Coastal Erosion as a Natural Resource Management Problem:
The State of Economic Science and Policy

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Abstract
Natural forces render the coastal environment an evolving landscape, with the majority of coastline in the U.S. exhibiting net erosion in recent decades. Predictions suggest that 25 percent of homes within 500 feet of the coast could be lost to erosion in the next 60 years, at a potential cost of $530 million dollars each year. Following a lengthy tradition of economic models for natural resource management, this paper explores dynamic optimization models for managing coastal erosion. The models conceptualize benefits of beach area as service flows accruing to nearby residential property owners, recreational beach users, and local businesses. The costs of maintaining beach area include pecuniary engineering expenditures, opportunity costs, as well as negative impacts on the coastal environment. Employing these constructs, an optimal control model can be specified that provides a framework for identifying the conditions under which beach replenishment is welfare-enhancing (i.e. will "pass" a comprehensive benefit-cost analysis), and an optimal replenishment schedule (e.g. periodic frequency and requisite sand volume) can be derived. We review the existing literature that has attempted the empirical measurement of benefits and costs of beach replenishment. Results are scrutinized to explore ways in which geophysical shoreline processes, including stochastic variation in periodic erosion, variability in erosion in the long shore dimension, and nonlinear relationships reflecting an attempt to maintain conditions far from historical equilibriums, can be incorporated. Sea level rise is introduced as an evolving erosion rate, which provides a framework for predicting the timeline of active shoreline management (i.e. how long should we attempt to "hold the line"?) and conditions under which movement to a passive management regime might be optimal. Natural resource economic approaches to shoreline erosion management are compared to and contrasted with existing U.S. Army Corps of Engineers procedures for evaluating shoreline protection projects.

Introduction

Unremitting waves and occasional storms bring dynamic forces to bear on the coast. Sediment flux results in various patterns of erosion and accretion, with an overwhelming majority (80 to 90 percent) of coastline in the eastern U.S. exhibiting net erosion in recent decades (Galgano and Douglas 2000). Climate change threatens to increase the intensity of storms and raise sea level 18 to 59 centimeters over the next century (IPCC 2007). Predictions for the U.S. suggest that 25 percent of homes within 500 feet of the coast could be lost to erosion in the next 60 years, at a potential cost of $530 million dollars each year (Heinz Center 2000).

Options for the management of coastal erosion include shoreline armoring, beach replenishment, and shoreline retreat. Shoreline armoring can be effective at preventing land loss due to chronic erosion, but most often has destructive and deleterious impacts on the natural environment, including loss of beach sand, coastal vegetation, and habitat. Beach replenishment involves alteration of the sediment budget – adding sand to the beach system in order to combat erosion; this process provides storm protection to coastal property, enhances recreation potential, and may improve beach and dune habitat, but does not prevent future erosion and thus must be repeated periodically. Beach replenishment can be very expensive and may impose additional environmental costs at the sites where sand is excavated, pumped, or placed. Shoreline retreat entails moving coastal buildings and infrastructure landward (or simply demolishing structures) to allow coastal landforms to evolve over time. This approach does not fit well with the existing legal system of land entitlements, as it implicitly allows some land to be lost as structures are moved. Vital questions remain as to where structures will be moved to and who should incur the cost of lost land.

Policies for managing coastal erosion in the U.S. currently favor beach replenishment, with judicious use of shoreline armoring. The complications surrounding shoreline retreat have resulted in limited consideration of this approach. The U.S. Army Corps of Engineers (USACE) has federal authority to conduct storm protection/beach enhancement projects that promote federal National Economic Development goals, and this organization is most often the primary party responsible for replenishment projects on public beaches. There are, however, some private entities that engage in beach replenishment (e.g., affluent communities such Sea Island, Georgia). Public funding for beach replenishment projects has been reduced significantly in recent years, under both the Clinton and Bush administrations. Currently, a community that meets the guidelines for a public beach replenishment project (including sufficient public parking and beach access) must provide 50% of the project funding (NOAA 2010). There are equity and social justice issues surrounding who should pay for such projects (Cooper and McKenna 2008). Private oceanfront property often reaps direct benefit from additional beach sand, both in terms of recreation potential and storm protection. Beach visitors, however, also benefit if resulting beach conditions are more conducive for recreation and leisure activities. Increased visitation attributable to improved beaches will benefit local businesses, including tourism related services, restaurants, and providers of overnight accommodations. Increased local economic activity can benefit local governments through increased tax and fee revenue. Whether general tax revenue, user fees, or local property or sales taxes should be used to pay for beach replenishment is an important question that is beyond the scope of this paper.

In this paper, we focus on economic efficiency of beach replenishment employing economic models of natural resource management. We provide an overview of dynamic optimization models for managing coastal erosion. The models conceptualize benefits of beach and dune sediments as service flows accruing to nearby residential property owners (reflecting recreation opportunity and storm-protection), local businesses (enhancing business opportunity and revenue), recreational beach users (providing space for recreation and changing functional density), and perhaps others. Benefits can also include improvements in habitat for beach- and dune-dependent plant and animal species. The costs of maintaining beach sediment in the presence of coastal erosion include expenditures on dredging, pumping and placing sand on the beach to maintain width, height, and length. Other costs can comprise negative environmental impacts on the near shore environment.

Employing these constructs, an optimal control model can be specified that provides a framework for identifying the conditions under which beach replenishment is welfare-enhancing (i.e. will "pass" a comprehensive benefit-cost analysis), and an optimal replenishment schedule (e.g. periodic frequency and requisite sand volume) can be derived under a constant sea level and erosion rate (*short term*) as well as an increasing sea level and erosion rate (*long term*). Under some simplifying assumptions, the conceptual framework can be used to identify the time horizon of management responses under sea level rise. As such, optimal control models can be helpful in exploring whether active management (specifically, beach replenishment) might be economically justified in the foreseeable future, or if passive management (shoreline retreat—i.e. letting erosion proceed unabated) is likely to become optimal in the long run. In the event of the latter, the model can be used to estimate the timing of a shift in management regimes and explore factors that influence this shift. Such information could be very valuable for coastal planning and investment purposes.

Following a brief overview of the models, this paper provides a detailed review of the types of data necessary to employ the models for normative policy analysis. We review the existing empirical literature on benefits and costs of beach maintenance. We explore the way in which natural resource economic models have characterized shoreline geomorphology and how this element of the models might be improved. We then bring these pieces together to illustrate how beach management decisions can be informed through the use of dynamic optimization models. Lastly, the welfare-theoretic approach of natural resource economics is compared and contrasted with procedures employed by the USACE in analysis of coastal protection projects.

Natural Resource Economics and Coastal Erosion
Economic study of natural resource management problems dates back, at least to Faustmann's (1849) model of optimal rotation of forest stock. Other contributions in economics have focused on non-renewable resources, such as optimal mineral extraction (Hotelling 1931), and renewable resources, such as fisheries (Gordon 1954). Building upon these foundations, Landry (2008) and Smith, et al. (2009) cast beach replenishment as a dynamic optimization problem. In these models, resource managers select the optimal quantity of replenishment sand, and the optimal timing of the additional sand, in order to counteract coastal erosion. Assume that additional sediment is of similar quality to native material. The beach erodes at some exogenous rate, θ, reflecting sea level rise,

dominant wave and current patterns, and coastal storms. The erosion rate can be specified as a constant, as random variable drawn from a known distribution (to reflect variability in storm and weather patterns), or as an evolving parameter (reflecting increasing erosion pressure due to sea level rise). Smith, et al. (2009) also introduce an exponential decay factor to reflect the beach's return to equilibrium after replenishment. Let resource quality be represented by a time-dependent variable, q_t, which represents beach width. This beach width measure reflects average beach quality (neglecting within-site variation in beach conditions).

Economic Benefits of Beaches

Willingness-to-pay (WTP) is a standard measure of economic value for provision of a resource to which individuals do not have a prior entitlement.[1] It reflects tradeoffs that individuals are willing to make and is conditioned on individuals' perceived values of the proffered resource and their ability to pay (i.e. level of income or wealth). Empirical measures of economic value are typically derived from revealed (RP) or stated preference (SP) methods. RP data reflect observations of or inquiries into past or current behavior and reflect individual choices under time and income constraints. SP data are derived from inquiries into planned behavior under hypothetical or expected conditions (such as changes in beach width or access). RP and SP data are often combined, which allows for testing particular biases and can provide a more complete characterization of individual preferences and improved statistical efficiency of parameter estimates (Azevedo, Herriges, and Kling 2003; Eom and Larson 2006; Whitehead et al. 2008b; Whitehead et al. 2010). Landry, Keeler, and Kriesel (2003) identify chief beneficiaries of beach erosion control as coastal property owners and beach visitors. We review the literature on economic benefits for each of the groups in turn.

Property Owners

Local beaches provide erosion and flood protection to coastal housing, in addition to recreation and leisure potential. Beaches and dunes also may supply scenic amenities. If buyers and sellers of coastal property value these services, the value of beaches can be capitalized in home sales prices. As such, the influence of beach quality on coastal property values can be analyzed with hedonic property price analysis. This RP approach utilizes the variation in housing prices in order to estimate the capitalization of spatial amenities and dis-amenities, such as environmental quality and risk factors, in sales prices.[2]

The hedonic price function is typically represented as:
$$P = P(x, q), \qquad\qquad\qquad\qquad\qquad [1]$$

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[1] If a prior entitlement exists, willingness-to-accept (WTA) compensation for sacrifice of the resource is the appropriate measure of economic value.

