Canadian Science Publishing

ARTICLE

Engineered coastal berm-dune renourishment in New Jersey: can coastal communities continue to hold the line?

Jesse Kolodin, Jorge Lorenzo-Trueba, Porter Hoagland, Di Jin, and Andrew Ashton

Abstract: Following the significant coastal changes caused by Hurricane Sandy in 2012, engineered berm-dunes were constructed along the New Jersey coastline to enhance protection from future storms. Following construction, property values on Long Beach Island, NJ, increased in three beachfront communities. The projects were financed entirely through federal disaster assistance, but the percentage of future maintenance costs must be covered by local communities. Whether communities are willing or capable of financially contributing to maintenance remains unclear because (*i*) some homeowners prefer ocean views over the protection afforded by the berm-dune structures, and (*ii*) stakeholder risk perceptions can change over time. To investigate the relationships between berm-dune geometries, values of coastal protection, and ocean view values, we developed a geo-economic model of the natural and anthropogenic processes that shape beach and dune morphology. The model results suggest that coastal communities may exhibit significant differences in their capabilities to maintain engineered dunes depending on stakeholder wealth and risk perception. In particular, communities with strong preferences for ocean views are less likely to maintain large-scale berm-dune structures over the long term. If these structures are abandoned, the vulnerability of the coast to future storms will increase.

Key words: beach nourishment, berm-dune systems, engineered dunes, coastal risk, risk perception, government subsidies.

1. Introduction

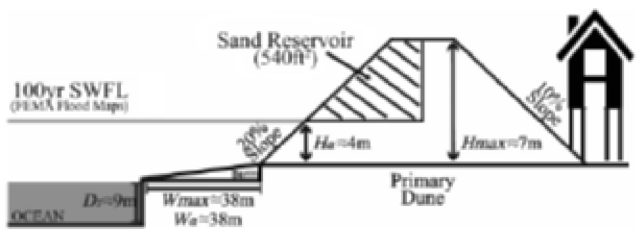
Coastal erosion is expected to increase with the significantly higher rates of sea-level rise expected over the coming centuries due to anthropogenic global warming (Vermeer and Rahmstorf 2009; Engelhart and Horton 2012; Kopp et al. 2019). When confronted with coastline change, a basic management question 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 and Neumann 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;

Received 31 December 2020. Accepted 19 July 2021.

J. Kolodin and J. Lorenzo-Trueba. Earth and Environmental Studies Department, Montclair State University, Montclair, NJ 07043, USA.
P. Hoagland and D. Jin. Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1050, USA.
A. Ashton. Geology and Geophysics Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1050, USA.
Corresponding author: Jesse Kolodin (email: kolodinj@montclair.edu).

Fig. 1. Berm-dune construction Beach Haven, NJ.

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



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 study 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 berm-dune systems.

After the impact of Hurricane Sandy in late October 2012, the State of New Jersey (NJ) adopted large-scale engineered berm-dune structures as their primary coastal protection strategy (Fig. 1). Berm-dune structures were built by the US Army Corps of Engineers (USACE), following the FEMA "540-Rule", with engineered dunes 22 feet (~7 m) high and berms 125 feet (~38 m) wide (Fig. 2; Dewberry and Davis 1989; USACE 2014). Prior to Hurricane Sandy, only a few beachfront communities along the coastline of New Jersey had large dunes on 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 (USD) (USACE 2014; Young 2014). With the estimated coastal and inland damages caused by Hurricane Sandy totaling $37 billion (USD) (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. To maintain these newly engineered landscapes, the USACE estimates that it will need to renourish the berm-dunes every seven 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 as sea-level rise accelerates, beachfront communities will be faced with rising renourishment costs. Moreover, property owners' preferences 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, 2015).

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 (Anonymous 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, we present a geo-economic model developed to capture the interplay between natural processes and beach nourishment practices (Fig. 3). We then apply the model to different scenarios of nourishment cost and risk perception among 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) (Fig. 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.

