) estimates that the FEMA "540-Rule" sand reservoir provides adequate protection from most major storm surge impacts, residing above the 100-year still water flood level (SWFL), at an estimated height of ~22ft (~7m), and extending ~15ft (~9m) into the dune crest. Therefore, as the dune's foredune (i.e., frontal) crest meets the halfway mark of the total trapezoidal crest; it essentially meets the critical threshold D_{CT} value before the dune's protection value becomes compromised.

trapezoid, representative of an engineered dune. Therefore, we simply display all boundary conditions to visually show how a manager would this situation.

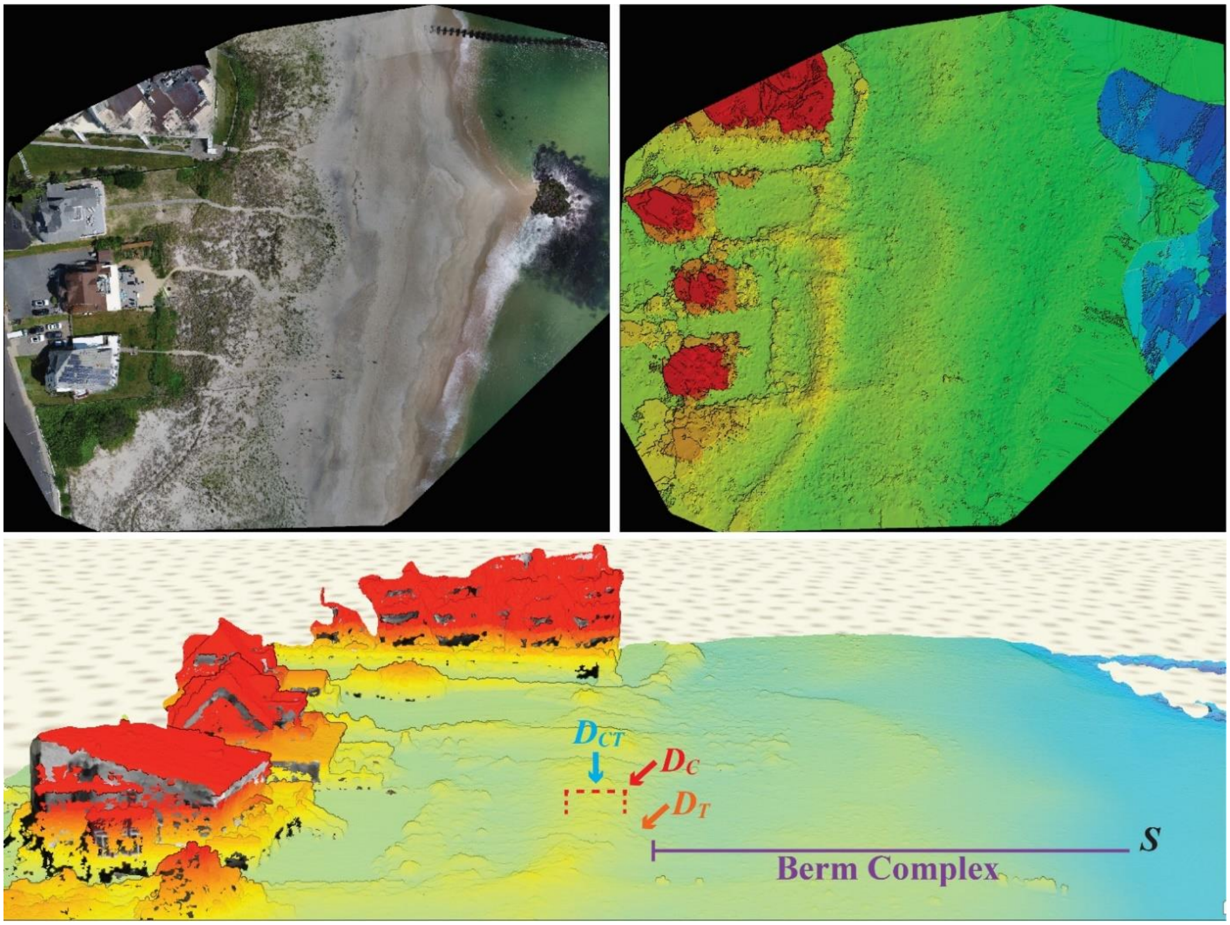

Figure 3.9 - Orthomosaic image (Top-Left), the corresponding Digital Surface Model (DSM) (Top-Right), and Oblique DEM (Bottom) created using SfM (Location: Long Branch, NJ – North End).

