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Beaches and dunes of human-altered coasts

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Abstract: Landforms are created, reshaped or eliminated to suit human needs. These alterations affect the mechanisms of change, freedom of movement, locations of sources and sinks for sediment, internal structure, outward appearance and spatial and temporal scales of landform evolution. The processes by which landscapes are transformed by human agency follows a progression of alterations that may be subtle or overt, planned or unplanned, but most of them are predictable. Models of change for human-altered coasts may be formulated by viewing them as open or closed systems. Alternative methodologies for examining evolution of these coasts include: 1) comparing and contrasting a developed area with an undeveloped area that is assumed to have the same process controls; 2) assuming that the kind of shoreline change that occurred in the recent past will continue unabated by local actions; or 3) basing predictions on probabilities of future human action. Evidence suggests that human alterations are an integral component of landscape evolution. Future challenges for scientists include: 1) formulating conceptual and predictive models of landform dynamics that evaluate humans as an endogenic process and include assumption about human actions; and 2) providing scientific criteria for maintaining landforms in developed areas in ways that safeguard or promote an optimal diversity of landforms, species and ecosystems. Controlled disturbance may be required to create landforms compatible with natural landforms in appearance and function if not in genesis.

Key words: beaches, coasts, dunes, geomorphic systems, landforms, sediments.

I Introduction

Coastlines of the world have been altered over millennia (Marsh, 1885; Walker, 1981a; 1984; Innocenti and Pranzini, 1993; Warne and Stanley, 1993), and there is no indication that development will cease, despite accelerating costs of land and protection from coastal hazards (Pilkey and Wright, 1988; Titus, 1990; Nordstrom, 1994). Increasing population pressure, combined with the desirability of shorelines for human investment, habitation and use, make the development of the coastal fringe widespread, inevitable and, in many cases, irreversible and incontrovertible under present management practice (Walker, 1981a; Fabbri, 1985; Nordstrom, 1990; 1994).

The proportion of publications devoted explicitly to human-altered coastal landforms is relatively small compared to so-called natural landforms, considering the scale of human impact. Articles on the geomorphology or sedimentology of developed coasts are rare in basic research journals, with some important exceptions (Morton, 1979; Kim and Huntley, 1986; Short, 1992), although the number of contributions has increased recently as a result of the initiation of the *Journal of Coastal Research*. Articles in environmentally orientated journals (e.g., Carter *et al.*, 1981; Zabawa *et al.*, 1981) and publications orientated towards planning, management or societal aspects of coastal change (e.g., Platt *et al.*, 1987) are plentiful and contain valuable insight to the human processes operative in developed coastal systems and the way shorelines have been modified from natural conditions. Numerous specialty conferences, hosted by planners, managers and engineers, provide a steady stream of articles on the effects of shore-protection strategies and the trade-offs between loss of natural components of the landscape and human benefits as a result of human development. Books and reports that discuss the regional geomorphology of developed coastlines (e.g., Chapman, 1989) also provide useful baseline data that can be used to formulate or evaluate models of developed systems. Despite the vast literature on human-altered coastal systems in these forums, there is little research conerned with the processes that create and shape the landforms themselves or the geomorphic significance of human agency on long-term evolution of coastal landscapes. Human alterations are often viewed as an aberration rather than as an integral component of landscape evolution (e.g., Pilkey, 1981; Wolff, 1989), despite the omnipresence of humans in the coastal zone (Walker, 1984).

The purpose of this review is to examine the literature on developed coasts to identify the many ways that human activities alter coastal landforms, to reveal the pervasive nature of the conversion process and to demonstrate why human alterations should be viewed as an integral component of landscape evolution. The review is confined to publications that have appeared since 1980, with the exception of a few key works that appeared prior to that time. The focus is on beaches and dunes and their vegetative cover on the coasts of oceans and seas. Space constraints preclude inclusion of the vast literature on estuarine environments, although human alterations of the coasts of estuaries have been profound (Walker, 1984; Williams, 1991; Nordstrom, 1992), and many of the modifications in estuaries affect open-coast processes and landforms adjacent to them (Carter, 1985; Orford *et al.*, 1988). I have also excluded human alterations on coastal cliffs (e.g., Williams and Davies, 1980) and alterations landward of the coastal zone that affect sediment budgets and indirectly affect landforms, such as changes in land use within watersheds (Caputo *et al.*, 1991; Innocenti and Pranzini, 1993; Hands *et al.*, 1993). There is no attempt to provide coverage of physical processes and landform evolution on undeveloped coasts (recently reviewed in Sherman and Bauer, 1993a; 1993b), except where required to place landforms on developed coasts in perspective. Studies from the planning or engineering literature are not discussed unless there is a strong geomorphological component.

