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# *The relative influence of humans on barrier islands: Humans versus geomorphology*

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## ABSTRACT

**Humans are an integral component of barrier island systems throughout the world. The diversity of cultures (e.g., economics, politics) present has as much influence on barrier island evolution as the diversity of environments (e.g., climate) in which they are found.**

**The actions of humans affect three inherent properties of barrier islands: Each island is individually unique in its physical and ecological setting (affected by direct "local" human activity), each island is linked to a chain of adjacent islands through longshore transport (affected by "regional" activity elsewhere), and each island responds dynamically to environmental change through cross-shore transport (affected by regional activity and shoreline stabilization).**

**Geomorphic carrying capacity is the resilience of barrier islands to human impacts. Geomorphic risk factors serve as a basis for predicting resiliency, providing both a measure of dynamic change (erosion rate and storm frequency) and available buffer space (island width and elevation). As risk factors increase, the dynamic and spatial character of an island comes into greater conflict with human landscape elements and is more likely to be altered.**

**The relative influence of humans on barrier island evolution can be estimated by comparing the anthropogenic impacts on the three major island properties to the island's carrying capacity. When the three properties have been completely altered, an island becomes entirely human-dominated, or "terminated." Carrying capacity can indicate whether stabilization, retreat, or abandonment is the best long-term management option.**

**Keywords:** barrier islands, coastal engineering, human impacts, shoreline stabilization, coastal hazards, coastal morphology.

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## INTRODUCTION

Barrier islands are complex natural landforms consisting of five distinct but interconnected sedimentary environments that include the barrier island (an elongated, usually sandy body) as well as tidal inlets and tidal deltas, a lagoon, and the shoreface (Oertel, 1985). Each environment is characterized by a unique combination of physical processes, and change in any one environment precipitates feedbacks and adjustments in one or more of the other environments. Barrier islands possess a variety of smaller-scale landforms that must include a beach and may also include dunes, maritime forest, blowouts, ponds, overwash fans, tidal flats, salt marsh, and/or mangrove forest. Davis (1994) provides general descriptions of these and other characteristic features of barrier islands.

Processes at a variety of spatial and temporal scales affect barrier island morphology. Table 1 lists some of the major barrier island processes and their influence on island morphology. Notice that the dominant processes on long, temporal scales such as sea-level change also tend to dominate over large spatial scales, as described by Baker (1986).

Barrier islands also possess inherent, qualitative properties unique among geomorphic systems. These qualities relate to three spatial patterns of sediment transport: intraisland, island-island, and island-shoreface. Every barrier island is an individual entity, possessing a unique combination of intraisland landscape features that vary according to its distinct physical and ecological setting (Dijkema et al., 1993). Each island is additionally a member of a longer chain of islands that are linked by alongshore sediment transport across tidal inlets. Third, barrier islands are linked by cross-shore sediment transport to the shoreface, which allows islands to shift dynamically and migrate in response to changing sea level, sediment supply, and wave action.

Humans have been an integral component of barrier island landscapes for thousands of years, directly and indirectly altering barrier island dynamics (Nordstrom, 2000). Cultural variability adds an additional level of complexity to barrier island dynamics. The intensity of cultural utilization of barrier islands ranges from negligible to extreme (e.g., grass huts on Ilha Bazaruto, Mozambique, versus high-rise buildings in Miami Beach, Florida). The intensity and type of human activity plainly affects the magnitude of the impact on barrier island dynamics, but differences among each island's natural physical and ecological characteristics also affect how a particular action will significantly impact an island. Each island has a "carrying capacity" that determines the extent of human influence necessary to displace natural island features and processes. The long-term evolution of barrier island systems will considerably depend upon the relative balance between natural and human dynamics.

This paper describes a new framework for describing barrier islands according to the relative influence of humans on island dynamics, incorporating humans as a distinct geologic agent—the anthropic force (Haff, 2002)—that drives landscape change in consort with environmental forces. This method involves assessing the human impact on the integrity of the three essential, inherent properties of barrier islands, and quantifying the natural island features and processes that determine an island's carrying capacity. Examples from a spectrum of physical and cultural settings are used to illustrate the potential usefulness of this approach. The anthropic force and its driving variables, as manifested on barrier islands, is also addressed.

### What Is the Anthropic Force?

The anthropic force is the sum of all human activities, in this case those that specifically affect barrier islands, spanning a large range of types and scales (Haff, 2002). Human activities are designed with a specific purpose and entail specific landscape alterations that enhance those activities. Common types of human activities on barrier islands include industry (e.g., sand and gravel mining, fossil-fuel extraction), agriculture (e.g., grazing, arable farming), recreation (e.g., roads, piers, buildings), and effects associated with navigation (e.g., dredging, jetties, marinas). Stabilization (e.g., seawalls, beach nourishment) may be introduced to defend any of these activities against natural dynamic changes on the island.

Anthropogenic activities alter an island's physical and ecological continuity and can disrupt the dynamic link between an island and its adjacent islands or the shoreface. On a small scale, these alterations can be manifested by eliminating landforms, altering their mobility, reshaping them, and altering them indirectly through use (Nordstrom, 2000). The impacts of human alterations can be broadly categorized as global (e.g., sea-level rise due to global warming), regional (e.g., subsidence due to oil drilling on the Mississippi and Niger Deltas), or local (e.g., loss of vegetation due to building construction).

