COASTAL EROSION AS A NATURAL RESOURCE MANAGEMENT PROBLEM: AN ECONOMIC PERSPECTIVE

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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. Climate change threatens to increase the intensity of storms and raise sea level 18 to 59 centimeters over the next century. Following a lengthy tradition of economic models for natural resource management, this paper provides a dynamic optimization model for managing coastal erosion and explores the types of data necessary to employ the model for normative policy analysis.

The model conceptualizes benefits of beach and dune sediments as service flows accruing to nearby residential property owners, local businesses, recreational beach users, 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 and height. Other costs can include negative impacts on the nearshore environment. Employing these constructs, an optimal control model is specified that provides a framework for identifying the conditions under which beach replenishment enhances economic welfare and an optimal schedule for replenishment 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 examine the time horizon of management responses under sea level rise, identifying the timing of shift to passive management (shoreline retreat) and exploring factors that influence this potential shift.

Natural Resource Economics and Coastal Erosion

Landry (2008) and Smith, et al. (2009) cast beach replenishment as an optimal rotation problem, where resource managers select the appropriate time to add specific amounts of beach sediments 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). Let resource quality be represented by a time-dependent variable, q_t, which represents beach width. Both Landry and Smith, et al. focus on average beach quality (neglecting within-site variation in beach conditions).

The coastal planner's problem is to maximize net benefits of management actions subject to the erosion equation which describes how beach quality evolves over time. The coastal planner chooses the amount of beach replenishment to be conducted in each time period. The beach is a non-renewable resource that exhibits a decaying tendency, and the management control represents a contribution to the level of resource quality that counters this decay. 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.

Using control theory, the short-run management problem (over T years) can be represented as:

$$\max_{n_t} \sum_{t=0}^{T-1} \eta^t \{WTP(q_t) - C(N_t)\} \qquad [1]$$

subject to

$$q_{t+1} - q_t = -\theta + \tau\, n_t \qquad [2]$$

$$N_t = n_t \times l \qquad n_t \geq 0 \qquad [3]$$

$$q_{t=0} = q_0,\ q_T = free \qquad q_0 \geq 0 \qquad [4]$$

where WTP reflects aggregate willingness-to-pay (economic value) for beach quality level q_t; η^t is a discount factor; $C(N_t)$ represents the economic costs of beach replenishment, with N_t representing the total volume of beach fill added to the beach in period t; n_t is the volume of beach fill *per unit of beach length* (l); $q_{t+1} - q_t$ describes the dynamic motion for beach width; τ is a parameter that converts sand volume to incremental beach width; and q_0 is the initial beach quality condition. Equations [1] through [4] describe an optimal control problem with one control variable (n_t) and one state variable (q_t). Critical elements that must be specified by the empirical researcher are the economic value of beach quality (*WTP*), the economic costs of beach replenishment ($C(\cdot)$), and the morphodynamics of the shoreline (equation [2]).

Empirical evidence suggests that fixed costs are an important part of the economic costs of beach replenishment, as large amounts of capital equipment are required to produce any appreciable amount of replenishment sand. The existence of fixed costs leads to a rotation-type solution, with intermittent periods of nourishment followed periods of no activity. The rotation pattern can be incorporated and the model [1] – [4] solved through application of numerical dynamic programming (discretizing the state and control spaces and applying backward recursion). 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:

$$V_J(q_t) = \max_{n_t \geq 0}\{WTP(q_t) - C(n_t) + \eta V_{J-1}(q_{t+1})\}, \qquad [5]$$

where J represents the number of periods remaining. For the long-run problem (no set T), the value function in [5] can be iterated in order to find an steady state for different levels of erosion and these pieces of information can be combined in order to ascertain properties of the long-run management solution. Terminal time for beach replenishment can be defined by incorporating a transversality condition and imposing some regularity conditions on [5].

Economic Benefits of Beach Maintenance

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. It reflects tradeoffs that individuals are willing to make and is conditioned on individual's perceived values of the proffered resource and their ability to pay. Landry, Keeler, and Kriesel (2003) identify chief beneficiaries of beach erosion control as beach visitors and coastal property owners.

Recreation demand models can be used to assess visitors' value of access to beach sites. For example, Bin et al. (2005) estimate the value of a beach day in North Carolina at $11 to $80 per person, while Lew and Larson (2009) estimate the value of a California beach day at $21 to $23. Note, these are estimates of net economic value, and do not include the expenditures that visitors pay in order to access and enjoy the coast; such expenditures lead to economic impact for local and regional economies. Increases in beach area provide additional space for coastal recreation and leisure activities, and may enhance value by allowing for increased utilization of beach resources or by decreasing congestion for existing users. Landry, Keeler, and Kriesel (2003) find evidence that the value of a beach day increases with modest improvements in beach width, while Whitehead et al. (2008) find a positive but insignificant effect of increased beach width on visitor economic values.

The influence of beach quality on coastal property values can be analyzed with hedonic price analysis. This approach examines the variation in housing prices in order to test whether sales prices capitalize the value of spatial amenities. Pompe and Rinehart (1999) find that beach quality increases home values in South Carolina; a one foot increase in high-tide beach width increases the average coastal home value by about $81 and the average oceanfront home value by $311. Landry and Hindsley (2010) find that beach and dune width influence the value of homes within 300 meters of the beach. Increasing high-tide beach width by one meter increases the average property value by $421 to $487. These welfare measures reflect perceived storm and flood protection benefits, as well as recreational and leisure value of local beaches accruing to nearby residents.

Economic Costs of Beach Maintenance

Economic costs of beach erosion control include monetary costs of beach replenishment activities, transaction costs associated with permitting and planning, opportunity costs stemming from the use of resources owned by the agency or contractor conducting operations, and environmental costs associated with the impact of replenishment activities on the nearshore environment. Western Carolina University's *Program for the Study of Developed Shorelines* has archival data on monetary costs of beach replenishment for the majority of beach projects extending back to the early 1960s. Monetary costs typically include direct expenditures and some types of transaction costs. The government agency in charge of public beach maintenance projects, U.S. Army Corps of Engineers, uses cost calculation methods that attempt to capture the opportunity cost of capital used for beach replenishment. For other agencies and contractors, it is unclear whether the archived cost data include such adjustments. Little information exists on environmental costs of beach replenishment, but these costs can include environmental damages at the borrow site, the target beach, or adjacent communities (Greene 2002).

Shoreline Geomorphology

The transition equation [2] represents the geophysical part of the erosion management problem. Under some simplifying assumptions, the short term the τ parameter can be approximated by using information on berm height and "depth of closure". In the short term, the historical erosion rate, which reflects the average effect of coastal storms and the background rate of sea level rise, can be used as an estimate of θ. Under these conditions, the erosion control problem in [1] – [4] is time autonomous. Smith, et al. (2009) employ a composite erosion rate that includes a linear portion (reflecting historical recession) and an exponential portion (reflecting return to equilibrium profile); while more realistic, this setup renders the problem non-autonomous, making solution more difficult.

Landry (2008) posits a time path for θ that reflects long term seal level rise, and incorporates an evolving τ parameter as well. Dynamic erosion renders the optimal control problem as non-autonomous, and the problem become more difficult to solve. Under some simplifying assumptions, the terminal time for beach replenishment can be identified as the period in which total contemporaneous costs and benefits are equalized. 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%.

Conclusions

The optimal erosion management model offers a theoretical 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. Long run applications 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 this research is estimation of the optimal timing of such a transition. 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.

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