Recently, the beachfront community of Bay Head, NJ experienced severe erosion of their newly constructed FEMA "540-Rule" berm-dune system, occurring mainly from a single-season onslaught from multiple high-intensity nor'easters (Figure 3.10). Mikle (February 2021) explains how the beachfront community's immediate response was to seek emergency funds to pay for renourishment to the severely scarped dune features, signaling a potential limitation in available funds appropriated from the town's budget. Ultimately, the initial request to the federal government was shut down; as the justification suggested that, the rotation period of renourishment events would have been too close in time. Moving forward, this situation could encourage a town like Bay Head, NJ to increase their municipal budget that goes towards future renourishment projects. Correspondingly, if beachfront communities were to experience a lull in storm activity, a decreased sense of immediate risk may lead to a decrease in the town's overall budget for renourishment moving forward, also totally arbitrary and unknown to the political influence in the future.

Figure 3.10 - Bay Head, NJ berm erosion and dune scarping (Doug Hood February 4, 2021 – Left and Mikes Davis & Thomas P. Costello February 5, 2021 – Right).

Varying risk-perceptions of local stakeholder's can be interpreted as a direct relationship associated with changes in the town's annual budget for beach renourishment MR_F, or the fraction of the town's cumulative property value MR_N, however they choose. Using the GUI tool, we construct the measure of property value benefit as a function of the berm-dune volumetric changes between average renourishment episodes. The beachfront LBI, NJ communities studied in Kolodin et al. (2021 *accepted for publication*) all seem to have budgetary line items directed towards beach renourishment, which since 2013 have not changed, even when assessed values increased following dune construction in 2017 (Table 3.4). Therefore, the MR_N-value would have decreased accordingly, as the annual budget per meter alongshore (*Budgets$/yr/mAS*) did not (Figure 3.11). This raises a fundamental problem with the way some beachfront communities may be going about budgeting for their future berm-dune maintenance. As the rate of erosion increases due to the acceleration of natural external forces that are the cause, shifting budgets should also be taken into consideration. It is clear these municipalities do value the protection gained from the installation of an engineered dune, but there is a fundamental disconnect from the mitigation of socioeconomic risk. Of the three communities, Ship Bottom is the farthest from contributing a sustainable budget at $6,000/year, Beach Haven $100,000/year, and Long Beach Township $500,000/year. Regardless, all communities in that study seem to be far off from being able to contribute to their 12.5% local cost-share. A substantial policy reform would need to be established at some point moving forward. The New Jersey Department of Environmental Protection’s (NJDEP) Shore Protection Master Plan also underlines the addition of countywide funding that also supports beach renourishment practices. The percentage amount of a certain community’s cost-share though is arbitrary, but does have tangible benefits, which are key subjects of future research (NJDEP 2020). For more information about this data table and other data references/codes, please refer to the corresponding GitHub repository (https://github.com/KolodinJesse).

Table 3.4 - Aggregate PV_{total} for LBI, NJ Communities

Audit Year	2013	2014	2015	2016	2017	2018	2019
Ship Bottom	$1.10B	$1.10B	$1.12B	$1.14B	$1.31B	$1.32B	$1.31B
Long Beach Twp	$7.58B	$7.61B	$7.70B	$7.78B	$7.85B	$7.91B	$7.99B
Beach Haven	$1.65B	$1.66B	$1.67B	$1.68B	$2.07B	$2.08B	$2.10B