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 on whether 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.

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 (Fig. 5). For the dune, we assume an average steady-state triangular configuration

Fig. 3. Coupled natural-human berm-dune flow chart.

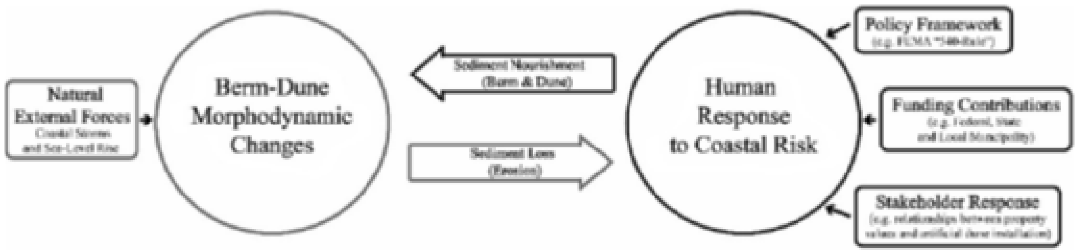
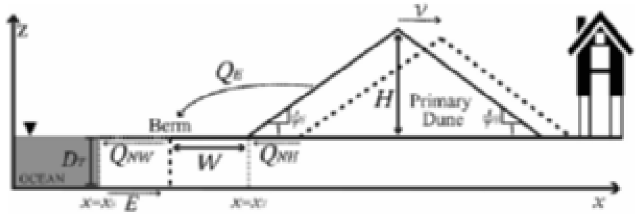


Fig. 4. Map of Long Beach Island, NJ (Ocean County), and the three beachfront communities used in the study (Google Imagery 2020).

Fig. 5. An idealized triangular berm-dune profile demonstrating the coupled natural-human evolution and stabilization of the system through system processes and state variables.



characterized by a foreslope, Ψ_S, and a backslope, Ψ_B, as opposed to a more general trapezoidal shape (Fig. 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.

Additionally, consistent with the "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 Fig. 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 used an origin located at the initial shoreface toe location, with x increasing horizontally landward and z vertically upward (Fig. 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. 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 beach and dune renourishment. The net dune erosion rate, Q_E (m^3/m/year), 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/year) represents the natural dune migration rate via aeolian processes. To model the berm evolution, we define the background erosion rate, E (m/year), which can be associated with either a 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/year), 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/year).

Combined, we can then compute the change in dune height as follows:

$$(1)\quad \frac{dH}{dt} = \frac{Q_{NH} - Q_E}{p \cdot H}$$

where $p = 1/\psi_S + 1/\psi_B$ is the dune shape factor. Equation 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 the work of Davidson-Arnott et al. (2018). In contrast, Durán and Moore (2013) found a steady-state dune configuration based on bio-physical feedback. Our focus in this study, 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 the shoreline location as follows:

$$(2)\quad \frac{dx_S}{dt} = E - \frac{Q_{NW}}{D_T} - \frac{Q_E}{D_T}$$

As stated by eq. 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 the dune toe location is computed as follows:

$$(3)\quad \frac{dx_T}{dt} = \frac{Q_E}{H} + v - \frac{Q_{NH}}{H}$$

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 eqs. 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. However, we recognize that changes in dune height, ocean shoreline, and dune toe locations are a function of a number of processes occurring across a wide range of spatial and temporal scales (Brodie et al. 2019; Cohn et al. 2019*a*, 2019*b*), and event-scale responses could also affect the interplay between renourishment decisions and changes in the berm-dune geometry.

Combining eqs. 2 and 3, we can describe the dynamics of the beach width, W (where $W = x_T - x_S$), as follows:

$$(4)\quad \frac{dW}{dt} = \frac{Q_E}{H} + v - \frac{Q_{NH}}{H} - E + \frac{Q_{NW}}{D_T} + \frac{Q_E}{D_T}$$

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, which 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 faced by many coastal communities (Burroughs and Tebbens 2008; Richter et al. 2013; Cohn et al. 2019*b*; Héquette et al. 2019; Davidson et al. 2020).