TABLE 1. EXTENT OF BARRIER ISLAND PROCESSES AND THE ANTHROPIC FORCE

| Process | Anthropic force | Spatial extent | Temporal extent | Affected subenvironments |
|---|---|---|---|---|
| Sea level | Fossil fuels, subsidence | Global, regional | Centuries to millennia | Inlet, island, lagoon, shoreface |
| Sediment supply | Dams, mining | Regional | Decades to centuries | Inlet, island, lagoon, shoreface |
| Longshore transport | Dredging, jetties, groins | Regional | Years to decades | Inlet, island, lagoon, shoreface |
| Storms—overwash, retreat | Seawalls, beach nourishment | Regional | Years to decades | Island, shoreface |
| Eolian processes, vegetation | Bulldozing, buildings, grazing | Local | Days to years | Island, lagoon |

Categorizing anthropogenic impacts as global, regional, and local provides a convenient way to relate the impacts to one of the three inherent properties of barrier islands. Global and regional impacts on an island result from human activities not occurring on the island itself. They alter either the alongshore link between adjacent islands or the cross-shore link between the island and the shoreface. Local impacts result directly from activity on the island. These alter the unique physical and ecological features of the island.

Table 1 summarizes some major global, regional, and local impacts of anthropogenic activities on barrier islands, and lists the island processes and landforms most frequently affected by them. Worldwide observations suggest that temperatures are substantially higher than a century ago (Serreze et al., 2000) as a result of fossil-fuel burning (Crowley, 2000). Global sea level has also risen measurably, and this rise is expected to accelerate (Leatherman et al., 2003). Regional subsidence is a particular problem along deltaic barrier islands where hydrocarbon extraction is intense (Coleman et al., 1998; Cencini, 1998). Dams have significantly reduced the sediment supply (Milliman and Meade, 1983) and freshwater discharge (Wolanski et al., 1998) on many deltaic barrier islands as well. Examples of local alterations on barrier islands are abundant but typically include grazing, dune modification, deforestation, and urban construction. Bush et al. (1996) and Nordstrom (2000) provide more thorough descriptions of these activities and their impacts.

The anthropic force is driven by societal forces, including population, cultural values, economics, politics, technology, and information along with many others (Haff, 2002). These factors shape the decisions that result in human alteration to the landscape. Economic and political factors tend to be the most influential societal forces. Table 2 lists some of the possible differences that might develop between islands as a result of these factors.

## What Is Geomorphic Carrying Capacity?

Geomorphic carrying capacity is defined as a measure of an island's potential to respond to natural dynamic environmental forces while also influenced by human forces. The term "carrying capacity" is not applied here in the traditional sense of defining the population that a landscape or resource can sustainably support, although such a determination could be made for barrier islands. The geomorphic carrying capacity of a barrier island is exceeded when its evolution becomes human-dominated. This condition results from the loss of its three essential qualitative properties and thus its ability to respond to natural dynamic forces.

A fundamental assumption of this concept is that geomorphic carrying capacity is closely related to the likelihood that island processes might disrupt a human activity somewhere on the island. Natural barrier island processes such as erosion and flooding, which disturb human landscape elements, are typically perceived as hazards. The recognition of hazards often elicits a human response to further modify the natural landscape or halt the natural process to preserve its human use.

Each barrier island has its own unique physical and ecological landscape, is linked to adjacent islands by longshore sediment transport, and is linked to the shoreface by cross-shore sediment transport. The physical and ecological diversity of barrier islands arises from the variability of such elements as climate (Hill et al., 1994), wave energy and tidal amplitude (Hayes, 1979), sediment supply (Roy et al., 1994), sediment composition (Carter and Orford, 1984), underlying geology (Riggs et al., 1995), and vegetation (Godfrey et al., 1979). An island's characteristics will influence what impacts human activity will have.

The magnitude of a dynamic landscape process and its proximity to the human landscape determines the level of risk associated with a particular "hazard." The migration of dynamic landscape elements (e.g., shoreline erosion, inlet migration) toward fixed or expanding areas of human activity often results in an increase in risk over time. This may occur naturally or as an indirect result of other modifications by humans, such as jetty construction or inlet dredging. Human activities on the island that are farthest away from and minimally disturb island processes are subject to the least risk. A wide, stable island would thus have a greater geomorphic carrying capacity than a narrow, rapidly eroding island, in that it offers more possibilities to minimize risk. This potential is often not realized because of short-term decisions to develop unstable or marginal areas of an island.

A handful of easily determined island characteristics, or geoindicators (Bush et al., 1999), can be used to estimate an island's geomorphic carrying capacity. These include the island width, island elevation, rate of shoreline change, and storm frequency. These four factors are chosen because they will inevitably impact the evolution of barrier islands over the course of several decades (Bush et al., 1999).

Island width provides a measure of available space to minimize proximity to dynamic processes, the most dynamic of which is usually the active beach. The rate of shoreline change is the most important measure of an island's long-term stability with respect to sea level and sediment supply, and therefore allows a prediction of a human artifact's "expected lifetime." Storms are primarily responsible for flooding and damaging human development, whereas island elevation is a measure of an island's susceptibility to flooding.

Many other factors influence the impact of human alterations to the barrier island landscape. These will vary depending on the climatic setting, the scale of interest, and the human actions of

TABLE 2. CULTURAL VARIABILITY ON BARRIER ISLANDS

| Cultural Factor | Examples |
|---|---|
| Economics | Subsistence, industry, tourism |
| Politics | Zoning, construction setbacks |
| Technology | Seawalls, beach nourishment, relocation |
| Information | Storm history, erosion rate |
| Values | Conservation, business, recreation |

TABLE 3. FACTORS USED TO DETERMINE THE VALUE OF THE ANTHROPIC INDEX

| Factor | None | Clustered | Complete | Examples |
|---|---|---|---|---|
| Local | 0 | 1 | 2 | Buildings, roads, dune or vegetation removal |
| Regional | 0 | 1 | 1 | Jetty, dam, subsidence |
| Stabilization | 0 | 1 | 1 | Seawall |

particular concern. Such factors could include vegetation density, wind, or precipitation.