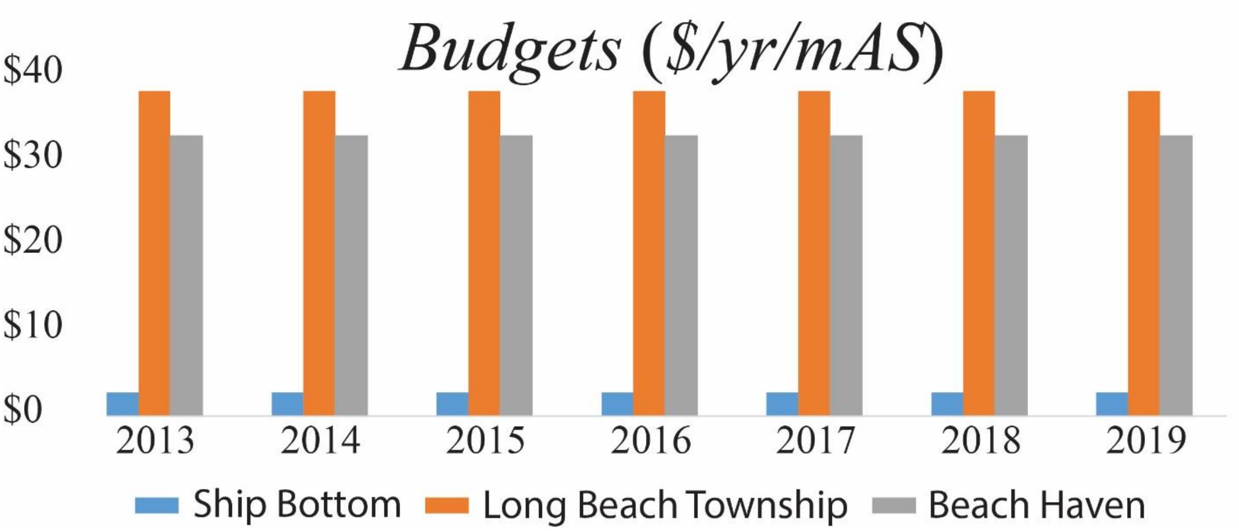

Figure 3.11 - Aggregate annual municipal budgets per year per meter alongshore for the town Budgets (*$/yr/mAS*).

3.3.3 Future Work and Potential Caveats

The additional tax revenue generated through such a change would allow the municipality to budget, and therefore, continuously sustain adequate local cost-shares for future renourishment projects. Not only is this an adequate tool for the local municipalities, but a better way for the state government's departments to effectively monitor the local progress being implemented at the local-level, especially those communities keen on building a more resilient future along the coast. As beachfront communities continue to plan for future resiliency projects, the verified outputs by the GUI tool proposed in this paper can help guide officials on how to manage their budgets moving forward.

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APPENDICES

Chapter 2 Appendix A.1 - Comparing a 1st order estimation approach and HPM to measure a beachfront community's marginal price elasticity

We incorporate a previously similar "geo-economic" framework (Kolodin et al. 2021 *accepted for publication*), using the benefit function that explains how a beachfront community's property value responds to the protection gained from the installation of a "540-Rule" dune (Equation (2.2)). In addition to measuring dune benefits, we can incorporate past research focused on the positive relationship that coastal berm-renourishment strategies have had on local property values (Gopalakrishnan et al. 2012, Hoagland et al. 2012, etc.). Furthermore, it is speculated that the installation of a "540-Rule" dune had an instantaneous positive impact on three southern communities of LBI, NJ real estate, post dune installation in the Spring of 2016. Mean aggregate data of real estate assessments confirm that for specific properties with newly installed "540-Rule" dunes, the average homeowner in Ship Bottom, Long Beach Township, and Beach Haven all benefited in 2017, the year following dune installations (Figures 2.4 and 3.4). The positive responses were greatest in Ship Bottom and Beach Haven, while Long Beach Township experienced a minimal gain. We assume the trends in Long Beach Township are directly correlated with the opposition expressed before the installation of these projects (Insurance Journal, Anonymous March 2013; Zernike Sept 2013; Schapiro May 2015, Spoto, May 2013). Therefore, it's important for us to fully understand how much influence the installation of "540-Rule" dunes have had on these mounting real estate trends between 2016 and 2017; the significant factor for the project's overall validation.

Kolodin et al. (2021 *accepted for publication*) uses a first-order estimator approach to reveal the added value new "540-Rule" dunes have on existing property values θ, also known as our theoretical hedonic value (Appendix Equation (5.1)). The authors compare the changes in mean property values between the years 2016 and 2017, by taking the derivative of a property's benefit function (Appendix Equation (3.2)), with respect to the time interval, thereby quantifying the marginal implicit response "540-Rule" dune construction has on local property values. Among the three beachfront communities, we measure the changes in property values ΔB as a direct relationship with the addition of "540-Rule" dunes. The additional asset is counted towards the average annualized rental value α, per meter of alongshore beach ($/yr/m). The units are a function of multiplying the mean property value by the current discount rate δ, and dividing by the average alongshore width per household (~25m). All economic and geologic input parameters are shown in Appendix Table 5.1. The resulting first-order estimation values for "540-Rule" dune construction θ are shown in Appendix Table 5.2, expressing a comparable trend observed in Figure 3.4. Note: due to the simplicity of using a first-order estimation for our θ-values, our Appendix Equation (5.1) only takes into account the changes in a property's value due to the installation of a "540-Rule" dune, rather than any structural attributes α of the property that would add to the overall benefit. Therefore, our θ-values revealed in Appendix Table 5.2 are considered the upper-limit, while our ω-values from Table 3.3 validate the practicality of Appendix Equation (5.1).