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, 2016; Jin et al. 2013), we assume that 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 eqs 1–4:

$$(5)\quad \mathrm{Max}_{Q_{NW},Q_{NH}} \int_0^{\infty} e^{-\delta t}(B(W(t),H(t)) - C(t))\cdot dt$$

where δ is the discount rate (time preference), B is the 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 that 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

[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.

$$B(t) = \alpha \cdot \left(\frac{W}{W_\alpha}\right)^\beta \cdot \left(\frac{H}{H_\alpha}\right)^\theta \tag{6}$$

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 the 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 eq. 6 to allow α to have units of \$/year/m, as the exponents in this equation are fractional.

Equation 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 the community value 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

$$C(t) = \phi_N \cdot (Q_{NW} + Q_{NH}) \tag{7}$$

where the parameter ϕ_N (\$/m^3) in eq. 7 represents the cost per unit volume of the beach renourishment material. The renourishment flux control variables, Q_{NW} and Q_{NH}, are expressed in units of m^3/m/year, or simply m^2/year, given the idealized cross-sectional profile per meter of alongshore beach (Fig. 5).

2.3 Model solution

The current value Hamiltonian, using eqs. 1, 4, 6, and 7 can be written as

$$J = \alpha \cdot \left(\frac{W}{W_\alpha}\right)^\beta \cdot \left(\frac{H}{H_\alpha}\right)^\theta - \phi_N \cdot (Q_{NW} + Q_{NH}) + \lambda_{NW} \cdot \left(\frac{Q_E}{H} + v - \frac{Q_{NH}}{H} - E + \frac{Q_{NW}}{D_T} + \frac{Q_E}{D_T}\right) + \lambda_{NH} \cdot \left(\frac{Q_{NH} - Q_E}{p \cdot H}\right) \tag{8}$$

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 Pontryagin's maximum principle (Kamien and Schwartz 1981), the 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:

$$\lambda_{NW} = \phi_N \cdot D_T \tag{9}$$

$$\lambda_{NH} = p \cdot \phi_N \cdot (D_T + H) \tag{10}$$

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

$$\frac{\partial J}{\partial W} + \dot{\lambda}_{NW} - \lambda_{NW} = 0 \tag{11}$$

$$\frac{\partial J}{\partial H} + \dot{\lambda}_{NH} - \delta \lambda_N = 0 \tag{12}$$

Solving for interior solutions under a steady state (i.e., $dW/dt = dH/dt = \dot{\lambda}_{NW} = \dot{\lambda}_{NH} = 0$), using eqs. 8–12, the optimal beach width, W^*, and dune height, H^*, can be solved as follows:

$$\left[\frac{1}{\beta\alpha}\cdot\left(\frac{H^*}{H_\alpha}\right)^{-\theta}\cdot W_\alpha\cdot\delta\cdot\phi_N\cdot D_T\right]^{\frac{\beta}{\beta-1}}\cdot\frac{\theta\alpha}{H_\alpha}\cdot\left(\frac{H^*}{H_\alpha}\right)^{-\theta}=\delta\cdot p\cdot\phi_N\cdot(D_T+H^*) \tag{13}$$

$$W^*=W_\alpha\cdot\left[\frac{1}{\beta\cdot\alpha}\cdot\left(\frac{H^*}{H_\alpha}\right)^{-\theta}\cdot W_\alpha\cdot\delta\cdot\phi_N\cdot D_T\right]^{\frac{1}{\beta-1}} \tag{14}$$

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

3. Input parameter values

The solution of eqs. 13 and 14 require both geologic and economic parameters, as discussed 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). The economic parameters were obtained from a review of the literature and local real estate data (Table 2).