## METHODS AND ANALYSIS

### Quantifying the Relative Importance of the Anthropic Force on Barrier Islands

Understanding the relative importance of the anthropic force on barrier islands requires knowledge of the human actions that modify the island as well as the factors that affect geomorphic carrying capacity. Semiquantitative indices of these dual elements of island dynamics may be used to arrive at a preliminary estimate of the relative importance of humans to overall barrier island evolution. The "anthropic index" accounts for the intensity of human activity on the landscape, whereas the "geomorphic capacity" measures natural barrier island features and processes that determine its resilience to human impacts. The ratio of the anthropic index to the geomorphic capacity provides an estimate of the influence of the anthropic force relative to natural forces.

#### *Anthropic Index*

The anthropic index is expressed as an ordinal ranking based on three aspects of human alteration that correspond to impacts that affect local island features, linkage to adjacent islands, and linkage to the shoreface (Table 3). The total value for the anthropic index ranges from 0 (no impact) to 4 (greatest impact). Up to two points are assigned for direct, local impacts to the island surface. Patchy or clustered local development, which leaves a portion of the island surface unaltered, results in an impact of 1, whereas continuous development from end to end results in an impact of 2. A third point is assigned for impacts of regional actions that affect the linkage between islands, such as inlet dredging, jetties, groins, or other forms of sediment entrapment. Beach nourishment is also in this category despite the fact that increasing the island's sediment supply is construed positively by humans and could result in the restoration of some modified natural processes (Nordstrom, 2000). However, nourishment usually alters or eliminates processes such as overwash and eolian transport and often removes sediment from other portions of the island system. The final point is assigned for impacts to the link between the island and shoreface that allows dynamic change and island migration, such as seawalls and other forms of hard stabilization.

Barrier islands that have been urbanized from end to end, separated from adjacent islands by jetties, and stabilized by seawalls no longer possess their unique and essential properties, and are almost entirely human-dominated, or "terminated." The modern urban landscapes of Miami Beach, Florida, and Atlantic City, New Jersey, for example, are virtually interchangeable, although their native landscapes were very different. They are also unable to respond to dynamic change and have a greatly reduced sediment supply.

#### *Geomorphic Capacity*

The geomorphic capacity also ranges from 0 (low geomorphic capacity/high risk) to 4 (high geomorphic capacity/low risk). The index is based on an ordinal ranking of the four factors discussed above: rate of shoreline change, island width, island elevation, and storm frequency (Table 4). One point is assigned for each element that qualifies as low risk. The cutoffs between low risk and high risk, while somewhat subjective, are values that are significant on decadal time scales. An erosion rate of 0.5 m/yr or less is defined as low risk and greater than 0.5 m/yr as high risk, following the risk assessment methodology of Webb (1996). Island width of 0.5 km or less is defined as low risk and greater than 0.5 km as high risk: The global mean barrier island width of ~0.5 km (Stutz, 2002) provides the primary basis for this distinction. Island elevations of 3 m or less are considered high risk for flooding and overwash and greater than 3 m low risk: Three meters is generally higher than the maximum storm surge elevation for extratropical storms and for tropical storms less than category 3 on the Saffir-Simpson scale. Storm frequency was determined from the Global Tropical/Extratropical Cyclone Climatic Atlas (U.S. Navy, 1995). Tropical storm frequency was determined by counting the number of storms passing within 50 km of the island (Muller and Stone, 2001), whereas extratropical storms that passed within 250 km were counted due to the larger size of these storms. Tropical storm frequencies of more than one in

TABLE 4. FACTORS USED TO DETERMINE VALUE OF GEOMORPHIC CAPACITY

| Factor | | High risk (0) | Low risk (1) |
|---|---|---|---|
| Island width (km) | | 0.0–0.5 | ≥>0.5 |
| Island elevation (m) | | 0–3 | ≥3 |
| Rate of shoreline change (m/yr) | | >0.5 | ≤0.5 |
| Storm frequency (no./yr) | Tropical | ≥1/20 | <1/20 |
| | Extratropical | ≥5 | <5 |

TABLE 5. ANTHROPIC INDEX AND GEOMORPHIC CAPACITY INDEX FACTORS FOR 12 REPRESENTATIVE BARRIER ISLANDS

| Island | Width (km) | Elevation (m) | Erosion (m/yr) | Storms (freq)[†] | Local impacts (Index rating) | Regional impacts (Index rating) | RAI (Total rating) |
|---|---|---|---|---|---|---|---|
| El Choncho (CO) | 0.3 (0) | 1–3 (0) | 1–2 (0) | Trop: 0<br>Extra: 0 | 0 | 0 | 0.0 (Low) |
| Bazaruto (MZ) | 3.0 (1[‡]) | >10 (1) | 0 (1) | Trop: 10<br>Extra: 0 | 1 | 0 | 0.33 (Low) |
| Fraser (AU) | 5.0 (1) | >10 (1) | < 1 (1) | Trop: 15<br>Extra: [§] | 1 | 0 | 0.33 (Low) |
| Niger Delta (NG) | 3.5 (1) | >3 (1) | >3 (0) | Trop: 0<br>Extra: 0 | 1 | 1 | 0.67 (Mod) |
| Ajuruteua (BR) | 0.3 (0) | 1–3 (0) | >3 (0) | Trop: 0<br>Extra: 0 | 1 | 0 | 1.0 (Mod) |
| Kiawah (USA) | 1.0 (1) | 1–3 (0) | 0 (1) | Trop: 20<br>Extra: 14 | 1 | 1 | 1.0 (Mod) |
| Shishmaref (USA) | 1.0 (1) | 1–3 (0) | 1–2 (0) | Trop: 0<br>Extra: 10 | 1 | 0 | 1.0 (Mod) |
| Ameland (NL) | 1.0 (1) | >3 (1) | 1–2 (0) | Trop: 0<br>Extra: 8 | 1 | 2 | 1.5 (Mod) |
| Miami Beach (USA) | 1.0 (1) | 1–3 (0) | 1–2 (0 | Trop: 23<br>Extra: 2 | 2 | 2 | 4.0 (High) |
| Lido (IT) | 0.5 (0) | 1–3 (0) | >1 (0) | Trop: 0<br>Extra: 6 | 2 | 2 | >4 (High) |
| Futzo (TW) | 0.5 (0) | 1–3 (0) | >3 (0) | Trop: 49<br>Extra: [§] | 2 | 2 | >4 (High) |
| Nile Delta (EG) | 0.5 (0) | 1–3 (0) | >3 (0) | Trop: 0<br>Extra: [§] | 1 | 1 | >4 (High) |

[†]Tropical cyclone frequency = number per 100 years within 50 km; extratropical cyclone frequency = number per year within 250 km.
[‡]Index value shown in parentheses.
[§]No data.