$$\Delta B = \alpha \cdot \theta \cdot (H_{max} - H_{\alpha}) \cdot \left(\frac{1}{H_{\alpha}}\right) \cdot \left(\frac{H_{max}-H_{\alpha}}{H_{\alpha}}\right)^{\theta-1} \quad \text{(A.1)}$$

Table A.1 - Input parameters

Symbol	Symbol Name	Value	Reference
α	Annualized avg. beachfront rental value per meter alongshore (avg. ≈25m)	$0 -$3K $/yr/m	Ocean County Sr1a Data
ΔB	Difference between 2017 and 2016 average annualized beachfront rental values per meter alongshore	$32-$259 $/yr/m	Ocean County Sr1a Data
H_{max}	"540-Rule" Dune Height	7m	USACE 2014
H_{α}	Baseline Reference Dune Height	4m	100yr Still Water Flood Level (SWFL)

Table A.2 – First-order estimations, with respect to time, between the years 2016 and 2017. Included are variable inputs for changes in the aggregate averages of annualized property rental values, per year, per meter of alongshore beach.

Beachfront Community	Annualized Beachfront Community Rental Values per meter of alongshore beach (α & ΔB)		θ-Value
Ship Bottom	α = $1,825/yr/m	ΔB = $259/yr/m	0.1739
Long Beach Township	α = $2,670/yr/m	ΔB = $32/yr/m	0.0122
Beach Haven	α = $2,701/yr/m	ΔB = $524/yr/m	0.2593