[2] Numerous studies have estimated household values for spatially variable environmental amenities in coastal housing markets. Proximity to water (Shabman and Bertelson 1979; Milon, Gressel, and Mulkey 1984; Edwards and Gable 1991; Pompe and Rinehart 1995, 1999; Earnhart 2001; Parsons and Powell 2001; Landry, Keeler, and Kriesel 2003; Bin, Kruse, and Landry 2008; Pompe 2008), water view (Kulshreshtha and Gillies 1993; Lansford and Jones 1995; Benson et al. 1998; Pompe and Rinehart 1999; Bin et al. 2008), and water quality (Leggett and Bockstael 2000) have all been shown to influence coastal property values, and estimates of marginal WTP for these amenities have been produced using property sales data.

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where P is the sales price, which is a function of structural and neighborhood characteristics, x, and, in our case, beach quality, q. Assuming that $P(\bullet)$ is continuously differentiable, the first derivative of [1] with respect to any continuous attributes produces an estimate of implicit attribute price, which in equilibrium is the representative households' marginal WTP for an additional unit of that attribute (Rosen 1974). Under the semilog specification of equation [1], marginal WTP is given by:

$$MWTP = \partial P/\partial q = \beta \alpha e^{\beta q}, \qquad\qquad [2]$$

where β is the coefficient on beach width and $\alpha = e^{\omega' x}$ represents the baseline housing value, which reflects the influence of other housing characteristics (x, with hedonic price parameter vector ω). For this model, β is a half-elasticity, indicating the percentage change in sales price for a one unit change in beach width. For the log-linear specification of [1], marginal WTP is given by:

$$MWTP = \partial P/\partial q = \beta \alpha q^{(\beta-1)}. \qquad\qquad [3]$$

For this model, β is an elasticity, indicating the percentage change in sales price for a one percent change in beach width.

     A number of studies have attempted to estimate marginal WTP for beach width by hedonic price regression. Pompe and Rinehart (1995) estimate the implicit price of beach width at $558 (for a one foot increase in high-tide beach width from 79 feet) in coastal South Carolina (in 1983 U.S. dollars). They include an interaction term for beach width and distance from the shore in the regression model and find that the implicit price of beach width is diminishing with distance from the beach. For coastal Georgia, Landry, Keeler, and Kriesel (2003) produce half-elasticity estimates (equation [2]) for beach width of 0.0017. Evaluated at the means of the data, this suggests an implicit price of $233 for a one-meter increase in low-tide beach width (1996 dollars).[3] Each of these studies includes multiple years of sales data, but only observations on beach width from one point in time. Landry, Keeler, and Kriesel (2003) recognize potential bias in this approach given the dynamic nature of beaches and the possibility of periodic interventions due to beach replenishment operations.

     Using time-series beach quality data to address this problem, Pompe and Rinehart (1999) estimate a one foot increase in high-tide beach width (from 228 feet) increases the average coastal home value in South Carolina by about $81 and the average oceanfront home value by $311 (1989 dollars). While this approach may address the problem of mis-measurement of beach width due to coastal dynamics and policy interventions, an issue remains as to what exactly is capitalized in housing values. Market prices reflect the discounted present value of housing services, but beach quality is expected to change over time due to natural forces and may be manipulated via beach replenishment. As such, the interpretation of hedonic price parameters that reflect coastal resource quality depends upon market participants' knowledge of coastal processes and expectations of future coastal management actions.

     Landry and Hindsley (2011) examine this problem by specifying the hedonic price function to depend upon a series of expected beach quality levels that are perceived by the buyer. If homebuyers expect beach width to remain constant over time, either due to natural forces or regular beach replenishment, marginal WTP can be interpreted in the

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[3] Unfortunately, estimates of α cannot be recovered from the information contained in these papers. Given the econometric specification, the estimate of β cannot be recovered from Pompe and Rhinehart (1995, 1999).

conventional manner. If, however, buyers expect beach width to decay over time, marginal WTP is a lower bound on marginal value because buyers evaluate beach quality at a lower expected level when forming their bid. Given a diminishing marginal value function, marginal WTP for the expected quality level will be no less than the estimated implicit price, with the degree of bias determined by elasticity of the marginal value function. Employing data from coastal Georgia, Landry and Hindsley find that high-tide beach width, low-tide beach width, and dune width influence the value of homes within 300 meters of the beach (reflecting their value as local public goods). They estimate half-elasticities (equation [2]) for high-tide beach width between 0.0027 and 0.0032 and half-elasticities of low-tide beach with between 0.0018 and 0.0031 for homes within 300 meters of the beach (for initial widths of 26.5 meters and 76 meters for high-tide and low-tide beach widths, respectively).[4] Evaluated at the means, increasing high-tide (low-tide) beach width by one meter increases the average property value by $421 to $487 ($272 to $465) (1999 dollars). If homeowners expect beaches to decay over time, however, these welfare estimates are lower bounds on the true value.

Gopalakrishnan et al. (2010) examine the possibility that beach width at locations that engage in beach replenishment may be endogenous to the hedonic price equation. Their rationale is that housing values play a role in benefit-cost analysis of beach replenishment,[5] and thus stretches of beach with more costly housing are more likely to qualify for beach replenishment and likely to receive higher volumes of beach sand during nourishment operations. One would expect that this positive feedback leads to an overestimation of the beach quality coefficient, but the authors find evidence of downward bias. They attribute this negative bias to increased erosion on replenished beaches (as they return to equilibrium profile) and measurement error in expected beach quality (as discussed in Landry and Hindsley (2011)). Gopalakrishnan et al. use topological characteristics of the shore profile – distance to the continental shelf and presence of dune scarps – as instruments for beach width; each of these geographic features should be correlated with coastal erosion but may be uncorrelated with housing values (conditional on a given level of beach quality). Employing data from several beach communities in North Carolina, they produce evidence suggesting that beach width is endogenous and find that their instruments are valid. Estimates from Two-Stage Least Squares suggest that beach width coefficients are four to five times larger than their Ordinary Least Squares counterparts. They find that the influence of beach width on property values extends 300 meters or more from the shoreline. They estimate a half-elasticity (equation [2]) of 0.011 and an elasticity (equation [3]) of 0.603. Their results suggest that a one foot increase in beach width (from 95 feet) increases the average oceanfront home price by $4,210 (log-linear model) to $8,800 (semi-log model).

Under the standard assumptions and setup, the hedonic property model in [1] is only capable of producing point estimates of marginal attribute values via [2] and [3]. In order to recover the entire marginal value function, more information must be obtained (typically derived from multiple housing markets) (Palmquist 2004). This has not been attempted for hedonic property models of beach quality. Landry (2008), Smith et al. (2009), and Gopalakrishnan et al. (2010) use the parameterized hedonic price function to

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[4] Their estimates of baseline property value (α) are between $153,220 and $200,512 for the high-tide beach width models, and $156,785 and $211,023 for the low-tide beach width models.

[5] We discuss policy for evaluation of beach replenishment plans in a subsequent section of this paper.

estimate property owner benefits attributable to beach width. This approach assumes that there is no heterogeneity in individual preferences for beach quality (Palmquist 2004). Integrating under the hedonic price function produces a rough estimate of total value associated with quality level q. For the semi-log model, we have:

$$WTP(q) = \alpha(e^{\beta q} - 1) + C \qquad [4]$$

where C is the constant of integration. For the log-linear model, we have:

$$WTP(q) = \alpha q^{\beta} + C. \qquad [5]$$

Unfortunately, the constant of integration is of an unknown magnitude; any constant value would drop out in the marginal analysis implied by the first-order conditions of the hedonic price model. In practice, the constant is often set equal to zero. These measures of economic welfare derived from property values should reflect perceived storm and flood protection benefits, as well as recreational and leisure value of local beaches accruing to coastal property owners.

Beach Visitors

     Beach visitors include tourists and locals that don't own property at the beach. Recreation demand models can be used to assess visitors' value of access to beach sites. These models recognize recreation trips as economic goods that are produced by individual households using purchased commodities (e.g. automobile, gasoline, automobile maintenance) and personal travel time.   These elements determine the cost of a recreation trip (travel cost), which is used as a price instrument to examine the tradeoff that visitors make between the number of recreation trips, the quality of recreation trips (as reflected in site characteristics), and other economic goods and services. All else being equal, we expect those that live further away from recreation sites to take fewer trips (due to the higher high travel costs) than visitors who live closer. And, if an individual selects a trip to a faraway site, this reflects a preference for characteristics of that site vis-à-vis other available sites.