3.1. Geomorphic parameters

The FEMA "540-Rule" design (Fig. 2) includes a dune with a seaward-facing sand reservoir of 540 ft^2 (~50 m^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 foot (~38m) berm, as illustrated in Fig. 2 and presented in Table 1.

3.2. Economic parameters

Aggregating beachfront property data for all beachfront communities from 2015 to 2019 (Fig. 6), we obtained a first-order estimate of the elasticity for dune height θ for three municipalities within Long Beach Island, NJ (Fig. 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 (Anonymous 2013; Zernike 2013; Spoto 2013; Schapiro 2015) experienced only a small increase in property value.

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 35–40 m, 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 (eq. 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:

$$\Delta B=\alpha\cdot\theta\cdot(H_{max}-H_\alpha)\cdot\left(\frac{1}{H_\alpha}\right)\cdot\left(\frac{H_{max}-H_\alpha}{H_\alpha}\right)^{\theta-1}\cdot\left(\frac{W_{max}}{W_\alpha}\right)^{\beta} \tag{15}$$

where α is the average beachfront rental value per meter alongshore for each community in 2017 (Table 3). The ratio $(W_{max}/W_\alpha)^\beta$ approaches 1, given our observations of W_α and W_{max}. The values of θ were found to be within the range 0.01–0.26 (Table 3), suggesting that 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 valued approximately equally.

Table 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	Still water flood level
D_T	Shoreface depth of closure	9	m	USACE 1999; Ortiz and Ashton 2016
Ψ_S	Dune foreslope	1V:5H	—	USACE 2014
Ψ_B	Dune backslope	1V:10H	—	USACE 2014

Table 2. Economic parameters.

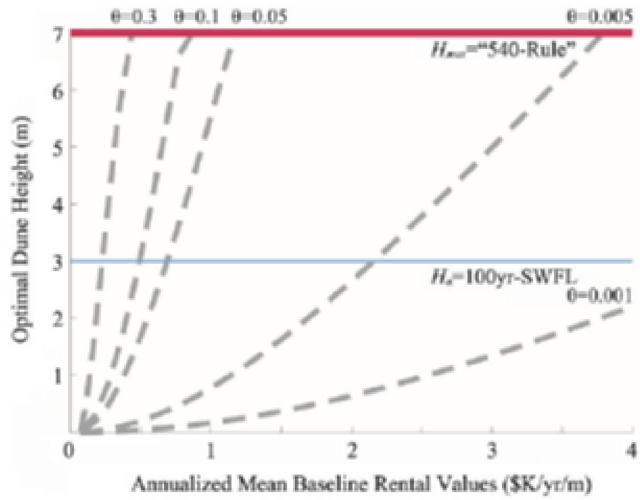
Symbol	Symbol name	Range	Reference
δ	Discount rate	6.9%	USACE 1999, 2014
α	Annual average beachfront property rental value per meter alongshore (beachfront lengths average ~25m)	\$0–\$4000/year/m	Ocean County Taxation Database 2020
ϕ_N	Yearly renourishment cost per meter alongshore	\$4.2–\$13.1/m^3	Valverde 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)

Fig. 6. Aggregate beachfront property value trends for 2015–2019, following dune installations in 2016 (Ocean County Taxation Database 2020).

Table 3. θ value estimations from eq. 15.

Beachfront community	α (2017 values)	ΔB (2016–2017)	θ value
Ship Bottom	\$1825/year/m	\$259/year/m	0.26
Long Beach Township	\$2670/year/m	\$32/year/m	0.01
Beach Haven	\$2701/year/m	\$524/year/m	0.17

Fig. 7. Optimal dune height, H^*, for an annualized beachfront property value, based on a positive range of θ values.