20 yr and/or extratropical storm frequency of more than five per year were designated as high risk. The storm frequency parameter is poorly defined elsewhere, and these estimates are intended to provide a macroscopic definition of storm climatology. An island is considered high risk if either of the two storm frequencies are above the threshold.

### *Relative Anthropic Impact (RAI)*

The ratio of the anthropic index to the geomorphic capacity can be plotted as the relative anthropic impact (RAI) (Table 5; Fig. 1). An RAI of 0–0.5 indicates low relative influence of the anthropic force; 0.6–1.9, moderate influence; and 2–4, high influence. The divisions between low, moderate, and high are based on the approximation that a 1:1 ratio between the anthropic index and geomorphic capacity represents a balance between human and natural processes, and therefore a moderate human impact. A high ratio was then defined as 2:1 and a low ratio as 1:2. Several examples are provided to illustrate differences between islands with low, moderate, and high relative impacts.

*Low impact: Bazaruto Island, Mozambique.* Bazaruto (Fig. 2) is an extremely wide barrier island (over 5 km), possesses dune ridges up to 100 m high (Fig. 2A), and is at low risk from flooding and erosion. It is geologically complex, consisting of a modern dune complex overlying several Pleistocene eolian

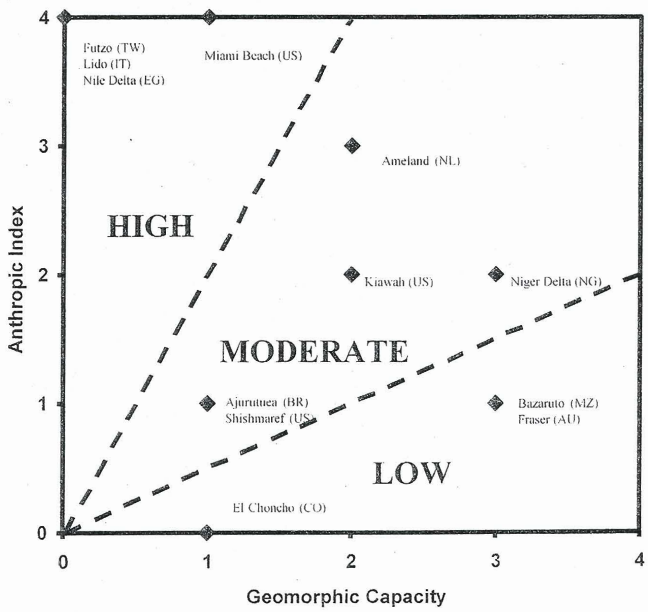


Figure 1. A plot of the anthropic index and geomorphic capacity for 12 selected barrier islands. The relative influence of humans on barrier island processes increases with an increase in the anthropic index or decrease in the geomorphic capacity. Bazaruto, Mozambique (low), Ameland, Netherlands (moderate), and Lido, Italy (high), are described in the text as representative islands on this scale. AU—Australia; BR—Brazil; CO—Colombia; EG—Egypt; IT—Italy; MZ—Mozambique; NG—Nigeria; NL—Netherlands; TW—Taiwan; US—United States.