     One perspective on recreation demand considers choice among recreation sites as a function of site characteristics (x_{ij}) and individual characteristics (s_i). This is the Random Utility Model (RUM) framework. Define utility for individual i at site j as:

$$U_{ij} = V_{ij}(x_{ij}, s_i; \gamma) + \varepsilon_{ij} \qquad [6]$$

where V_{ij} is the part of utility that is driven by observable factors, with parameter vector γ, and ε_{ij} is the part of utility that is unobservable to the researcher. A 'no-trip' option can be included in the choice set, setting a base utility U_{i0} associated with foregoing beach recreation. Given unobservable factors, the utility maximization site choice model is probabilistic; the probability of individual i choosing site j over other sites h, is:

$$P_{ij} = \Pr[V_{ij}(x_{ij}, s_i; \gamma) + \varepsilon_{ij} > V_{ih}(x_{ih}, s_i; \gamma) + \varepsilon_{ih}, \forall h \neq j]$$

$$P_{ij} = \Pr[\varepsilon_{ih} - \varepsilon_{ij} < V_{ij}(x_{ij}, s_i; \gamma) - V_{ih}(x_{ih}, s_i; \gamma), \forall h \neq j]. \qquad [7]$$

Expression [7] is a cumulative probability distribution, indicating the likelihood that the difference in the error terms is below the differences in the observed portions of utility (Train 2003). Given an assumption about the distribution of the difference in errors $g(\varepsilon_i)$, the choice probability can be obtained as:

$$P_{ij} = \int_e I[\varepsilon_{ih} - \varepsilon_{ij} < V_{ij} - V_{ih}, \forall h \neq j] g(\varepsilon_i) d\varepsilon_i, \qquad [8]$$

where $I(\bullet)$ equals one when the expression in brackets is true, zero otherwise. If ε_{ij} are independently and identically distributed Type I extreme value variates, the error difference is logistic and [8] can be estimated by the multinomial logit model, which has a simple closed-form solution. More flexible models can be estimated under different assumptions. For example, the nested multinomial logit model can accommodate the 'no-visit' option as a separate decision (and as a function of individual characteristics, s_i) and can allow for more realistic substitution patterns by grouping similar sites into choice 'nests'. The multinomial probit model can allow for individual level random taste variation and correlation in unobserved factors across sites. The mixed logit model also allows for random taste variation and correlation in unobserved site factors across sites, and will accommodate any distributional assumption for model coefficients (or, equivalently, components of the error term) (Train 2003).

The 'observable' portion of utility, V_{ij}, is typically assumed linear in attributes. As such, parameter estimates from [6] can be interpreted as estimates of marginal utility associated with site attributes (e.g. beach quality, q). The coefficient on travel cost is an estimate of the marginal utility of money income. Marginal WTP for an incremental change in beach site characteristic k is given by a ratio of choice model parameters:

$$MWTP_k = \frac{\Delta x_k \times \gamma_k}{-\gamma_y},$$ [9]

where γ_k is the coefficient on site attribute k, Δx_k is the magnitude of the small change in x_k, and γ_y is the coefficient on travel cost. While this framework can be used to analyze the value of large, non-marginal changes in site characteristics, like beach quality, marginal WTP in [9] is constant if the attribute is in equation [6] with a simple linear functional form; other forms, such as logarithmic and quadratic, can be employed to allow for non-linear marginal utility, but these forms will not necessarily be consistent with diminishing marginal value. If the estimated marginal WTP fails to capture diminishing marginal utility, WTP for increases (decreases) in an attribute like beach quality will be an upper (lower) bound on the true benefit measure. To analyze situations where multiple site attributes change or sites are lost from the choice set, WTP is given by:

$$WTP(x^0, x^1) = -\frac{1}{\gamma_y} \left[\ln \sum_{j^1} \exp[V(x^1, s; \gamma)] - \ln \sum_{j^0} \exp[V(x^0, s; \gamma)] \right],$$ [10]

where x^0 (x^1) is the initial (subsequent) vector of site characteristics, and j^0 (j^1) is the initial (subsequent) collection of sites in the choice set.

Lew and Larson (2009) estimate the value of San Diego, CA county beach access by evaluating a version of [10] at 'choke' travel prices that would drive visitation at all beaches to zero. Using RP data, they find that the average household is willing-to-pay $21 to $23 for a California beach day or $1,300 to $1,400 for beach access over a two month period (2000 dollars). Given substitution possibilities, however, the loss of a single beach in the choice set has relatively small costs of $0.01 to $0.39 per household, per trip, depending on the beach. Along similar lines, McConnell and Tseng (2000) estimate the costs of lost access to Chesapeake Bay beach sites at $1.87 to $3.55 per household, per trip, again depending upon the site. Parsons, Massey, and Tomasi (2000) estimate costs associated with lost beach access ranging from $3.15 to $16.86 for popular sites in Maryland, Delaware, and New Jersey, while the loss of unpopular beach sites has

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much lower costs, ranging from $0.00 to $0.14 (all estimates per household, per trip in 1997 dollars).

At least two studies have included measures of beach width and length in the RUM framework. Parsons, Massey, and Tomasi (2000) include nominal (AKA dummy) variables to identify sites that have less than 75 feet or greater than 200 feet of beach width; each coefficient is negative in their preferred specifications, indicating a preference for moderate beach width. Parsons, Massey, and Tomasi estimate welfare losses associated with all Delaware beaches eroding to a width of less than 75 feet to range between $5.78 and $10.94 per household, per trip (1997 dollars). Given their specification, however, an approximate WTP function for beach width (as in [9]) cannot be recovered from the parameter estimates. Whitehead, et al. (2010) estimate a site choice model for southern North Carolina beaches. They find a positive and significant coefficient on beach width, implying a marginal implicit price (equation [9]) of $0.03 per foot for each individual during each trip (or $3 for a 100 foot increase in beach width – 2003 dollars). As stated above, this WTP function could be used in benefit transfer (briefly discussed below), but assumes a constant marginal value of beach width. Beach length is positive and statistically significant in each of these studies, indicating a preference for longer beaches.

A slightly different approach to analysis of preferences for beach recreation focuses on the number of trips to a site or group of sites. Suppose that consumer i's utility function depends on the number of visits to a j-vector of recreation sites, v_i, with quality vector q, and the quantity of composite of others goods and services, h_i. The round-trip travel cost associated with a visit to site j is given as p_{ij}. With the price of the composite good normalized to equal one, the consumer's budget constraint is given by $p_i' v_i + h_i \leq y_i$, where y is income. The consumer's optimization problem is to maximize her utility function, $U_i(v, h, q)$, subject to the budget constraint. Utility maximization leads to the standard Marshallian demand function for recreational use of the site j:

$$v_j = f_j(p, y, q) \qquad [11]$$

(i subscripts suppressed). To be properly specified, this demand function should be estimated including the travel costs to other substitute sites and may include other demographic factors that shift the demand curve as well. This site demand equation can be estimated in isolation or in a system of equations for different recreation sites. For single-site demand, parameters for the q vector cannot be recovered unless quality varies across individuals or panel data are available (with quality variation over time).

Integrating under the demand function produces an estimate of consumer surplus (CS), an approximate measure of WTP that reflects individual or household benefit attributable to site visitation:

$$CS_j = \int_{\bar{p}_j}^{p_j^c} f_j(p, y, q) dp, \qquad [12]$$

where $\bar{p}$ is current travel cost and p^c is the 'choke' travel cost price, at which expected recreation demand is zero. Using this RP framework, Bin et al. (2005) estimate the value of a beach trip in North Carolina at $11 to $80 per person, per day (2003 dollars), while Landry and McConnell (2007) estimate the value of a beach trip to Jekyll Island, Georgia (Tybee Island, Georgia) at $7.71 ($16.81) per person, per day (or $171 ($332) per household, per year for Jekyll (Tybee)) (1998 dollars). von Haefen, Phaneuf, and

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Parsons (2004) employ the Generalized Corner Solution model of Phaneuf, Kling, and Herriges (1998) to estimate a system of demand equations as in [11]. They estimate the value of beach access for Rehobeth, Delaware at $49.77 to $73.36 per household per season, while all Northern Delaware beaches are valued at $102.99 to $152.47 (1997 dollars).

Focusing on cross-site variation in beach width within a system of RP demand equations, von Haefen, Phaneuf, and Parsons (2004) estimate WTP to avoid loss of beach width (such that all beaches would be 75 feet wide or less) in Virginia, Maryland, and Delaware at $33.75 to $57.28 per household, per year (1997 dollars). Combining RP and SP data, Whitehead, et al. (2008a) assemble panel data to examine the influence of hypothetical increases in beach width on beach recreation demand, finding a positive but insignificant effect for southeast North Carolina beaches. Using a subset of the data, however, Whitehead, et al. (2010) estimate WTP for a 100 foot increase in beach with is $7 to $15 per household, per year (2003 dollars).

Increases in beach area provide additional space for coastal recreation and leisure activities, and may enhance economic value by improving scenic and aesthetic amenities, by allowing for increased utilization of beach resources (i.e. accommodating more people), by decreasing congestion for existing users, or all three. Landry, Keeler, and Kriesel (2003) employ an SP approach (Contingent Valuation Method (CVM) – details on this method below) to value modest improvements in beach width in Georgia for current users, finding that the value of a beach day increases (by about $6.75 – $9.90 per trip (1999 dollars)). Silberman and Klock (1988) use CVM to estimate the change in economic value associated with improvements in beach width in northern New Jersey. In contrast to Landry, Keeler, and Kriesel, they find a small and statistically insignificant increment to user value, a $0.30 increase from $3.60 to $3.90 per individual, per day, but a large impact on anticipated visitation. Focusing only on current users, they estimate a 65% net increase in visitation across all New Jersey beaches (controlling for substitution from outside the project area). Notably, neither of these papers explicitly controls for congestion in their evaluation of changes in beach value attributable to replenishment. In an application of CVM to valuation of Rhode Island beaches, McConnell (1977) finds that an increase of 100 people per acre decreases the average consumer surplus by 25%. Since beach replenishment increases beach area, one might expect a decrease in congestion. For the use of federal funds, however, the U.S. Army Corps of Engineers requires enough parking spaces to accommodate peak demand and access points every quarter mile.   The increase in accessibility, combined with the possibility of greater regional appeal, could possibly lead to an increase in overall beach congestion. The relationship between beach area, available parking & access, visitation levels, congestion, and economic value remains an important area for future research.