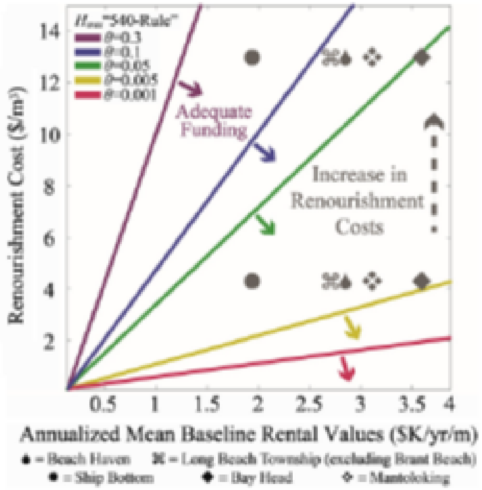
4. Long term feasibility of coastal dune maintenance

Using the steady-state solutions described by eqs. 13 and 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 (Fig. 7). A range of positive values for θ was based on the estimates included in Table 3, and a range of values for α was based on publicly available beachfront rental values in New Jersey (Table 2).

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 $H^* = 7$ m) 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. Furthermore, 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 of 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 (Fig. 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 $\alpha = \$3658$/year/m and Mantoloking $\alpha = \$3057$/year/m); both of which were opposed to installations on the record (Mikle 2017). For comparative changes in

Fig. 8. Optimal dune height, H^*, as a function of different variable renourishment costs of $\phi_N = \$4.2/m^3$ and $\$13.1/m^3$, and annualized baseline rental values, α, for high θ values ($\theta = 0.3$), intermediate θ values ($\theta = 0.1$, 0.05, and 0.005), and low θ values ($\theta = 0.001$).



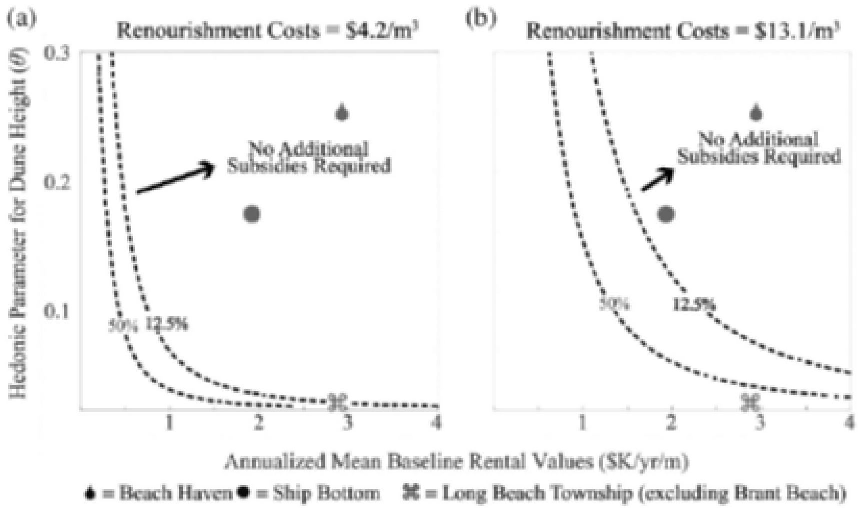
annual rental values per meter of alongshore beach, α, 2017 values were used in the comparison.

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 (Fig. 8). For high to intermediate height elasticities (e.g., $\theta = 0.3$, 0.1, and 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 0.001), none of the coastal communities would maintain the engineered berm-dunes.