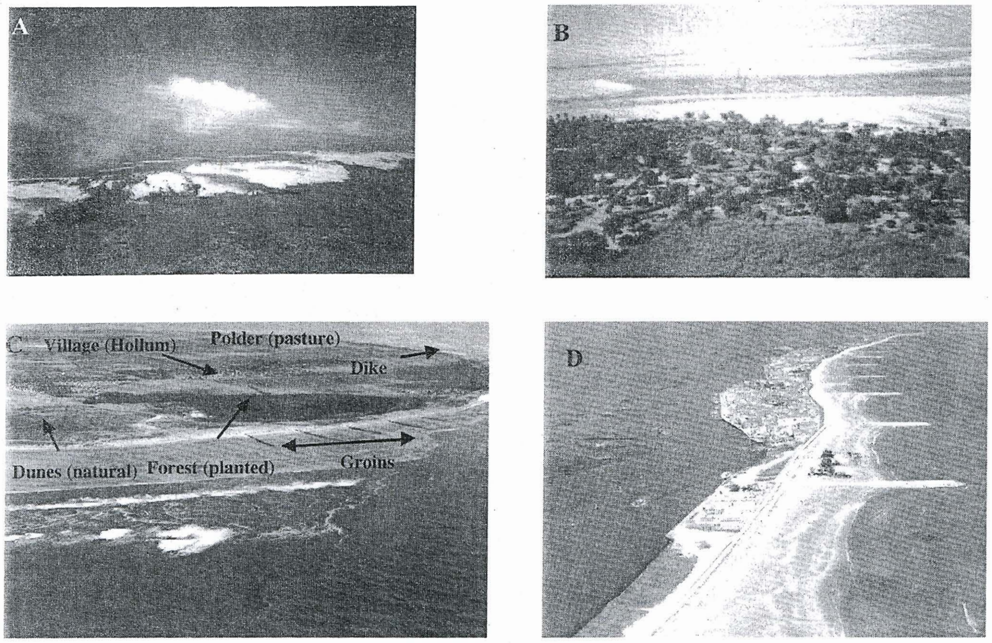


Figure 2. A: Bazaruto, Mozambique. High (~100 m) partially vegetated dunes on the seaward-facing side of the island, backed by a 2–5 km wide zone of older dunes and low-lying marshes and ponds. B: Typical village on Bazaruto consisting of several dozen small huts, located on the mainland-facing side of the island. Modified vegetation patterns are visible in and around the village. C: Ameland, Netherlands. Engineered or altered features on Ameland include an extensive dike/polder area, groins, artificial dune, and aforestation. Photo by Rijkswaterstaat. D: Lido, Italy. Seawalls and revetments surround the island of Lido, and groins extend along the entire shoreline. City development extends completely along and across the island, eliminating virtually all natural island features.

deposits (Cooper and Pilkey, 2002). Sea level has receded slowly since reaching a highstand 5000–6000 yr ago (Ramsay and Cooper, 2002), and therefore erosion rates are low. Beach rock provides additional resistance to erosion (Cooper and Pilkey, 2002). Bazaruto is subject to occasional tropical cyclones originating in the Mozambique Channel and is affected by swells from extra-tropical storms generated in the Southern and Indian Oceans. These characteristics give Bazaruto a geomorphic capacity of 3.

The population of Bazaruto is ~2000 (Pilkey, 2003). Most people occupy small straw huts in scattered villages typical of an east African subsistence-based society (Fig. 2B). Bazaruto is far removed from any coastal or river engineering that would create regional impacts and is not stabilized. The anthropic index is 1, resulting in an RAI of 0.3, reflecting a low influence of the anthropic force on Bazaruto. Because the dunes are large and transgressive, development occurs preferentially along the lower-elevation, landward shoreline, which does increase the probability of flooding.

Other low-impact barrier islands include Fraser Island, Australia, and El Choncho, Colombia (Table 5). Fraser Island is larger than Bazaruto, and its geology and environmental settings are similar. The entire island is designated as a World Heritage Site, thus development is sparse and human influence is low. The tropical island of El Choncho is low and narrow and has a much lower geomorphic carrying capacity than Bazaruto or Fraser Island. El Choncho is presently undeveloped, although a village was sited there until 1998, when it was relocated to an inland beach ridge complex (Correa and Gonzalez, 2000).

***Moderate impact: Ameland, Netherlands.*** Ameland is a drumstick-shaped island on the North Sea coast. The narrow portions of the island have high dunes once backed by salt marsh (Fig. 2C). Much of the fringing marsh has been reclaimed by dikes and converted to farmland that surrounds four scattered villages. Erosion is greater than one meter per year, and winter storms are frequent, which results in a geomorphic capacity of 2.

The island has been impacted by centuries of both island and lagoon reclamation. The effect of lagoon reclamation has been to reduce the lagoon area, which diminished the tidal prism and increased the rate of inlet migration to the east (Fitzgerald et al., 1984). Beach nourishment is periodically performed, and local sections of the beach are stabilized with groins. A significant area of the island remains unaffected by engineering, and the anthropic index is 3. The RAI for Ameland is a moderate impact of 1.5.

Other moderately impacted islands include Kiawah Island, South Carolina, the Niger Delta, Ajuruteua, Brazil, and Shishmaref, Alaska (Table 5). Kiawah Island is similar in shape to Ameland but is largely unstabilized. A healthy building setback has preserved the smaller primary dune and some interior dunes, but an increase in the island erosion rate would likely trigger shoreline stabilization. Most islands on the Niger Delta are several kilometers wide and densely vegetated. Native villages are subsistence-based, but subsidence and extensive engineering by the oil industry, including jetties, river dredging, mining, and dams, have regionally impacted the delta islands, resulting in local erosion rates of 30 m/yr (Ibe, 1996). The narrow tropical island of Ajuruteua is similar to El Choncho with low elevations. It is one of the few northern Brazilian barrier islands with road access, and a small seasonal tourist industry supports some modest buildings. The erosion rate varies greatly along the island and is as high as 25 m/yr in some locations, but stable in others (Souza-Filho and Cohen, 2003). Buildings are regularly moved landward, but stabilization is not currently present. Shishmaref Island has a small Inupiat village located on the Bering Strait. Development is confined to the northeastern end, but frequent storms and high erosion rates prompted the introduction of hard stabilization along the developed portion (Pilkey, 2003).

***High impact: Lido, Italy.*** The barrier island Lido that protects Venice Lagoon is narrow with low elevations. Erosion rates are historically high, and flooding frequently occurs during *aqua alta* or "high water" (Pirazzoli and Tomasin, 2002). These elements give Lido a geomorphic capacity of less than 1.

Very few natural features remain on Lido (Fig. 2D). The two adjacent inlets are jettied, the entire oceanfront is seawalled, and the lagoon shoreline is diked. Development on the island itself runs end to end. Subsidence is a particular problem for the entire coast due to hydrocarbon withdrawal on the Po Delta just to the south (Cencini, 1998). The resulting anthropic index is 4 and the RAI is $\infty$.

Lido is the stabilized endpoint of the anthropic force. The point at which island processes are virtually halted, such as on Lido, can be called "island termination." Miami Beach, Florida is typical of "terminated" islands in the United States, with multistory urban development, long seawalls, nourished beaches, and jettied inlets. Many Taiwanese islands, such as Futzo Island, are no longer even true barrier islands. Complete lagoon reclamation has connected the former islands to the mainland to allow industrial development (Pilkey, 2003).

Based on this study, ~12% of barrier islands on the U.S. Atlantic and Gulf of Mexico coasts have reached "island termination," and another 36% are in the high-influence category. Globally those numbers are ~5% and 15%, respectively.