Non-use Values

Stakeholders may harbor value for beaches that are independent of their own current use of beach resources. Examples of non-use values include: i) *option value* – WTP to ensure beaches are available for possible future personal use; ii) *vicarious use value* – WTP to ensure beach exists for use of others; iii) *bequest value* – WTP to ensure beaches are available for future generations; and iv) *existence value* – WTP to ensure beaches exist for natural or intrinsic purposes. As non-use values can be independent of

resource utilization, SP methods (such as contingent valuation method (CVM), contingent behavior (CB), and choice experiments (CE)) must be employed to produce empirical estimates of non-use values. These SP methods rely on descriptions of hypothetical situations or contingent markets and attempt to measure intended or planned behavior under these circumstances. CVM elicits WTP for hypothetical increases in public goods using a simulated referendum or market exercise (i.e., would you vote for a policy to improve beaches if it increased taxes by $X per year? Or, would you purchase a beach pass at $Y per trip if beaches were wider?). CB inquires about changes in planned behavior under hypothetical conditions; for example, Whitehead, et al. (2008a, 2010) measure changes in visitation with improvements in beach width. Lastly, CE allow subjects to choose between project options that vary in their characteristics (such as improvements in beach width, access, and program costs). (More details on this approach below.)

Silberman, Gerlowski, and Williams (1992) use CVM to attempt to estimate 'existence value' for users and non-users of New Jersey beaches; their focus is primarily on preserving recreation use for others, so the value concept is more in line with vicarious use value. Using onsite and mail survey data, they estimate vicarious use values from one-time voluntary payments for beach replenishment in New Jersey to be on the order of $9.34 to $19.65 per household (1985 dollars). They note the difficulty in trying to separate use from non-use values for those that intend to use replenished beaches. Using CVM, Shivlani, Letson and Theis (2003) compare estimates of WTP for beach width, both with and without identifying improvements in sea turtle habitat as an additional benefit. They estimate an approximately 25% greater WTP when sea turtles are identified as additional beneficiaries of the beach nourishment project ($1.69 v. $2.12 per household, per visit (1999 dollars)). Aside from these studies, there has been little empirical research on non-use values for beaches.

Other Values and Economic Impact

Consumer surplus and WTP are estimates of economic value that resides with users and non-users of natural resources. Welfare estimates derived from hedonic property price models indicate implicit economic value for homeowners; estimates produced by recreation demand models indicate net economic value for visitors, and estimates from SP models, like CVM and CE, reflect economic value of those surveyed. Improvements in beach quality can also affect local businesses, by increasing their profitability (which can be interpreted as producer surplus). We are unaware of any existing research on economic benefits of beach maintenance accruing to local businesses. Welfare estimates do not include changes in transfer payments, such as increases in property and sales tax revenues or the impact of tourists' travel expenditures. Local and state governments, however, are often concerned about these measures of economic impact. Input-output models (such as IMPLAN) can be used to quantify the direct, indirect, and induced impact of tourist expenditures on local and regional economics.

Benefit Transfer

Given the difficulty and expense in measuring economic benefits and costs, a methodology for transferring existing estimates to new projects under consideration is

desirable. The general idea is known as 'benefit transfer' and is often applied by government agencies that lack funding and data for more comprehensive analyses. The results of benefit transfer are generally less accurate and reliable. Van Houtven and Poulos (2009) review the basics of benefit transfer and illustrate a more robust, theory-based approach, known as structural benefit transfer, for assessment of beach erosion control projects.

Economic Costs of Beach Maintenance

Economic costs of beach replenishment include: i) monetary costs of beach replenishment activities (expenditures on equipment, personnel, energy, etc.); ii) transaction costs associated with permitting and planning; iii) opportunity costs stemming from the use of resources owned by the agency or contractor conducting operations (i.e. costs that would not show up as direct expenditures, but nonetheless entail the use of scarce resources and must be counted from an economic perspective); and iv) external environmental costs associated with the impact of replenishment activities on the nearshore environment. Consider a production function for replenishment sand (N):

$$N = N(k, l, e; \lambda), \tag{13}$$

where k represents the level of capital equipment, l represents the amount of labor, e represents the amount of energy, and λ is an index representing the availability of beach-quality sand in the nearshore environment (or some other location, perhaps on land). We assume all inputs have positive and diminishing marginal product: $\partial N/\partial j > 0$; $\partial^2 N/\partial j^2 < 0$ for $j = k, l, e$. The δ index can be thought of as a measure of distance to beach quality sand reserves, with $\partial N/\partial \lambda < 0$. The objective of a rational project manager is to minimize the costs of producing any quantity of replenishment sand, which gives rise to a 'private' economic cost function:

$$C(\boldsymbol{r}, N; \lambda) = \min FC + r_k k + r_l l + r_e e \quad \text{subject to } N = N(k, l, e; \lambda), \tag{14}$$

where FC represents fixed costs of beach replenishment, which include expenditures on mobilization/demobilization of equipment, permits and fees, and environmental impact statement (EIS); expenditures on capital, labor and energy represent variable costs (assuming the levels of these inputs can be changed during the planning period); $\boldsymbol{r}$ is a vector of exogenous input prices; and N is the desired level of sediment. The cost function in [14] is labeled 'private' because it does not reflect external environmental costs (which are borne by the public at large). Under standard assumptions: $\partial C/\partial \boldsymbol{r} > 0$; $\partial C/\partial N > 0$; and $\partial C/\partial \lambda > 0$. Anecdotal evidence indicates that the fixed cost component can be of significant magnitude (especially mobilization/demobilization costs), such that beach replenishments are undertaken periodically. This periodicity may also reflect scarcity of capital equipment – dredges, in particular. If dredges are scarce, it should be reflected in the opportunity cost of capital, r_k.

Empirical estimates of [14] can be derived from data on project expenditures, input price levels, sand quantities, and sand 'borrow area' depth and distance (reflecting λ). Western Carolina University's *Program for the Study of Developed Shorelines* (PSDS) has archival data on monetary costs of beach replenishment (as well as sediment quantities and shoreline lengths) for the majority of beach projects extending back to the early 1960s. Monetary costs typically include direct expenditures and some types of transaction costs. It is unclear whether the archived cost data include opportunity costs of capital equipment if these costs are not reflected in direct expenditures. The PSDS data

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do not include information on inputs utilized, input prices, or other details of replenishment operations (such as details on borrow area).

Landry, Keeler, and Kriesel (2003) use historical data on beach replenishment at Tybee Island, GA to produce a rough average estimate of approximately $1 million per year (1996 dollars) to maintain beach width. Landry (2008) uses the historical PSDS data to estimate a 'reduced form' cost equation for beach replenishment. Pooling data for the mid-Atlantic, southeast, and Gulf beach replenishment projects, he estimates a panel data model (Least Squares Dummy Variables (LSDV) model) with state-level fixed effects, sediment quantity (in quadratic form), and a time trend. His results suggest that costs are increasing and convex in sediment quantity (indicating decreasing returns to scale) and that real costs (controlling for price level) are trending upwards over time. Landry speculates that the increasing time trend could reflect dwindling reserves of high quality beach fill sand in close proximity to the shore.

In order to account for all costs associated with beach replenishment, the economic cost function should also include external costs imposed upon the environment. The social cost function is thus:

$$\widetilde{C}(\boldsymbol{r}, N; \lambda) = C(\boldsymbol{r}, N; \lambda) + EC, \qquad [15]$$

where EC represents external costs of beach replenishment. External environmental costs can include damages at the mine/borrow site (damage to habitat and benthic communities), the target beach (increased turbidity in water or compaction of sediments), or adjacent communities (Greene 2002). Speybroeck, et al. (2006) provide a detailed account of possible ecological impacts at the target site, focusing on effects i) occurring during construction activities, ii) relating to the quality of sediments, and iii) stemming from the quantity of sediment. They also consider differential impacts of competing beach replenishment technologies. Limited empirical information exists on environmental costs of beach replenishment. Using CE, Huang, Poor, and Zhao (2007) estimate the costs of wildlife impacts (disturbance of habitat with no threat of extinction) due to beach replenishment at $3.33 to $4.98 per households (for New Hampshire and Maine) (2000 dollars).

Shoreline Geomorphology

Economic models of shoreline erosion management incorporate beach dynamics using a state equation for beach quality. Landry (2008) and Smith, et al. (2009) focus on an average level of beach width. Let the background erosion rate be given by θ; this erosion rate is a simple average and reflects historical sea level rise and land subsidence, as well as occasional tropical and sub-tropical storms. The erosion rate can also be repeatedly drawn from a known probability distribution in order to introduce stochastic erosion. A simple equation describing average beach width at any time t is:

$$q(t) = q_0 - \theta t, \qquad [16]$$

where q_0 represents some arbitrary starting point. Consider a control variable, $n_t = N_t/d$, that represents incremental sediment (due to any beach replenishment undertaken) per unit of project length (d) during period t. First differencing equation [16] produces a discrete-time equation of motion (or state equation) that allows for introduction of the control variable:

$$q_{t+1} - q_t = -\theta + \tau n_t, \qquad [17]$$

where τ is a parameter that converts sand volume to incremental beach width (Landry 2008). The short-term τ parameter can be approximated by:

$$\tau = (M + b)^{-1}, \tag{18}$$

where M represents the height of the beach berm (in meters above sea level), and b represents the "depth of closure" (in meters below sea level) (Dean 1991). Equation [17] is a time-autonomous[6] equation of motion for beach quality, which provides for a simple solution to the dynamic optimization model using backwards recursion.

In the long-term, the erosion parameter θ will be evolving over time as sea level rises. More frequent and violent coastal storms may also increase erosion pressure on barrier islands and other coastal landforms. Landry (2004) posits a time path, $\theta(t)$, with two distinct segments, the first corresponding with sea level rise below the mean height of the barrier island and the second corresponding with sea level rise above the mean height of the island. In this model, the amount of sand required to maintain the barrier island increases dramatically once sea level rise eclipses mean island height, as sand must be added to the entire island profile, essentially raising the island. Over the long-term, the τ parameter also changes with time. Incorporation of dynamic erosion renders the optimal control problem as non-autonomous, and the problem become more difficult to solve.