II Large-scale landscape conversions

The scale of human alterations to coastal landforms runs the gamut from unconscious actions taken by individual shorefront residents or visitors to preplanned and massive construction projects that convert entire natural landscapes to cultural landscapes employing a considerable investment of capital and labour. Most coastal communities undergo incremental development that progresses through stages, from an exploration stage, through a period of commercial involvement and infrastructure development, followed by a settlement-expansion stage and then an increase in intensification of sites already developed (Meyer-Arendt, 1990). Isolated shorefront communities may undergo periods of stagnation, disinvestment and economic decline because of obsolescence of facilities, diversion of investment interest elsewhere or loss of beach resources (Meyer-Arendt, 1990; Stansfield, 1990; Hoffman, 1992), but buildings remain in place to affect coastal processes, and shore-protection projects may still be implemented to protect the existing infrastructure. Human structures can affect processes and shoreline morphology millennia after they are constructed and have lost their human value (Paskoff and Oueslati, 1991).

The scale and types of shore-protection projects also undergo a fairly predictable progression. The dimensions of structures increase through time as structures that fail are built to increased size and cost (Pilkey, 1981; Kana, 1983; Reynolds, 1987). The types of structures change in frequency of implementation depending on changing preferences of residents and attitudes of planners and engineers, usually revealing an early preference for groins, followed by a period of construction of shore-parallel structures, to a period of beach nourishment that is currently in vogue (Caputo *et al.*, 1991; Kana, 1991; Paskoff and Kelletat, 1991; Nordstrom, 1994).

The literature is filled with examples of locations where recent coastal development has been rapid or now dominates the landscape (Walker, 1988). The pace of development of resorts is especially rapid. Marco Island, Florida, progressed from a wilderness to a fully developed shoreline, complete with protection structures, in fewer than 20 years (Reynolds, 1987). Coastal tourism is a rapid-growth industry that may be the most important asset of developing countries (Huber and Meganck, 1990), but in many locations growth has been with little direction and control, and construction is frequently incompatible with beach dynamics because selection of sites for resorts is based on nongeomorphological factors (Wong, 1990). The coast of the Mediterranean Sea is another location that has recently experienced accelerated construction to accommodate fast-growing tourist and residential populations, resulting in decreased space for both natural areas and recreation (Fabbri, 1985; Cencini *et al.*, 1988; Haeseler, 1989; Caputo *et al.*, 1991; Warne and Stanley, 1993).

Changes on the coasts of The Netherlands and Japan, in constrast, represent more consciously planned approaches. Changes in The Netherlands include closure of tidal inlets and construction of massive dikes in addition to the large-scale beach-nourishment projects that characterize other developed coasts (Rijkswaterstaat, 1990; Louters *et al.*, 1991; Short, 1992). The coastline of Japan has been drastically altered by massive engineering projects (Nagao, 1991), and the total length of protection structures along the coast is 10 000 km (Nagao, 1991). Many coastal areas in Japan have been built as human artifacts and bear little resemblance to the landscape that formerly existed (Kawaguchi *et al.*, 1991; Maeda *et al.*, 1991; Nagao and Fujii, 1991; Yamazaki *et al.*, 1991).