## INFLUENCE OF THE ANTHROPIC FORCE ON BARRIER ISLAND EVOLUTION

The global impact of the anthropic force on barrier islands is accelerating, with an increase in the amount of island development almost inevitable. Between 1950 and 1975, the amount of urban development on barrier islands in the United States increased 150% (Lins, 1980). At the same time, sea-level rise is accelerating (Leatherman et al., 2003) along with island erosion rates, overwash frequency, and island migration rates.

The variables and derivative indices used to estimate human impacts are intended to reflect processes and changes that occur over a decadal scale or greater (Bush et al., 1999). Island development progresses over many years, and the impacts of jetties and hard stabilization may not become apparent for a few decades (Pilkey and Wright, 1988). Likewise, erosion is often evident only on longer time scales. Storm events of memorable strength occur relatively infrequently but are pivotal events in an island's history. An island that appears to be only slightly impacted by humans may become severely impacted over decades, given a modest erosion rate.

Several models describe the stages of barrier island evolution related to human development (Meyer-Arendt, 1993; Nordstrom, 1994; Pilkey, 2003). Nordstrom's evolutionary stages may be summarized as (1) initial clustered development, (2) alongshore expansion, and (3) island stabilization. In Stage 1 the influence of the anthropic force is confined to small clustered areas, and it spreads along the entire island during stage 2. Natural island features and alongshore heterogeneity are gradually eliminated between these stages. Transition to stage 3 results in complete development of the island surface and total severance from the adjacent islands and shoreface. This is a typical sequence of events on American and European barrier islands, taking anywhere from a few decades to a century to reach an endpoint. These three stages also generally correspond to low, moderate, and high relative influence of the anthropic force on island evolution.

The development of Nags Head, North Carolina, serves as a historical analog to many barrier islands (Pilkey, 2003; Pilkey et al., 1998). Native Americans spent only the summer months on the island and built no permanent structures. During initial European settlement, a few small buildings harbored those seeking isolation—from the law as well as society in general—within the maritime forest along the lagoon shore. Tourism in the nineteenth century saw more earnest structures such as hotels, still located near the lagoon, and then ushered in small fishing shacks near the beach. True beach houses did not appear until ca. 1900 and were rolled back by mules and logs when the shoreline came too close. These original lots were up to 600 ft (183 m) deep. The real shoreline rush occurred after World War II, when houses increased dramatically in size and density, and high-rise buildings appeared. Stabilization is now imminent with a 14-mile-long (23.3 km) nourishment project approved for initiation in 2004.

Existing models all highlight characteristic patterns in human development. None include the parallel history of storms or long-term erosion that at various times forced decisions to move buildings, build seawalls, or nourish beaches, although Nordstrom (2000) separately describes patterns of storm damage and recovery on developed islands. Nor do these models account for the fact that each island is affected differently by storms due to their geomorphologic variability, although such knowledge is well established (Bush et al., 1996, 1999).

The long-term evolution of barrier islands is probably more closely linked to their physical uniqueness than generally acknowledged by models of barrier island development—

although human decisions at critical evolutionary stages will most likely determine the ultimate fate of barrier islands. These decisions inevitably involve a response to a perceived hazard due to dynamic island processes. This could be caused by long-term erosion, erosional inlet cycles, or storm damage. The risk gradually increases as the island is progressively altered and development encroaches on the most dynamic areas. Stabilization is not the only endpoint of human development: Humans can alter their use to be more compatible with dynamic natural landforms and processes (i.e., retreat), or else abandon the island entirely. These decisions may be heavily influenced by economic, political, and technological factors.

Figure 3 presents an alternative model for barrier island evolution in tandem with the anthropic force. The important difference between this and other models is the inclusion of four decision pathways that link island processes and human decisions (growth, retreat, stabilization, abandon). The model is highly individualized for each island, depending on the island environment, and depends upon the type of human activity. The progression between "stages" is not necessarily linear as in other models. Rather, the process shown in Figure 3 is cyclic to accommodate the human decision-making process, which may change through time.

**Path 1: Growth**

This commonly represents islands in the initial development stage, when the relative influence of the anthropic force is low to moderate. Development tends to be clustered, as on Bazaruto,

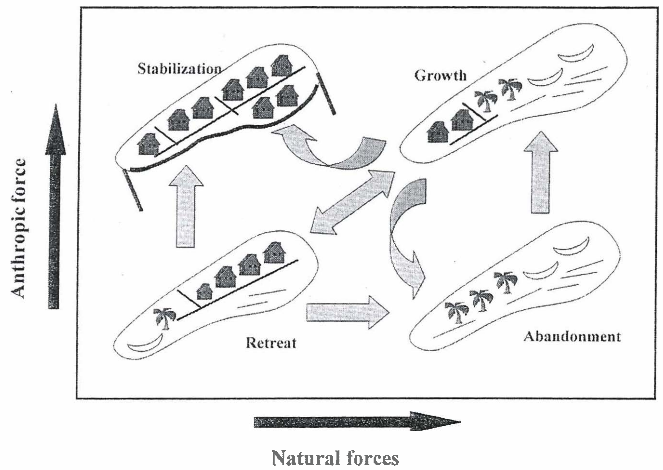


Figure 3. Conceptual model of human-influenced barrier island evolution. Evolution involves inputs and feedbacks from both humans and natural processes. Humans initially utilize the island (growth) with little or no impact on the island evolution, although its extent generally increases with time. As natural processes increase the risk to human landscape elements, humans can decide to alter its use (retreat), abandon its use, which removes human influence, or stabilize dynamic island processes, which removes natural influence.

and stabilization is unnecessary. This stage may eventually result in complete alteration of the island surface. Kiawah Island is nearer the transition point than Bazaruto. Therefore, the relative strength of the natural and anthropic forces in Figure 3 can vary greatly. Islands with a high geomorphic carrying capacity and a low rate of development will progress more slowly through this phase than rapidly developed or high-risk islands.