Smith, et al. (2009) employ a composite erosion rate that includes a linear portion (reflecting historical erosion) and an exponential portion (reflecting return to equilibrium profile). If $0 \leq \mu \leq 1$ represents the proportion of initial beach width that erodes due to return to equilibrium, and $(1 - \mu)$ represents the proportion of initial beach width that erodes due to historical factors, beach width at time t is:

$$q(t) = (1 - \mu)q_0 + \mu q_0 e^{-\eta t} - \theta t, \tag{16'}$$

where η is the erosion rate associated with return to beach profile equilibrium. Differentiating equation [16'] produces a continuous-time equation of motion that includes the control variable, n_t:

$$\dot{q}(t) = -\eta \mu q_0 e^{-\eta t} - \theta + \tau n_t. \tag{17'}$$

While more realistic, this setup renders the problem non-autonomous, making solution more difficult. An alternative is to ignore the return-to-equilibrium process and adjust the τ parameter in [17] to account for loss of replenishment sand associated with equilibration of the beach profile.

Neither the approach of Landry (2008) nor Smith, et al. (2009) considers the long-shore dimension of coastal erosion management, effectively ignoring variability in beach quality and erosion. While most previous research focuses on replenishment of a representative beach profile in isolation, Slott, Smith, and Murray (2008) consider the influence of beach replenishment operations on adjacent beaches. They find external benefits of replenishment on downdrift beaches, which reduces the overall cost of beach maintenance by as much as 25%.

Dynamic Optimization Models for Coastal Erosion Management

The coastal planner's problem is to maximize the difference between total benefits (represented, at the individual level, by equations [4/5] and [9/10]) and total

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[6] A time-autonomous equation is one that is not a function of t. In other words, the dynamic processes are stationary across time periods.

costs (represented by equations [14/15]) of management actions subject to the equation of motion for beach quality (equations [17/17']). This problem is a non-renewable resource management problem, but differs from the conventional non-renewable problem because society benefits from preservation rather than extraction of the resource. The non-renewable resource exhibits a decaying tendency, and the management control represents a contribution to the level of resource quality that counters this decay. The benefits of preservation are service flows over time, while the costs are incurred in the period in which beach replenishment is undertaken. Under certain conditions, a sustained corner solution (e.g. no addition of sand) can be construed as a *de facto* policy of shoreline retreat in the long term.

Short-run Application

In Landry (2008), the coastal planner chooses the amount of beach replenishment to be conducted in each time period. Using control theory, the short-run management problem (over T years) can be represented as:

$$\max_{n_t} \sum_{t=0}^{T-1} \kappa^t \{WTP(q_t) - \tilde{C}(r, N_t; \lambda)\} \qquad [18]$$

subject to the equation of motion [17], a specified initial condition for beach quality, and a free boundary condition for subsequent beach quality (at time T). The symbol $\kappa^t = (1 + \delta)^{-t}$ is a discount factor, where δ is the discount rate; $WTP(q_t)$ reflects aggregate benefits for beach quality level q_t, so it should include all beneficiary groups (property owners, recreational visitors, regional and local businesses, and those holding non-use values) and reflect the number of individuals within each group; $\tilde{C}(r, N; \lambda)$ represents the economic costs of beach replenishment (which should also include external environmental costs, if relevant). Equations [18] and [17] describe an optimal control problem with one control variable (n_t) and one state variable (q_t).

Anecdotal evidence suggests that fixed costs are an important part of the economic costs of beach replenishment, as large amounts of capital equipment (e.g. dredges, pumps, pipes, etc.) are required to produce any appreciable amount of replenishment sand. Mobilization and demobilization of large amounts of capital equipment entails significant fixed costs. The existence of large fixed costs leads to a rotation-type solution, with periods of nourishment followed periods of no activity. The rotation pattern can be incorporated and the model solved through application of numerical dynamic programming. This is most readily accomplished by discretizing the state and control spaces and applying Bellman's backwards recursion algorithm. The approach of backward recursion is based on Bellman's Principle of Optimality, which states that an optimal policy must constitute an optimum with regard to the remaining periods regardless of preceding decisions. As such, one can solve the problem by working backwards. Bellman's equation for the beach erosion management problem is:

$$V_J(q_t) = \max_{n_t \geq 0} \{WTP(q_t) - \tilde{C}(r, N_t; \lambda) + \kappa V_{J-1}(q_{t+1})\}, \qquad [19]$$

where κ is the discount factor, and J represents the number of periods remaining. Application of the backwards recursion algorithm (using MATLAB software) produces an optimal replenishment schedule and specifies the amount of sand to be added to the beach during each replenishment operation. In an application to Tybee Island, GA,

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Landry (2008) determines that the optimal beach width is 30 meters, and the optimal rotation length is about 12 years. Landry (2008) does not account for beach profile adjustment in returning to equilibrium, which would reduce the value of the τ parameter and affect the rotation length. A graph of the state variable across time displays a zig-zag pattern as beach width erodes and is replenished at regular intervals.

Explicitly recognizing the rotation style solution that arises with time-autonomy, Smith, et al. (2009) build upon the work of Faustmann (1849) and Hartman (1976) in formulating an optimal rotation model. They define the choice variable as the rotation length, $\tilde{T}$, or period of time between beach replenishment operations, and their optimization problem is thus:

$$\max V(\tilde{T}) = [B(\tilde{T}) - C(\tilde{T})]/[1 - e^{-\delta\tilde{T}}]. \tag{20}$$

Equation [20] represents the present discounted value of an infinite number of beach replenishment rotations. Property value benefits associated with rotation $\tilde{T}$ are:

$$B(\tilde{T}) = \int_0^{\tilde{T}} e^{-\delta t} \delta WTP(q(t)) dt, \tag{21}$$

where $q(t)$ is assumed to evolve according to equation [17'], and the discount factor, δ, is used to convert the capitalized value of beach width into a flow. Costs of beach replenishment are given by:

$$C(\tilde{T}) = FC + \phi[\mu q_0(1 - e^{-\eta\tilde{T}}) + \theta\tilde{T}], \tag{22}$$

where ϕ is the variable (or marginal) cost for a increment of beach width, and the term in brackets results from the equation of motion in [17'] under the assumption that replenishment always resets beach quality to q_0. Smith, et al. (2009) show that at the optimal rotation length, $\tilde{T}^*$, the following condition must hold:

$$\partial B(\tilde{T}^*)/\partial\tilde{T}^* - \partial C(\tilde{T}^*)/\partial\tilde{T}^* = \delta(B(\tilde{T}^*) - C(\tilde{T}^*))/(e^{\delta\tilde{T}^*} - 1). \tag{23}$$

This condition can be interpreted as follows: at the optimal rotation length, the marginal net benefit of extending the rotation one additional period (LHS) is just equal to the interest payment that would be lost by delaying all future rotations after the current one (RHS). MATLAB is used to numerically solve equation [20] or [23] to estimate $\tilde{T}^*$.

Smith, et al. (2009) derive comparative statics for the optimal rotation length, which includes the following results. The optimal rotation length will increase if the fixed costs of nourishment increase; this is intuitive, as the existence of fixed costs provides rationale for the rotation style solution. The optimal rotation length can increase or decrease with an increase in variable costs, depending upon the relationship between the decay rate of nourishment sand stemming from return to equilibrium (η) and the discount rate (δ). The optimal rotation length decreases with an increase in the marginal value of beach width or baseline property value (α), implying that communities exhibiting a higher economic value for beach width or coastal location should be nourished more frequently. The optimal rotation length decreases with an increase in the baseline erosion rate (θ), indicating that more highly erosive areas should be nourished more often (all else being equal). And the optimal rotation length decreases as the discount rate (δ) increases, reflecting the diminishing importance of replenishment costs (which are incurred at the end of the rotation period).

<u>Long-run Application</u>

Several extensions of these models can be made to examine long-run coastal erosion management problems. The model of Landry (2008) can be made more similar in structure to Smith, et al. (2009) by assuming an infinite time horizon (no set *T*). To solve the infinite rotation problem in Landry's framework, the value function in [19] can be iterated in order to find a 'steady state' rotation solution for beach width and replenishment and quantity (though the nature of the solution remains the same). For each model, the suitability of beach replenishment as a management strategy can be evaluated by assuring that the present value of net benefits is positive: $V(q_t) > 0$ in equation [19] and $V(\tilde{T}^*) > 0$ in equation [20], respectively.

Under some simplifying assumptions, the terminal time for beach replenishment can be identified. Since erosion is assumed to increase monotonically with sea level rise (as represented by the time path $\theta(t)$), the replenishment costs of producing a given beach width, conditional on some arbitrary starting point, should be increasing monotonically as well. With a $WTP(q_t)$ function that is bounded from above, the terminal time for beach replenishment can be implicitly defined by the balance of benefits and costs. Under the assumption that the shadow value of beach quality should be driven to zero in the long run, Landry (2004) defines the terminal time for beach replenishment as:

$$WTP(q_{T-1}) = \tilde{C}(\boldsymbol{r}, N_{T-1}; \lambda). \qquad [24]$$

Condition [24] indicates that the total benefits of beach management must equal the total costs in the penultimate period. Given that costs will be increasing monotonically and economic returns from beach quality are (assumed) bounded, this condition implicitly defines the time at which beach replenishment should be abandoned. In the absence of beach replenishment, a policy of shoreline retreat is implicit. While economic costs of maintaining beach width and island location reflect sea level rise, erosion, and available sand resources, the benefits reflect not only the marginal value of beach width but also baseline property values (*α*). Baseline property values, in turn, will depend upon conditions in the coastal housing market, fundamental understandings of coastal processes on the part of buyers and sellers, and expectations of public and private interventions in shoreline evolution (beach replenishment, shoreline armoring, elevation of threatened properties, etc.). With sufficient notice on a shift to shoreline retreat, the baseline value of threatened properties could be driven to zero. In an application to Tybee Island, GA, Landry (2004) estimates terminal time of beach replenishment under zero baseline property value to be 23, 38, and 128 years under seal level rise trajectories of 80cm, 55cm, and 30cm (over the next century), respectively. If baseline property values were to remain at their 1998 levels, terminal times for beach replenishment are 98 years, 168 years, and indeterminate (greater than 500), for sea level rise trajectories of 80, 55, and 30 cm, respectively.