The northeast coast and California coast of the USA have been well studied because of their high density of population, the intensive pressure for further development and their vulnerability to damage from storms. The northeast coast of the USA is a shoreline of low relief, and human adjustments can readily dominate the landscape or substantially alter processes, sediment exchanges or landforms over large regions (Nordstrom, 1994). Large portions of New York, New Jersey and Maryland are dominated by cultural features. The New Jersey coast has the longest history of stabilized barrier-island shoreline in North America; it has the most developed coastal barriers and the highest degree of stabilization in the USA; and it has been identified as a template by which developing barriers can be evaluated to show the incompatibility of shorefront development (Pilkey, 1981; Mitchell, 1987; Nordstrom, 1987a; Pilkey and Wright, 1988; Hall and Pilkey, 1991). The conversion of the coast of California has been more subtle in its visual impact, but the natural beach/dune environment has been transformed considerably. Few visitors (or residents) realize that much of the city of San Francisco lies atop a massive coastal dune field (Sherman, in press); that the beaches in southern California have been modified by massive quantities of beach nourishment (Woodell and Hollar, 1991); or that foredunes (and some secondary dunes) have been consciously eliminated or prevented from forming landward of the beach along much of the developed shoreline (Nordstrom and Psuty, 1983; Sherman, in press).

III Creating, reshaping or eliminating landforms to suit human needs

The conversion of the natural landscape to buildings and shore-protection structures is apparent to nearly every visitor to the coast. The more subtle alterations to the natural landforms that comprise the shoreline are not as conspicuous, but they result in changes in the shape, size, location, internal characteristics and mobility of the landforms. The litany of 'consumptive' uses that alter landform characteristics and introduce disequilibrium conditions is long, particularly in the dune environment, and it includes the destruction of stabilizing vegetation through pedestrian trampling or off-road vehicles associated with recreational use (Eastwood and Carter, 1981; Wiedemann, 1984; Carter, 1985; Williams and Randerson, 1989; Guilcher and Hallégouët, 1991; Sanjaume and Pardo, 1992); mining for minerals, liming material or construction aggregate (Mather and Ritchie, 1977; Tinley, 1985; Haeseler, 1989; Guilcher and Hallégouët, 1991; Sanjaume and Pardo, 1992); refuse disposal (Mather and Ritchie, 1977); agriculture and harvesting, including cultivation (Mather and Ritchie, 1977; Carter, 1985; Tinley, 1985); forestry (Blackstock, 1985; Sturgess, 1992); thatch production (Randall, 1983; Westhoff, 1985); grazing (Garson, 1985; Leach, 1985; Oosterveld, 1985; Boorman, 1989; Chapman, 1989; Doody, 1989; Westhoff, 1989; van Dijk, 1992); introduction of wild fauna, such as rabbits (Westhoff, 1985; 1989; Angus and Elliott, 1992; Binggeli *et al.*, 1992); groundwater extraction, artificial recharge and artificial drainage (Westhoff, 1985; van der Meulen and Jungerius, 1989; van Dijk, 1989; Llamas, 1990; Angus and Elliott, 1992; van Beckhoven, 1992); and military use (Mather and Ritchie, 1977; Wiedemann, 1984; Tinley, 1985).

Examples of other alterations include removing sand washed onto roads (Bush, 1991); breaching barriers fronting lagoons to control flooding or to maintain salinities (Orford *et al.*, 1988); dredging navigation channels (Farrell and Sinton, 1983; Kana, 1983); and introducing fine-grained materials into the beach matrix to make beach sediments more resistant to wave erosion (Nelson, 1991). Accidental or indirect effects also occur, such as changing nutrient levels or acidity due to pollution in precipitation (Doing, 1989; Westhoff, 1989). These changes alter plant succession and, in turn, alter the morphology of the landform.

Grading of beaches and dunes by earth-moving equipment is one of the most ubiquitous alterations, but it is also one of the least well studied, and the practice is still controversial in terms of its benefits. Beaches and dunes are graded to facilitate shorefront construction, provide shore protection, prevent inundation by wind drift, provide views of the sea by shorefront residents, create a wider recreation platform or aid beach-cleaning operations (Kana, 1983; Nordstrom and Psuty, 1983; Cortright, 1987; Psuty, 1987; Nordstrom, 1988a; Thieler and Young, 1991; Wells and McNinch, 1991; Sanjaume and Pardo, 1992; Nordstrom, in press; Sherman and Nordstrom, 1994). The potential for dune building is actually greater in many resort communities than in adjacent natural areas because beaches are graded wide and flat, facilitating aeolian transport, but dunes are usually absent on developed resort shorelines because dunes are graded to increase the size of the beach or because visitor trampling destroys stabilizing vegetation.