**Path 2: Stabilization**

Densely developed islands inevitably face greater risk due to the cumulative impacts of alterations and the expansion of activities into areas that are most directly impacted by major risk factors such as storm flooding and erosion. Miami Beach, Florida, and Atlantic City, New Jersey, possess dense urban development patterns, and stabilization has been in place for decades. For these islands, development has essentially reached an endpoint since no further modifications to the islands are possible. Beach nourishment offers limited restoration potential for the beaches on such islands (Nordstrom, 2000). Beaches, however, represent only a small portion of the island, the vast majority of which is permanently altered.

Stabilization with seawalls, breakwaters, or other hard structures is illegal in several American states (Bush et al., 1996) and in the Netherlands (Koster and Hillen, 1995), and therefore beach nourishment is widely performed in its stead. Because hard stabilization often leads to beach loss (Pilkey and Wright, 1988), nourishment has also become ubiquitous on seawalled islands.

**Path 3: Retreat**

Stabilization is expensive to maintain and is not a viable economic option for many barrier island communities. These communities must adapt to risk or abandon use of the island. Prior to being abandoned, the village of El Choncho moved several times when it was threatened by erosion (Fig. 4A). Houses, assembled in panels so that they may be easily disassembled and rebuilt, were at various times moved landward, alongshore, or to an adjacent island. The Hunting Island, South Carolina, and Cape Hatteras, North Carolina, lighthouses have also been moved as opposed to stabilizing their islands (Pilkey et al., 2000).

On the island of Texel, Netherlands (Fig. 4B), another form of retreat has taken place. Maintenance of the shorefront artificial dune was discontinued in 1925, allowing a small natural tidal channel and salt marsh, called the Sluifter, to be reestablished (van der Meulen and van der Maarel, 1989). The dune was moved 1 km inland to preserve the continuity of the island's dike system. The Sluifter greatly enhanced the ecological and geomorphic diversity of Texel. This flexibility is possible on Texel, which is several kilometers wide, and has a relatively high geomorphic carrying capacity.

Similar approaches could be used to manage the Cape Hatteras National Seashore on Hatteras Island, North Carolina, where eight communities are separated by up to ten miles. Like Texel.

Hatteras Island has a large artificial dune that was constructed in the 1930s to protect the primary highway linking the island communities, and which promoted development. The dune prevented overwash and allowed dense vegetation to grow, transforming the island from its prior low, barren state, and eliminating a large area of ideal shorebird habitat. Halting the maintenance of the dune could restore much bird habitat, but Hatteras Island is less flexible than Texel because it is much narrower, and ceasing maintenance of the dune would require moving the highway into the existing marsh (Rice, 2000).

### Path 4: Abandonment

A large number of barrier islands throughout the world are undeveloped by humans, but many of these very same islands were occupied in the past. Abandoned islands are no longer locally influenced by human activity, although they can be affected by regional or global human impacts.

Islands can be abandoned for many reasons. Usually islands that are low, narrow, and rapidly eroding are most likely to be abandoned or remain undeveloped. Anthropogenic resources are highly vulnerable to large shoreline changes and catastrophic storm impacts, and the cost of protecting them are extreme. Wealthy societies are more likely to attempt stabilizing such islands, whereas poor societies may have no choice but to move to more stable ground.

Early in the 1900s, when large cities such as Galveston benefited from seawalls, many smaller coastal towns in the United States were abandoned. These include Eddingsville Beach, South Carolina, Broadwater, Virginia, and Diamond City, North Carolina. Abandonment is routine in remote coastal areas of Colombia, such as El Choncho, where earthquakes cause subsidence-induced erosion and occasionally produce devastating tsunamis.

## DISCUSSION

The concept of barrier island geomorphic carrying capacity provides a framework for identifying the resilience of islands to human impacts on time scales greater than one to two decades. In human-influenced landscapes, humans tend to dominate processes on short time scales (Haff, 2002). Local alterations to the island surface (e.g., roads, buildings) immediately change the landscape. Thus, short-term island evolution will be strongly determined by human decisions such as where structures are placed. For example, the high-risk beachfront is frequently developed before the island interior (Meyer-Arendt, 1993). On longer time scales, buildings will likely be subject to the impacts of erosion or a major storm regardless of their initial placement. Rapidly eroding islands are more likely to be stabilized in the long term, reaching termination more quickly than stable or accreting islands.

An association between risk and anthropogenic impacts is not new. The benefits provided to human development by natural island features were described by Pilkey et al. (1975) and were probably recognized by most early (i.e., pre–twentieth-century) barrier island inhabitants. Pilkey and Neal (1980) and Bush and Pilkey (1994) used the hypothetical "Fantasy Island" to illustrate development patterns that utilize and conserve natural features and processes. Geomorphic-based methodologies are widely used to identify coastal hazards and quantify risk (Bush et al., 1996; Webb, 1996; Bush et al., 1999; Rice, 1999; Sallenger, 2000; Morton, 2002).