Public Policy Analysis of Shore Protection Projects
Under various statutes of the Water Resources Development Act and its reauthorizations, the U.S. Army Corps of Engineers (USACE) has federal authority to conduct storm damage protection/beach maintenance projects that promote federal National Economic Development (NED) goals and meet other federal, state, and local criteria. The other criteria include avoidance or minimization of adverse environmental impacts, striking a balance between economic benefit and environmental sustainability, and demonstrating

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institutional acceptability (e.g., must address needs and concerns of the public, be financially and institutionally implementable, and garner public support). Pursuant to NED objectives, tangible benefits of a project must exceed economic costs, and 'each separable unit of improvement must provide benefits at least equal to costs' (USACE 2000). In addressing potential environmental impacts and effects on threatened and endangered species, USACE typically works with the Fish and Wildlife Service and the National Marine Fisheries Service to ensure that impacts are avoided or minimized and, where appropriate, mitigation is employed. Additional project objectives relate to preservation of cultural and historic resources.

A primary condition for federal involvement in beach replenishment projects is public ownership of land or hinterland; private ownership, however, is acceptable as long as adequate public access is provided with sufficient parking. Existing authority provides for restoration and protection of beaches, but does not provide for extending a beach beyond its historic shoreline (unless such extension is justified on engineering grounds, environmentally acceptable, economically efficient relative to restoration of the historic shoreline). The USACE requires that sea level rise scenarios be considered in project evaluation and selection. If sediment resources from the outer continental shelf are proposed for use in beach replenishment, a memorandum of agreement must be established with the Minerals Management Service (MMS).

Project Evaluation and Selection

Planning of federal water resources projects is based on the Water Resource Council Principles and Guidelines (P&G) (USACE 2000). The P&G provide a framework for planning and evaluation, requiring a balance of economic benefits and environmental protection and encouraging comprehensive analysis to explore a full range of alternatives that achieve planning objectives within the confines of existing constraints. With regard to NED, P&G clearly states that, 'contributions to NED are the direct net benefits that accrue in the planning area and the rest of the Nation. Contributions to NED include increases in the net value of those goods and services that are marketed, and also *of those that may not be marketed*.' (USACE 2000) [emphasis added]. The P&G require that non-structural alternatives be considered (e.g. shoreline retreat or property acquisition), in addition to no action. The NED plan is to be the alternative that provides for the greatest net economic benefit, while protecting the nation's environment. In addition to net economic benefit, project evaluation must also focus on environmental quality, regional economic development, and other social effects (collectively referred to as 'output and effects'). The P&G require evaluation of with- and without-project output and effects along each of the four criteria (completeness, efficiency, effectiveness, and acceptability) for each alternative, while allowing for some flexibility in the level of analytical detail (with appropriate justification).

For project evaluation, the USACE P&G require benefit-cost analysis for all output and effects that can be monetized. For instances in which benefits cannot be monetized, cost-effectiveness analysis (achieving a target outcome at lowest possible cost) is recommended as a decision tool. Following basic economic principles, the P&G require, where possible, incremental (or marginal) analysis. An accounting of sources and magnitude of risk and uncertainty is to inform project selection. Environmental and social effects are to be analyzed through impact assessment. The P&G encourage

collaboration with state and local interests, other federal agencies, while giving full consideration to viewpoints and concerns of the general public.

<u>Economic Benefits</u>

Following the Water Resources Development Act of 1986, the primary objective of coastal protection projects is hurricane and storm damage reduction. Control of coastal erosion not associated with storms has no separate status as a project objective. Benefits of hurricane and storm damage reduction stem from protection of existing coastal structures and infrastructure, with undeveloped land having a low priority and recreation benefits treated as an incidental output. The P&G dictate that recreation benefits may not be more than fifty percent of the total benefits required for economic justification.

For hurricane and storm damage reduction project, benefits are measured as 'reductions in actual or potential damages to affected land uses' due directly to a storm or storm-induced shoreline erosion, including wave damage reduction, inundation damage reduction, reduction of loss of land, structural damage prevention, reduced emergency costs, reduced maintenance costs, and other benefits (USACE 2000). The P&G lay out detailed procedures for estimation of hurricane and storm protection benefits. The following is paraphrased from the <u>Planning Guidance Notebook</u> (USACE 2000):

1. *Delineation of Study Area* – The areas to be affected by storms and erosion, as well as areas that could be affected under each of the proposed alternatives (i.e. down-drift areas) must be identified.
2. *Definition of Problem* – Existing storm damage and erosion problems are identified and described, including a historical account of storms, floods, and wave attack, and the resulting economic and social effects.
3. *Selection of Planning Shoreline Reaches* – Geomorphic conditions, land uses, and existing protective structures are described by 'reach' (stretch of shoreline that provides primary economic subunit of analysis).
4. *Establish Risk Frequency Relationships* – Hurricane and storm risk is defined by two types of probability distributions, one describing wave height and water level and the other describing the magnitude of shoreline erosion or accretion.
5. *Inventory Existing Conditions* – Affected structures and land are inventoried by land-use type; 'value', ground elevation, distance from water, construction materials, number of stories, and other information are recorded.
6. *Develop Damage Relationships* – Estimates of the value of structural or contents damages due to physical factors such as water depth, duration of flooding, wave height, and amount of shoreline recession are derived. The Principles allow for generalized damage (based on damage data from similar areas) or site-specific damage (based on historical damage data) relationships to be used.
7. *Develop Damage-Risk Frequency Relationships* – Risk-frequency relationships are combined with damage relationships to estimate probability distributions for each damage mechanism (erosion, inundation, wave attach, etc.) and each land use category.

8. *Calculate Expected Annual Damages and Benefits* – Expected annual damage (EAD) is the expected value of erosion and storm damages in a given year. EAD are calculated by computing the area under the damage-risk frequency curve, employing a life-cycle approach. EAD are computed for with- and without-project conditions, and the difference between the with- and without-project EAD represents the benefit associated with each project alternative.

Thus, the P&G require a life-cycle approach (accounting for arrays of output and effects over the lifetime of the project) and probabilistic analysis of benefits. Discounting is employed to convert all monetary measures to present value. This approach to risk analysis is intuitively appealing and computationally demanding. Numerous analytical computer modules have been designed to perform the risk analysis outlined in the above steps. See Gravens, Males, and Moser (2007) for a description of the most recent incarnation, 'Beach-*fx*'. With appropriate input (i.e., meteorologic, coastal morphologic, economic, and management measure data), the Beach-*fx* model is capable of estimating storm damage caused by erosion, flooding, and wave impact.

Land lost to erosion is to be valued at market value for nearshore land, but there is some ambiguity with respect to the 'value' of existing structures in Step 5. With regard to evaluating flood risk reduction projects, the P&G require the use of 'actual market values' and provide guidance in assessing benefits associated with improvements in location value (allowing for more valuable land uses in flood prone locations), intensification value (allowing for intensification of existing land uses in flood prone locations), and inundation-reduction. In practice, however, estimates of value of existing structures are based on analysis of comparable properties or measured by replacement cost minus depreciation (Yoe 1993).

Hurricane and storm damage reduction projects can entail both recreation gains and losses, depending upon the nature of the project and how recreation behavior adjusts under the with-project conditions. The Federal Water Project Recreation Act of 1965 requires full consideration of the effects of federal water projects on outdoor recreation. USACE P&G recognize travel cost models, stated preference methods (in particular, CVM), and other 'quantifiable methods' based on sound economic rationale as valid approaches to estimating recreation values (USACE 1983). Quoting USACE (1983), the criteria for acceptable recreation value estimation have the following characteristics:

1. Evaluation is based on an empirical estimate of demand applied to the particular project.
2. Estimates of demand reflect the socioeconomic characteristics of market area populations, qualitative characteristics of the recreation resources under study, and characteristics of alternative existing recreation opportunities.
3. Evaluation accounts for the value of losses or gains to existing sites in the study area affected by the project (without-project condition).
4. Willingness to pay projections over time are based on protected changes in underlying determinants of demand.

While travel cost and CVM have been previously described, the other common method employed by USACE has not. The 'unit day value' method relies on expert opinion and judgment to estimate the average user's willingness to pay for a day of beach recreation. Any of these methods can be employed using existing data (i.e. benefit transfer) or through gathering primary data. In addition to value estimation, analysis of

recreation behavior must estimate the total change in expected use of project facilities with and without the project (accounting for substitution from other adjacent resource areas) and existing site uses that may be restricted or diminished due to the project. If the storm damage reduction project area supports a specific amount of recreation or exhibits unique recreational resources, P&G requires a regional or site-specific study. In order for any public of private beach to receive federal support for beach replenishment, sufficient beach access must be provided. Under current guidelines, this entails access points at least every quarter mile with minimum of ten publicly available parking spaces at each access point. Nonetheless, recreation benefits can account for at most 50% of project benefit in benefit-cost analysis.