The dunes that are eliminated to facilitate shorefront construction are often rebuilt to provide protection to houses from wave overwash and flooding, but they are usually built at smaller dimensions, seaward of their former equilibrium location (usually occupied by houses) and maintained at the new location with the aid of sand fences, artificial vegetation plantings or earth-moving equipment (Nordstrom *et al.*, 1986; Psuty, 1989; Gares, 1990; Pye, 1990). The size and location of these dunes are different from natural dunes because they are dictated by human preference rather than the interplay among vegetation growth, sand supply and wave erosion. The dunes are often more difficult to maintain at their new location and condition, resulting in increased human effort and cost to maintain them, and adverse effects may occur, such as increased erosion of the dune and inundation of houses landward of them by blowing sand (Nordstrom, 1988b).

Beach nourishment is now used nearly routinely throughout the world (Swart, 1991; Davison *et al.*, 1992). Over 90 beaches in the USA have been nourished in more than 200 separate operations (Pilkey and Clayton, 1987). Beach nourishment is now used to protect nature reserves as well as buildings and infrastructure (Klomp, 1989), and artificial beaches may be constructed where no beach existed before (Walker, 1981b). The fill materials used in nourishment operations can come from sources outside the beach environment, where sediments may include particles that are considerably smaller or larger than the natural beach sediments, and the method of handling the borrow material in its transportation to the fill site will affect the textural composition further (Swart, 1991). Cost considerations prevent nourishment of the entire underwater profile of the eroding coast. Usually only the upper beach is nourished, because this is where coastal facilities require protection. The result is a temporarily widened, oversteepened upper beach with a shape and composition out of equilibrium with natural processes. The beach retreats rapidly as the fill is reworked by waves and swash to adjust the beach to a gentler upper slope. A prominent vertical scarp is often conspicuous at the upper limit of wave reworking at high tide. Initially, the great width of the nourished beach and the presence of fine material lead to excessive transport by wind (Draga, 1983), but removal of the fine sediment leaves a surface of coarser shell or gravel that resists transport. Recently nourished areas are often readily distinguishable from adjacent areas because of their great width, the presence of the scarp and coarser sediments on the backbeach than on the eroding foreshore.

Dunes tend to become smaller under developed conditions because the value of property close to the water and the desire to view the water from shorefront homes argue for making the dune as low, narrow and close to the water as is feasible. They often become more linear because of their protective value and the current preference for a conservative, engineering approach to management; the optimum shape to prevent overwash along a developed shoreline is a high linear feature, and dunes are often linear, whether created using sand fences, vegetation plantings or earth-moving equipment (Nordstrom, 1990).

Dunes created with the help of sand fences or vegetation plantings are composed of well sorted, fine to medium-sized sand, transported and deposited as a result of aeolian processes, and they may have bedforms and strata that are characteristic of this process, although they may be different from natural dunes because of the external shape, internal stratification and the degree to which vegetation permeates the dune (Nordstrom, 1990). The creation of a dune by earth-moving equipment neither replicates natural processes nor the internal structure that would be created by those processes. The surface of artificial dunes can be modified using earth-moving equipment to simulate natural dunes by blending the contours with adjoining unaltered areas, creating peaks at varying heights and distances with no flat ridge sections in between, and breaking up long slopes with intermediate contours (Adriaanse and Choosen, 1991; van Bohemen and Meesters, 1992). The shape of natural dune forms can be mimicked, but the sediments comprising a bulldozed dune are unsorted and may contain coarser sediments than a dune created by aeolian processes. Coarse particles can result in a surface lag that resists deflation and alters the mobility of the dune (Baye, 1990). Some artificial dunes have an interior of clay that could not be deposited as a result of aeolian processes. Newly introduced sediment in the inner dunes has different leaching characteristics that affect the flow of water and nutrients (Adriaanse and Choosen, 1991).