The results are also sensitive to increases in the cost of renourishment. For a higher cost scenario ($\phi_N = \$13.1/m^3$), 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 in which all communities can still economically justify adequate funding for future renourishment. For intermediate values (e.g., $\theta = 0.1$ and 0.05), the community with the lowest wealth (i.e., Ship Bottom) cannot prioritize long-term dune maintenance, whereas the wealthiest community (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 the 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 and spend 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 (Fig. 9; Table 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 eqs. 13 and 14 as follows:

Fig. 9. Municipal government "budget shortfalls" requiring external funds (subsidies) to maintain engineered dunes under costs of (*a*) $\phi_{N_q} = \$4.2/\text{m}^3$ and (*b*) $\phi_{N_q} = \$13.1/\text{m}^3$ scenarios for Long Beach Island, NJ, beachfront properties, with θ values obtained in Table 3.



$$\phi_{N_e} = \frac{\alpha \cdot \theta \cdot C_1 \cdot \left(\frac{C_2}{\theta \cdot C_1}\right)^{\beta}}{C_2} \tag{16}$$

where

$$C_1 = \left(\frac{\left(\frac{H}{H_\alpha}\right)^{-\theta} \cdot W_\alpha \cdot \delta \cdot D_T}{\beta}\right)^{\frac{\beta}{\beta-1}} \cdot H^{\theta-1} \cdot H_\alpha^{-\theta} \tag{17}$$

$$C_2 = \delta \cdot p \cdot D_T + \delta \cdot p \cdot H \tag{18}$$

The current variable renourishment cost, ϕ_{N_q}, was used to define the budgetary shortfall, *F*, percentage as follows:

$$F = \frac{\phi_{N_q} - \phi_{N_e}}{\phi_{N_q}} \cdot 100\% \tag{19}$$

With a low height elasticity (e.g., $\theta = 0.01$), Long Beach Township is the only community where it would be difficult to prioritize their berm-dunes with a renourishment cost of $\phi_{N_q} = 4.2/\text{m}^3$. In contrast, Ship Bottom has adequate funds to maintain dunes in the foreseeable future because of its relatively high elasticity (i.e., $\theta = 0.17$), despite being the community with the lowest annual rental values. If the average sand costs in New Jersey were to rise in the future up to Ocean City NJ's value ($\phi_{N_q} = 13.1/\text{m}^3$), both Ship Bottom and Beach Haven (i.e., $\theta = 0.26$) 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.

5. Discussion and conclusions

In this study, 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 on real estate market outcomes—for coastal protection versus ocean views. The 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 3), their property values benefited from the coastal protection provided by the engineered berm-dunes (Fig. 6). In general, these beachfront communities (e.g., Ship Bottom and Beach Haven) are 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 because of 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 are less likely to provide 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 Long Beach Island, NJ, where 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 (Anonymous 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 and Love 2007; Marcus 2017).

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 others not. Even with these land-transfer agreements in place, coastal communities with relatively high annual rental values might still 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., subsidies) to 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 protection is 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, 2013; Kirshen et al. 2020).

Competing interests

The authors declare there are no competing interests

Author contributions

With guidance from J.L.-T., J.K. developed the research theory, the general modeling framework, and executed all model runs. While J.K. took the lead in writing the manuscript, J.L.-T., P.H., D.J., and A.A. provided important feedback and revisions.

Funding

This study was supported by the National Science Foundation (NSF) under grant no. 1518503 "CNH-L: Coastal Processes and Human Response to Shoreline Change." The views presented herein are solely those of the authors, and not of the NSF.

Data availability

All model codes and data gathered for running model experiments, along with scripts used to generate manuscript figures, are available at our Github repository page https://github.com/KolodinJesse/Theoretical_bermdune_model.

Acknowledgements

This research was supported by the National Science Foundation (NSF) under grant no. 1518503; the views presented herein are solely those of the authors and not of the NSF. We are grateful to Nick Cohn and an anonymous reviewer who has improved the manuscript with constructive comments. Additional appreciation goes to our MSU Coastal Dynamics Laboratory current and former members, Arye Janoff Ph.D., Dan Ciarletta Ph.D., William Anderson, Isamar Cortés, Christopher Tenebruso, Norjmaa Khosbataar, Madeline Kolleger, and Shane Daiek for providing essential input during the development phase of this manuscript along with Rose Palermo from the Woods Hole Oceanographic Institute.

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