Economic Costs

USACE P&G on estimation of NED costs recognizes basic principles of economic theory of costs. All resources utilized in structural and non-structural alternatives should be valued at their opportunity cost – the value that is sacrificed when a decision on use of a scarce resource is made. Under competitive market conditions, marginal opportunity costs of resources correspond with market prices. Price signals will provide biased signals of opportunity cost under conditions of market power, or in the presence of price controls, taxes, or subsidies. Under these conditions, P&G recommend proxy or surrogate measures of opportunity cost be used.

The P&G organize economic costs into three categories: implementation costs, or explicit costs associated with project execution (incurred by federal agencies and cooperating entities); other direct costs, including the value of resources devoted to project execution, but for which direct outlays are not made (including use of resources with are owned by the implementing authority, value of donated facilities, and the value of positive or negative externalities); and associated costs that stem from execution of the project (and are necessary to achieve benefits) but which are paid by other agents (USACE 1983). Implementation costs include the value of resources used to minimize adverse impacts and/or mitigate fish and wildlife habitat losses as required under federal law, and direct costs associated with salvage or preservation of historical and cultural resources. Interest during construction is an 'other direct cost' that is always added to project costs in order to put construction costs on the same base year as benefits; since benefits may not begin to accrue until after the project is completed, construction costs must be inflated to reflect this time lag and to render benefits and costs comparable in real terms. Moreover, as water resource projects typically involve a significant time horizon, project costs must be assigned to the appropriate time period in which they will be incurred, expressed in terms of the expected price level, and appropriately discounting in order to make then comparable to present discounted value of benefits. The USACE P&G requires that benefits and costs be expressed as annuities, commonly referred to as 'average annual equivalent values'. Yoe (1993) provides a detailed account of NED cost estimation procedures.

Project Financing

All USACE water resource projects require some level of cost-sharing between federal and non-federal partners. The Water Resources Development Acts of 1996 and 1999 have established the goal of reducing the federal cost share associated with water

resources projects, placing greater financial responsibility on states and municipalities. Prior to the Water Resources Development Act of 1996, the cost share had been split 65% federal, 35% non-federal for projects that qualify for public support. Beginning in 2003, the cost-sharing has been 50/50 (NOAA 2010). The local sponsors' share of costs can include in-kind services, cash contributions, or real estate interests. In order for beach replenishment projects to receive federal funding, the Office of Management and Budget must receive a favorable recommendation from the USACE. The Clinton and Bush administrations, however, were marked by a clear move towards less funding for new beach replenishment projects. In Congress, beach replenishment projects have received low priority relative to other budget items.

Welfare Economics and Public Policy Analysis
While based on economic principles, the USACE P&G for evaluating coastal protection projects differ somewhat from the basic approach of welfare economics. Under circumstances of risk and uncertainty, welfare economics defines benefits of protection as an aggregation of individual willingness-to-pay (WTP), while P&G define benefits as foregone storm damages; these two measures will not necessarily correspond. Moreover, WTP should be based on actual market data for RP analysis; whereas P&G allow for use of comparable values or replacement costs (minus depreciation). Utilization of unit-day values for estimation of recreation benefits is a form of benefit transfer, but the practice would likely benefit from application of more up-to-date methods like structural benefit transfer. The limitation on the size of recreation benefits that may be included in benefit-cost analysis is arbitrary and has no basis in theory of welfare economics.

Individual WTP for a resource, project, or outcome is the appropriate measure of economic value for situations in which an agent does not have a pre-existing right or entitlement to the resource, project, or outcome.[1] This is well recognized in the USACE P&G for water resource project assessment. This basic tenet, however, is lacking from the primary benefit evaluation criterion for beach replenishment projects – foregone flood damage associated with the project. There are two potential problems with this approach: i) estimates of value ascribed to structures may be very different from actual market value, and ii) WTP to forego flood damage takes no account of individual risk preferences.

The benefits of living on the coast are be best estimated by the market value of coastal property; in a competitive market environment, property market values will reflect individual WTP for occupancy of the property, and will include values associated with access to the recreational beach, coastal view and ambience amenities, and rental income. Analysis of comparable properties and use of replacement cost adjusted for structure depreciation, however, may be provide poor estimates of WTP. Analysis of comparables as a property value assessment tool can be inaccurate in that it accounts for a limited number of observable characteristics and is not designed to adjust for unobservable factors (as some regression models can). Limited data and difficulties in accounting for various factors that influence sales values diminish the accuracy of using comparables.

Replacement cost reflects the present value of necessary expenditures to reconstruct a property of similar quality, usually at the original condition level. The depreciation adjustment changes replacement cost to reflect current physical condition.

Replacement cost is often used to specify coverage level for insurance contracts, and it is appropriate in this context because it describes the level of liability for the insurer and the payout to be received by the insured (to reconstruct a lost asset). Replacement cost could be an inaccurate measure of individual WTP; if the housing stock is old, depreciated replacement costs may value many parcels at close to zero dollars (depending upon the age of the structure and depreciation method employed). Land on barrier islands and along the coast is scarce, and competition among buyers and sellers can be significant. When market demand is strong (as has been the case on the east coast for the past 10 – 15 years, last couple of years excepted), market values can exceed replacement cost, as coastal parcels earn scarcity rents. Competition will affect the value of land more than structure, but since the two are linked market structure values can exceed replacement cost.[7]

Use of market values for valuing coastal property is the welfare-theoretic and analytically appropriate approach for benefits assessment (Parsons and Powell 2001; Landry, Keeler and Kriesel 2003; Landry 2004, 2008; Gopalakrishnan, et al. 2010; Landry and Hindsley 2011). There are, however, complications associated with employing sales values for benefit estimation: i) not all properties have changed hands recently (so no information on current sales value is available); ii) prices include value of both structure and land (so it can be difficult to separate the two for analysis of storm damage & erosion); and iii) market values reflect all characteristics of the property, and if these characteristics change over the course of analysis (e.g. second row home becomes beach front; distance to the shoreline or beach width changes) the housing values need to be adjusted. Regression models employing hedonic property price analysis can be used to solve each of these problems. A properly specified regression model can be used to estimate current market value, can be used to estimate the value of a vacant lot (if there are data on lot sales), and can predict the change in housing value associated with changing characteristics (Landry, Keeler and Kriesel 2003; Parsons and Powell 2001).

Alternatively, assessed values (from tax collector records) can be used to proxy for market values. Assessed values are usually measured at a common point in time (e.g. all reassessments done at the same time), so as long as recent estimates are available the complication of estimating current value is not a problem. Also, assessments are usually broken into land and structure value. Regression analysis can be used to adjust assessed values for changing property characteristics, as suggested above.

Assessed values, however, typically exhibit a limitation that is common to comparable values or replacement costs – they do not account for individual risk preferences. The concept of risk preference relates to individuals' willingness to bear risk, typically measured as their willingness-to-pay to reduce or eliminate uncertainty in outcomes (e.g. storm or erosion damage). Aversion to risk is defined by individuals exhibiting positive WTP to avoid or reduce risk. On the other hand, individuals would be classified as risk seeking if they would demand compensation for avoiding or reducing risk (negative WTP). As recognized by the USACE (1983), analysis of foregone storm

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[7] Also, the opposite phenomenon can occur, as we have recently seen in many housing markets across the U.S. – the housing market is upside down when market values are below replacement cost. In this case, it makes very little economic sense to build a house because the current market value will be below the cost of construction.

and erosion damages as a benefit criterion implicitly assumes risk-neutrality (neither risk averse nor risk seeking) on the part of coastal inhabitants.

Under circumstances of risk and uncertainty, market property values will reflect the expectation of the present discounted value of housing service flows for those individuals that bid the most for particular housing units. This expectation will depend upon individuals' subjective risk assessments (e.g. probabilities associated with different outcomes) and the value of housing services in different states of the world (e.g. with and without storm losses). Subjective risk perceptions are idiosyncratic and need not depend upon scientific data that quantify the actual risk. Thus, market values contain information on economic value, conditional on risk recognition, perception, and preference. The use of market prices (as in equation [1]) in analysis of storm protection takes account of individual perception of and preferences for storm, flooding, and erosion risk (Parsons and Powell 2001; Landry, Keeler, and Kriesel 2003; Landry 2004, 2008; Gopalakrishnan, et al. 2010; Landry and Hindsley 2011).

Dynamic optimization models for coastal erosion management also make use of marginal implicit prices. The models in equations [19] and [20] focus explicitly on the role of beach width, but other factors could be analyzed, such as changes in beach length, beach area, dune width, dune height, shoreline armoring (i.e. sea wall height), flood zones, etc. With variability in risk across space or time, marginal implicit hedonic prices (similar to equations [2] and [3]) will indicate estimates of incremental option value – the economic value or risk-reduction (Smith 1985). In the presence of insurance against the hazard, implicit hedonic prices will reflect the sum of *residual* incremental option value and (marginal) insurance costs (MacDonald, Murdoch, and White 1987). Residual incremental option value is the difference in insurance payout and expected losses, which will include deductible, financial losses that cannot be covered by insured, personal losses of sentimental items for which insurance does not compensate, and disruption in day-to-day life associated with catastrophe. Assessed values, comparable values, and replacement costs are not capable of providing such nuanced information on subjective risk perceptions and incremental option value.