IV Effects of protection structures and buildings

The body of literature on coastal engineering structures is enormous (Silvester and Hsu, 1993). Impetus for conducting most geomorphic studies of the effects of shore-protection structures is driven by the need to address the initial erosion problem, invariably related to local deficiency in the sediment budget and the need to address subsequent erosion problems in adjacent areas when the effects of the structure displace the locus of erosion to unprotected areas. Geomorphological investigations are most often couched in an applied investigative mode, examining the suitability of alternative means of protecting a section of coast. The functions of the various types of protection structures are well known (Silvester and Hsu, 1993), and there is ample evidence of accelerated erosion rates and truncation of the beach profile downdrift of them (Everts, 1979; Leatherman, 1984; Nordstrom *et al.*, 1986; Nordstrom 1988b). Many of the undesirable effects are so well known that the descriptions are hackneyed, and many studies, best unmentioned, are characterized by a conspicuous lack of scientific rigour and objectivity in their condemnation of protection structures. The purpose here is not to present a litany of the evils of structures but to identify investigations that examine the resulting beach morphology or the effect of the resulting sand starvation on geomorphic evolution of the coast. Studies of goins and jetties are used to identify the conspicuous effects of shore-perpendicular structures; seawalls are used to identify key aspects of shore-parallel walls.

Groins are designed to trap sediment moved alongshore, but they also affect wave refraction and breaking and surf-zone circulation, producing additional rip currents with conspicuous rips close to the structures, and they redirect sediment (Sherman *et al.*, 1990; Baur *et al.*, 1991; Short, 1992). They can interrupt existing beach-bar systems (Short, 1992) and create rhythmic features offshore of them (Gayes, 1991), resulting in a more complex topography. They also result in differences in sediment characteristics on the updrift and downdrift sides (Orme, 1980). Groins alter the topography of the subaerial profile as well, allowing the wind-blown sand and dune vegetation to occupy a more seaward location than it does along the adjacent shoreline. They create high dunes on the updrift side where the wide beach provides a source for dune building and protection from storm-wave erosion (Nordstrom *et al.*, 1986). Despite the considerable change in local process conditions and beach morphology caused by groins, they may not occupy as much attention by geomorphologists in the future as they did in the past because of the diminished likelihood that new groins will be employed in the future.

Jetties are designed to constrain and direct the flow of water at inlets and to provide a barrier to longshore transport to prevent shoaling of the channel. The effects of jetties on adjacent shorelines are well documented and include: migration of the pre-existing channel (usually towards and parallel to the updrift jetty); transport of sediments moved by ebb flows to deeper water; displacement of the ebb tidal delta and associated bars further seaward; and increase of erosion rate on the downdrift shoreline (Kieslich, 1981; Dean, 1988; Hansen and Knowles, 1988). Jetties can induce lower nearshore gradients and reduce breaker heights towards the jetties (Short, 1992). The complexity of inlet processes and morphology of the inlet shoreline is greatly reduced by these structures (Nordstrom, 1987b). Sand starvation downdrift of jetties (and large groins) can create rates of erosion that are too great for dune building to keep pace with landward displacement of the beach profile, converting the characteristic shoreline topography from dunes to overwash flat and altering vegetation assemblages (Roman and Nordstrom, 1988).

Seawalls, bulkheads and other shore-parallel walls (including sloped revetments) replace mobile coastal materials with a cohesive structure. Waves and swash break or reflect off the structure depending on its slope and location relative to water depth. Many criticisms of shore-parallel walls refer to scour and accelerated erosion seaward of these structures and a resulting reduction of beach width. Assessments of processes in front of seawalls are largely speculative (Tait and Griggs, 1990), and substantiation of detrimental morphological effects are usually made on the basis of conceptual arguments on the distribution of breaking wave energy. The long-term effect on scour seaward of these structures and reduction of beach width in locations where no new sediment is introduced into the system are now accepted by the research community as potential detrimental geomorphic effects of shore-parallel walls, but recent publications suggest that there is little evidence that erosion is actually accelerated in front of them (Kraus, 1988; Kraus and Pilkey, 1988; Nelson, 1991; Plant and Griggs, 1992). The scour that occurs under water is rarely revealed in the beach surface after it is reworked by swash, although small erosion troughs may sometimes be visible at the base of rip-rap structures (Nelson, 1991). The effects of shore-parallel walls in the deeper water seaward of them is poorly understood. Bars may pass in front of shore-parallel structures that lack an intertidal beach (Short, 1992), indicating that large-scale effects do not extend far seaward of them. Edge effects on shorelines adjacent to shore-parallel structures still remain problematic; locally important effects include accelerated erosion rates because of the elimination of the sediment source landward of the structure and scour from ebb channels created by drainage of seawater trapped behind the wall during storms (Lennon, 1991).