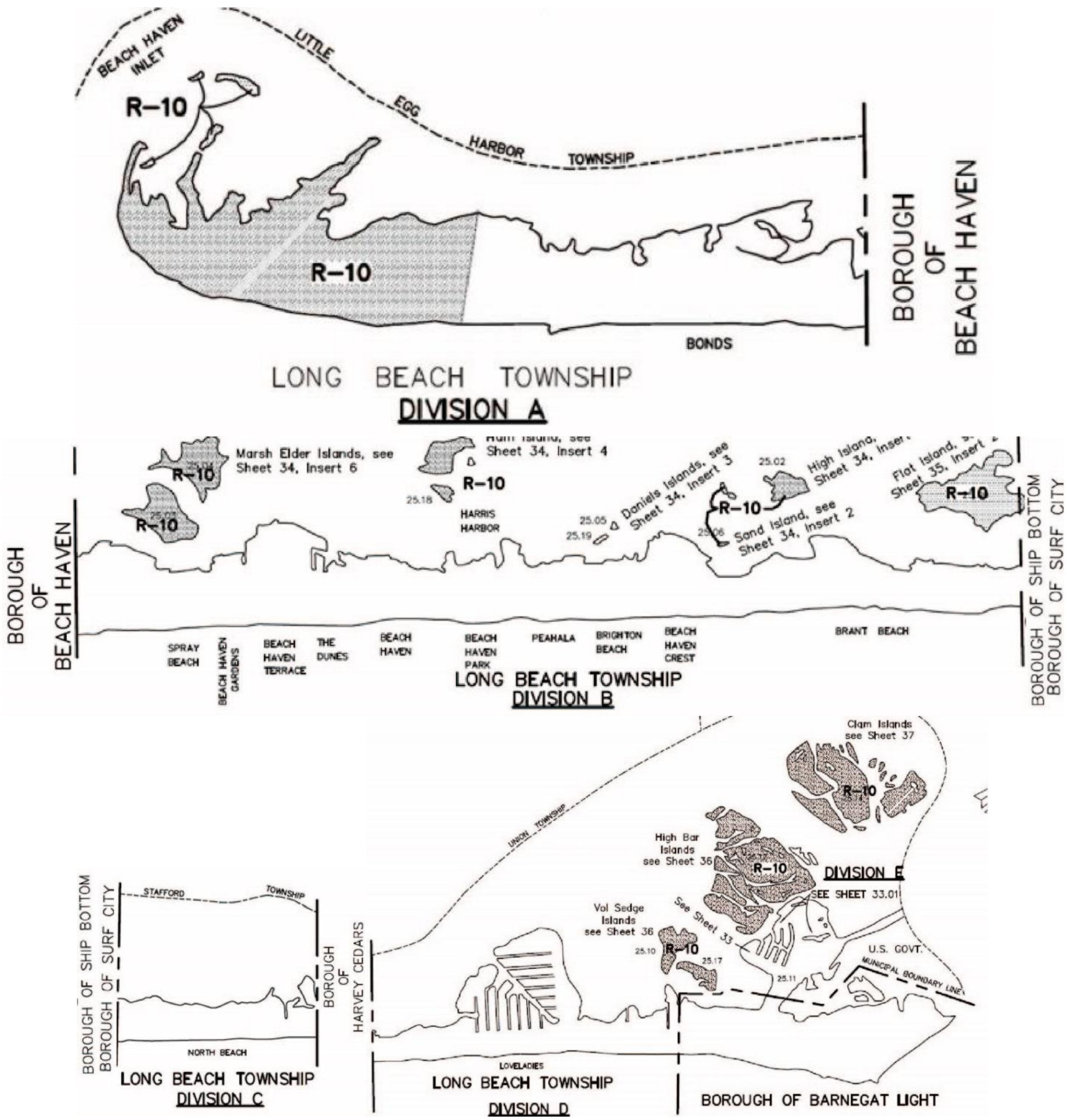

Figure A.1 – Long Beach Township sub-sectional zoning map (Long Beach Township 2011) Divisions A-E in detail.

Table A.3 - Results of HPM regression analysis using a more robust White-Estimator to check for heteroscedasticity UPDATE

Variable	Coefficient values (w/ Significance)	Std. Error
Housing Attributes α_{1_j}		
Year Built (ln)	0.1751	0.2553
Lot Size (SqFt) (ln)	0.3491***	0.0066
Finished area (SqFt) (ln)	0.2451***	0.0120
Total Rooms	0.0032	0.0025
Story Height	0.0190**	0.0064
Beds	-0.0062*	0.0033
Baths	0.0676***	0.0028
Secondary Homes	0.0514***	0.0049
Piling Foundation	0.0246***	0.0062
Basement	0.0443***	0.0051
Contemporary Roof	0.0208***	0.0060
Contemporary Design	0.0940***	0.0060
Wood Exterior	0.0194	0.0151
Asbestos Exterior	-0.0310*	0.0156
Aluminum Exterior	-0.0300*	0.0150
Electric Heating	-0.0162**	0.0056
Fireplace Attached	0.0371***	0.0040
HVAC Installed	0.0040	0.0052
Patio Attached	-0.0019	0.0089
Deck Attached	-0.0038	0.0042
Porch Attached	-0.0040	0.0042
Garage Attached	0.0054	0.0046
Pool Attached	-0.0142*	0.0065
Shed Attached	0.0081	0.0048
Hot Tub Attached	0.0574***	0.0068
Environmental ω_j		
"540-Rule" dune *SB*	0.1572***	0.0092
"540-Rule" dune *LBT*	0.0134***	0.0102
"540-Rule" dune *BH*	0.2071***	0.0134

R^2-value = 0.753 Model Significance = p-value < 0.001

Table A.4 - Results of HPM regression for the entire project

Variable	Coefficient values (w/ Significance)	Std. Error
Housing Attributes α_{1_j}		
Year Built (ln)	0.8452***	0.2503
Lot Size (ln)	0.3609***	0.0051
Finished area (SqFt) (ln)	0.2293***	0.0103
Total Rooms	-0.0013	0.0025
Story Height	0.0407***	0.0062
Beds	0.0028	0.0033
Baths	0.0740***	0.0028
Secondary Homes	0.0609***	0.0054
Piling Foundation	0.0094	0.0060
Basement	0.0385***	0.0053
Contemporary Roof	-0.0153*	0.0061
Contemporary Design	0.0884***	0.0060
Wood Exterior	0.0573***	0.0145
Asbestos Exterior	-0.0115	0.0154
Aluminum Exterior	-0.0142	0.0145

Electric Heating	-0.0205***	0.0059
Fireplace Attached	0.0539***	0.0042
HVAC Installed	0.0098	0.0057
Patio Attached	-0.0318***	0.0096
Deck Attached	-0.0282***	0.0044
Porch Attached	-0.0043	0.0045
Garage Attached	-0.0090	0.0048
Pool Attached	-0.0195**	0.0070
Shed Attached	-0.0043	0.0052
Hot Tub Attached	0.0679***	0.0070
Environmental ω_j		
"540-Rule" dune	0.0682***	0.0039

R^2-value = 0.721 Model Significance = p-value < 0.001

Online repository for codes, databases, and GUI tool: https://github.com/KolodinJesse