Psychological studies have produced copious results indicating that risk perceptions are not only subjective, but also can be influenced by the context of decision making (Slovic 2000). Studies of individual behavior under threat of catastrophic risk sometimes produce surprising results indicating significant risk aversion in some cases (often after traumatic events) and ignorance of risk in others (Kunreuther 1984, 1996; Kunreuther, Sanderson, and Vetschera 1985; Camerer and Kunreuther 1989; McClelland, Schulze, and Coursey 1993; Palm 1998; Krantz and Kunreuther 2007). As marginal implicit prices are conditioned upon individuals' subjective perception of hazards, application of hedonic price models for analysis of economic value will produce estimates that vary with knowledge, awareness, and tolerance of hazards. The method is not useful if individuals are unaware of hazards, as the hedonic price schedule will not adjust to compensate for variability in risk. Also, it is difficult to separately analyze multiple services flows associated with spatial attributes (e.g. beaches that provide storm protection and recreation potential) or service flows combined with risk (e.g. beachfront location that provides scenic amenity but higher storm surge and erosion risk) (Hallstrom and Smith 2005; Bin et al., 2008). Variability in risk recognition, perception, and

preference over time and across contexts can make transfer of benefit measures less reliable.

Analysis of recreation benefits associated with beach replenishment projects has the potential for a high degree of complexity. Beach area provides space for coastal recreation and leisure activities and provides scenic and aesthetic amenities for residents and visitors. Empirical evidence suggests that increasing numbers of users may enhance economic value at lower congestion levels, but reduces value at higher levels of congestion (McConnell 1977; Schuhmann and Schwabe 2004) and there is considerable heterogeneity in aversion to site congestion (Boxall, Hauer, and Adamowicz 2005). As a site attribute, congestion is an endogenous variable (because it is jointly determined with individual making choices about which beaches to go to and how often), which complicates analysis with RP models (Boxall, Hauer, and Adamowicz 2005; Timmins and Murdock 2007; Phaneuf, Carbone, and Herriges 2007). Moreover, if congestion is an important aspect of recreation demand that is neglected in empirical modeling, resulting parameter estimates and measures of economic value could be biased(Timmins and Murdock 2007; Phaneuf, Carbone, and Herriges 2007).

Beach replenishment increases beach space and may augment or detract from beach aesthetics. Projects sponsored by USACE must provide for public beach access, which includes access points (with at least 10 public parking spots) every quarter mile and aggregate parking that can accommodate peak demand. The changing access associated with beach replenishment could lead to situations in which overall congestion increases or decreases. The impact of congestion on economic value may vary with individual and site characteristics. The role of site congestion in recreation demand is an important topic for future research.

Beach values vary across single- and multiple-day users, and those the make trips expressly for beach recreation in comparison with those for whom beach recreation is incidental with other activities. The economic literature on travel cost method has attempted to address many of these issues, but they require concerted attention in survey design and data collection. Collection of primary data, however, is expensive, and it is likely that USACE and other organizations involved in beach replenishment will largely continue to make use of existing information in assessing recreational benefits. While unit-day values, employed by USACE, attempt to make adjustments for site quality and visitor types, structural benefit transfer methods that make use of existing valuation results within a theoretically consistent economic framework (Van Houtven and Poulos 2009) remains a promising alternative for assessment of recreational benefits. Perhaps reflecting uncertainty in recreation benefits estimation, current USACE guidelines permit recreation benefits to make up at most 50% of total project benefits. This limitation is arbitrary and has no basis in welfare economics.

Conclusions
Optimal management of beach erosion reflects a balancing of the economic benefits and costs of remedial actions, incorporating dynamic coastal processes. Economic benefits of preserving beaches include service flows accruing to nearby residential property owners (reflecting recreation opportunity and storm & erosion protection), recreational beach users (providing space for recreation & leisure activities and aesthetics), local businesses (enhancing business opportunity and potential revenue), and providing for environmental

habitat and non-use benefits. Non-market valuation methods provide a conceptual framework for producing empirical benefit estimates.

The hedonic property price method utilizes sales and housing characteristic data to parameterize a housing price regression model. The model can be used to predict current housing values, adjust values for changing characteristics, estimate marginal implicit prices of housing and environmental characteristics, and, depending upon the nature of the data on hand, can control for both observable and certain kinds of unobservable factors. With sufficient variation over time or space, marginal implicit prices can be derived for amenity and risk characteristics, such as beach width, beach length, dune width, dune height, presence of sea wall, flood zone, and others. Marginal implicit prices indicate individual marginal willingness to pay for characteristics associated with housing and reflect individual risk perceptions and preferences. Examples of models that can control for unobservable factors include the repeat-sales model (which uses information on multiple transactions for the same house) and the spatial regression model (which can account for spatial lag or autoregressive effects).

Recreation demand models focus on recreation trips as economic goods that are produced by households using purchased commodities (e.g. automobile, gasoline, automobile maintenance) and individual travel time. These elements determine travel cost, which is inversely related to the likelihood of visitation or number of trips (all else being equal). Recreation demand models examine trip intensity to given site or group of sites, or they study choice amongst a group of sites on a single or multiple choice occasion(s). Though, some models combine the two types of behavior. Recreation demand models can be used to estimate the economic value of a trip and the economic value of changing site characteristics. Difficulties in recreation demand modeling include accurately measuring travel cost (in particular opportunity cost of time) and problems incorporating site congestion.

Stated preference methods, like contingent valuation and choice experiments, can be applied to hypothetical housing or recreation choice, but also allow for measurement of non-use values. As the name implies, non-use values represent economic values that are independent of individual use of a resource. Non-use values include option, bequest, vicarious use, and existence values, any of which could be relevant for preservation of beaches. These benefits can reflect improvements in habitat for beach- and dune-dependent plant and animal species. Little empirical evidence exists on the magnitude of these values for beaches. Stated preference methods offer the only approach that currently exists to measuring non-use values.

Conceptually, economic benefits of beach maintenance accruing to local businesses could be estimated though analysis of firm behavior. Improvements in beaches may augment demand for recreation trips and complementary goods and services, such as sporting and recreation goods, food and beverages, overnight accommodations, sight-seeing and adventure tours, etc. The extent to which revenues exceed total costs of production, firms earn producer surplus, and changes in producer surplus stemming from beach replenishment are legitimate estimates of economic benefit for the firm. The author is not aware of any empirical evidence of these benefits. All economic benefits, rather measured through housing prices, recreation behavior, stated preferences, or firm behavior, can be estimated from primary data or approximated through the transfer of benefit information from previous studies. Structural benefit transfer, based on

specification of an underlying preference function to relate valuation results from different studies to economic benefits in a theoretically consistent manner, offers an improved methodology for transferring benefits from existing studies. (See, for example, Van Houtven and Poulos (2009).)

The economic costs of beach replenishment include expenditures on dredging, pumping and placing sand to maintain beach and dune area. Economic costs also include fixed costs for mobilization/demobilization, permitting, and other activities; transactions costs; and opportunity costs of any resources utilized for replenishment but not explicitly paid for (e.g. capital owned by a contractor for which no fee is charged). Other costs include negative environmental impacts on the near shore environment. The *Program for the Study of Developed Shorelines* at Western Carolina University has archived beach replenishment cost data extending back to the early 1960s. These data include monetary costs associated with direct expenditures and transaction costs, sediment quantities, and details on the project area (location, beach length). It is unclear whether the archived cost data include opportunity costs of capital equipment or other relevant measures of opportunity costs. The data do not include information on input prices or details of the 'borrow area' (e.g. depth and distance). Very limited empirical work exists on estimation of economic costs of beach replenishment, especially with regard to negative environmental costs.

Dynamic optimization models incorporate information on economic benefits and costs with representations of coastal dynamic processes, like erosion, storms, and sea level rise. The optimal erosion management models presented in this paper (equations [18] and [20]) offer a capital-theoretic approach that can incorporate all relevant economic benefits and costs and can be adapted to address beach replenishment rotations in the short term, as well as coastal protection in the long run. The models can be used to determine whether intervention in shoreline evolution is welfare enhancing, or justified on grounds of economic efficiency. In the short term, one can derive an optimal time path of the management and state variables, producing a schedule of optimal nourishment interval and requisite sediment loads.

In the long term, sea level rise increases erosive pressure on the shoreline and may render some coastal settlements indefensible. Much of the existing literature on coastal protection in the long run has focused on the value of coastal property that is threatened by sea level rise. As Yohe, Neumann, and Ameden (1995) point out, with full information on the risks of sea level rise, market depreciation over 30 years time could drive the value of this property to zero. While this outcome is complicated by uncertainty regarding sea level rise and the inherent lack of reliability in a commitment to abandon property, it can clearly be problematic to rely on such a subjective decision criterion for coastal policy making.

Employing the framework of the dynamic optimization models, an optimal long term strategy depends on the degree of erosive pressure (i.e. sea level rise), how this affects management costs, and the benefits of preserving the current shoreline. Long run applications of the models can examine whether beach replenishment is a tenable management practice over a long time horizon, given assumptions about sea level rise and costs and benefits. A termination of beach replenishment in the long run implies a policy of shoreline retreat, which would entail gradual migration of barrier islands and associated losses in property and infrastructure. A primary goal of the broader research

agenda on coastal erosion management should be estimation of the optimal timing of such a transition and an exploration of factors that influence this timing. Information on the optimal timeline of shoreline retreat could be instrumental in allowing the market value of threatened properties to properly adjust to the risk of sea level rise and invaluable for coastal planning and investment purposes. The dynamic optimization models utilized in this paper, however, are somewhat complex and do not readily lend themselves to heuristics or rules-of-thumb that could be applied by state and local governments in analysis of beach replenishment projects. Future research should focus on end-user applications that could be used for policy analysis.

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