Studies of the direct effect of roads and buildings are less well represented in the geomorphic literature than studies of the effects of structures emplaced to protect them. Roads and car parks provide impermeable surfaces that offer unobstructed pathways for overwash and entrained sand (Hall and Halsey, 1991). Buildings alter flow of wind and water and locally change the location of accretion and scour on beaches and dunes

(Nordstrom and McCluskey, 1985; Nordstrom *et al.*, 1986; Gares, 1990). Large buildings can cause a reversal of the regional wind flow and result in onshore transport during offshore winds and can deflate the backbeach at considerable distances from the buildings (Gundlach and Siah, 1987; Nordstrom, 1987a). Wind-blown sand accumulates against bulkheads, boardwalks and buildings. These features, and remnants of former natural dunes that were not levelled for construction of buildings, create a diverse dune landscape, characterized by shapes and locations distinct from those that would occur under natural conditions (Nordstrom *et al.*, 1986; Gares, 1990; Sanjaume and Pardo, 1992). Large buildings that are not raised above the ground may be located within the breaker zone during storms and may obstruct or redirect waves and currents. The effects of these structures are not possible to assess during a storm because of the difficulty of taking measurements in debris-laden storm waves, but the morphologic changes are conspicuous after the storm. These changes may extend considerable distances offshore. Gayes (1991) noted that beaches were steeper and nearshore bars were less well developed offshore of human structures than in other locations after Hurricane Hugo. There is considerable litter remaining from damaged structures after large storms (Stauble *et al.*, 1991), and cultural materials can be moved offshore to distances farther seaward than 4 m below mean low water (Gayes, 1991) where they may create local small-scale landforms.

V Distinguishing natural from human-altered landforms

Initial mobility of a landform shaped according to human needs may be high at the time it is created or whenever it is reshaped, but the feature does not migrate like its natural counterpart or undergo long periods of regrowth after destruction by storms because attempts are made to replace it immediately. Shore protection structures may dramatically alter the natural shoreline configuration initially, but they then tend to eliminate cycles of change or reduce the magnitude of the cycles (Everts, 1979; Nordstrom 1988b). Much of the variety of natural features is associated with cycles of growth and decay, commonly seen in coastal dune fields (Wiedemann, 1984; Wanders, 1989). Landforms in developed areas usually have less variety because they are stabilized for ease of management. What some managers view as instability is really a valuable glimpse of geomorphic evolution. When the time dimension is truncated, individual identity is lost, and the linkage between process and form is obscured (Nordstrom, 1990).

Scientists working in coastal dunes in The Netherlands and Great Britain have recently presented compelling arguments for maintaining coastal landforms in a dynamic, migrating state, based on the significance of these features for ecological productivity, diversity of habitat or recreational values (Doody, 1985; van der Meulen *et al.*, 1989). Numerous studies have examined the characteristics of stabilized dune systems and methods of achieving the form and management goals for these features (CERC, 1984), but little attention has been paid to the alternatives to stabilized dunes in sparsely developed areas or parks, where the range of perceived management alternatives may be expanded (Nordstrom and Lotstein, 1989). Management plans for some locations where dunes were stabilized using sand fences or were graded flat now include allowing the dunes to be shaped by natural processes. The result is a dramatically different landform, but the dunes still bear many of the imprints of their human-modified form (Nordstrom and McCluskey, 1984; van der Meulen and Jungerius, 1989b; DeKimpe *et al.*, 1991; Gares and Nordstrom, 1991; Sanjaume and Pardo, 1991).