Island termination occurs when an island becomes entirely human-dominated, losing all of its inherent natural properties. Two types of terminated islands can be distinguished. The first


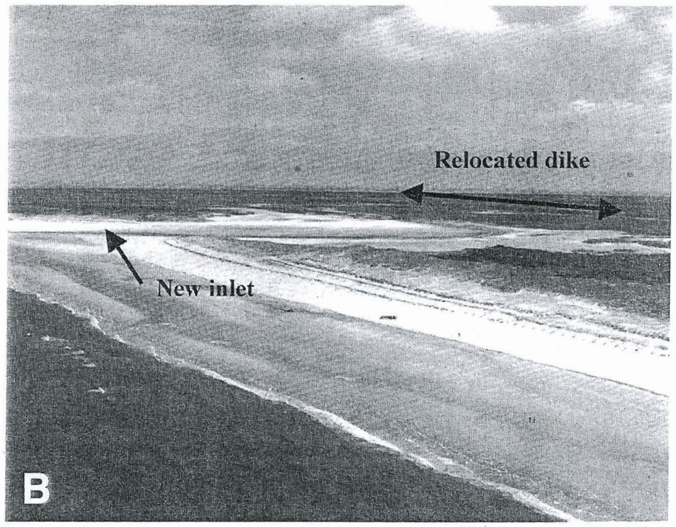


Figure 4. A: El Choncho, Colombia. A small structure threatened by erosion and overwash. Tectonic subsidence results in high erosion rates on the San Juan Delta. Mean sea level also rose 30 cm during the 1997–1998 El Niño, inducing overwash during ordinary high tides even in calm wave conditions. Note the ineffectual timber seawall in the background. Photo by R.A. Morton. B: Texel, Netherlands. The Sluifter, a small tidal channel and marsh once closed off by a sand dike. The inlet originally divided Texel from the island Eijerland. In 1925, the sand dike was moved approximately one kilometer inland, and the inlet was allowed to reopen, rejuvenating a natural salt-marsh community. Photo by Rijkswaterstaat.

type is dominated by tourism development (Meyer-Arendt, 1993; Nordstrom, 1994), common in, but not exclusive to, the United States, Europe, and Mexico. The second type is dominated by industrial development, common to deltaic barrier islands on the Niger and Mississippi Deltas as well as barrier islands in Taiwan and Abu Dhabi. It often takes many decades for tourist islands to reach termination, but industrial islands may reach termination much more quickly. Ninety percent of Taiwan's barrier islands have literally disappeared in half a century due to industrialization (Pilkey, 2003).

The criteria used to define the anthropogenic impact and geomorphic carrying capacity are intended to indicate fundamental shifts in the mode of island evolution—natural versus human-dominated—rather than quantitatively detailed landscape change. Therefore, the model is based on the general spatial pattern of development relative to the basic spatial patterns of island morphology and sediment transport (i.e., intraisland, island-island, and island-shoreface). It is applied on an islandwide scale because islands are whole entities and the development of each tends to evolve independently and be governed by its own municipality, which may result in major differences in development patterns of adjacent islands that are geomorphically similar.

The specific criteria used in this model do have certain limitations. For example, island length could be an additional consideration. Given an equal rate of development, 50 km long Hatteras Island would take a longer time to reach complete development than adjacent 20 km long Ocracoke Island, North Carolina. Island characteristics such as the width, elevation, and erosion rate also become more variable with greater length, making average values less meaningful. The island erosion rate, for example, might be better represented relative to the island width. A narrow island with a low erosion rate might take the same amount of time to erode as a wider island with a higher erosion rate.

The quantification of the anthropic index could also be revised and improved. As presented here, a single jetty is assessed the same impact (i.e., value) as two jetties, and the addition of other regional impacts, such as dam construction, would likewise not change the impact value. Clearly more detailed levels of differentiation can be achieved.

The concepts introduced in this paper could be developed further, depending on the scale of interest. Impacts of specific human activities could be compared on islands in different climates (e.g., grazing threshold in arid versus humid climate). Impacts of different alterations to a specific island feature, such as dunes, could be compared according to the degree of naturalness (Nordstrom, 2000). A comparison of the relative island response to major economic activities, such as beach nourishment, will be increasingly important (Haff, 2002).

Many barrier islands have yet to be strongly impacted by humans. There are considerable opportunities to apply some of these concepts—and those being developed in the area of risk mapping—to plan barrier island development to preserve much of an island's unique character. Islands with a high geomorphic carrying capacity are better candidates for a retreat strategy than those with a low carrying capacity, where stabilization or abandonment might be the only feasible alternatives. For example, retreat would be impractical on islands with high erosion rates or frequent storms because structures would need to be moved too often. Wide islands conversely provide enough space to allow retreat as long as the development density does not prohibit it.

## CONCLUSIONS

The relative influence of humans (the anthropic force) on barrier island evolution is a function of both human actions and island resilience. Human activity can affect the three fundamental properties of barrier islands—physical and ecological uniqueness, their link to adjacent islands, and their link to the shoreface. Local human activities alter the physical and ecological character of an island, whereas regional and global activities affect the island's links to adjacent islands and/or the shoreface.

An island's resilience, or geomorphic carrying capacity, is based on the morphology of an island and environmental processes that occur on that island. The island's size and its rate of dynamic change fundamentally affect human activity because they present a degree of risk to the human elements of the landscape. If the degree of risk is high (e.g., narrow, low elevation, rapid erosion), then humans perceive a need to stabilize the island, eliminating its links to adjacent islands and its ability to migrate, resulting in a greater reduction of natural island processes.

The anthropic index was developed to quantify human actions on an island based on the presence of local and regional impacts. The ratio of the anthropic index to the geomorphic carrying capacity, RAI, can provide a preliminary estimation of the relative influence of the anthropic force on barrier island evolution (i.e., human dominance versus natural dominance).

An island is "terminated" when its geomorphic carrying capacity is exceeded. Terminated islands can no longer migrate, are separated from adjacent islands, and no longer retain their locally unique natural features. At this point their evolution is completely human-dominated. Given an equal rate of human development, islands with a higher geomorphic carrying capacity will reach termination more slowly than islands with a low geomorphic carrying capacity.

The concept of barrier island geomorphic carrying capacity can be developed in greater detail to predict more specific impacts of human activity as a function of an island's climatic and geologic variability. It is also a useful framework for identifying islands that are vulnerable to extensive human impacts, as well as managing island development and preservation strategies that maximize the preservation of barrier island landscapes.

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