The conversion of landforms by humans often can go unnoticed in coastal locations that lack the highly visible structures that are most closely associated with human alterations. There are now virtually no dune systems in Great Britain that can be considered entirely natural, although most visitors would consider them so (Doody, 1989). The conversion of dunes to linear, stable features using sand fences and vegetation plantings is more widespread in the USA than is commonly perceived and includes seashore parks managed by local and state governments (Gares and Nordstrom, 1988) as well as National Seashores such as Cape Hatteras, and Fire Island (Godfrey and Godfrey, 1973; Psuty, 1989). These dunes often bear little resemblance to the ones that existed prior to the management projects.

One of the least conspicuous conversions of landforms results from introducing exotic plants or creating conditions whereby a single native species can dominate the ground cover. Some of the most important examples of vegetation that affect the morphology of coastal features and that owe their introduction or spread to human actions include: reedgrass (*Phragmites australis*) that has colonized locations above mean high-water level in North America; Japanese sedge (*Carex cobomugi*) introduced to coastal dunes in the USA from Asia (Pronio, 1989); pine trees (e.g., *Pinus nigra* ssp. *laricio* and *P. contorta*) used to stabilize dune systems throughout the world (Doody, 1989; Sturgess, 1992); Bitou bush (*Chrysanthemoides monilifera*) inadvertently introduced to Australia from Africa (Chapman, 1989); *Acacia cyclops* introduced to Africa from Australia (Hellström and Lubke, 1993); and European beach grass (*Ammophila arenaria*), introduced to stabilizie dunes on the Pacific coast of the USA (Cooper, 1958; Pinto *et al.*, 1972) and Australia (Barr and McKenzie, 1976). The effect of European beach grass is especially significant on the Pacific coast of the USA because it profoundly altered the morphology as well as the biota of the littoral zone (Cooper, 1958; Pinto *et al.*, 1972). It was first planted in the nineteenth century. It spread rapidly along the coast and provided a more complete trap to sand blown landward of the beach than the native vegetation and created a higher, more linear and better vegetated foredune than existed previously.

Several species of exotic vegetation have followed cycles, with stages clearly determined by human decisions and actions. The stages include: 1) accidental (or intentional) introduction; 2) rapid colonization; 3) acknowledgement of the advantages of the species for stabilization; 4) institution of planting programmes; 5) recognition of undesirable side-effects; and 6) attempts at eradication. The Bitou bush, for example, became well established in the dunes in Australia in the early 1900s and was identified as a good species for sand-drift control in the late 1940s; it was successfully utilized in this role until its detrimental effects were discovered (development of monospecific stands, visually boring, threat to vegetation variety and biological heritage); recommendations for its use in reclamation were withdrawn in 1971, and steps are being taken to eradicate it (Chapman, 1989).

Attempts to redress past direct and indirect human-induced alterations to coastal vegetation that affect processes and morphology include mowing, spraying, cutting, pulling or scraping vegetation from the surface (Rothwell, 1985; Klomp, 1989; Anderson and Romeril, 1992). These alterations may leave no immediate imprint on the morphology and, through time, the artificial appearance of the modified surface is eliminated, but vegetation succession may be altered, resulting in different future morphologic changes.

VI Effects of storms and climate change on the evolution of developed coasts

Damage assessments following moderate and high-intensity storms document the vulnerability of buildings and protection projects to damage by winds, waves and high water levels (Dean *et al.*, 1984; Nakashima, 1989; Seymour, 1989; Finkl and Pilkey, 1991; Kraus, 1993). These assessments are usually conducted within the first few months after passage of a storm. They concentrate on the poststorm landscape rather than the postreconstruction landscape that is profoundly altered by subsequent human activities and that represents the long-term effect of human alterations to restore human utility values. Destruction of natural landforms, coastal vegetation and fauna by storms is usually viewed as part of a cyle of events that includes restoration by natural processes. Destruction of buildings, in contrast, is viewed as a disaster and evidence of the incompatibility of human alterations, despite the evidence that the cultural landscape too will be restored, often at a more rapid rate than natural processes can restore natural features.

The equipment available to rebuild damaged communities is now highly sophisticated and efficient. Cultural debris and sand washed onto roads is removed almost immediately; inlets created by storms are closed artificially; sand lost from dunes is replaced, first by beach scraping, then by installation of sand fences and vegetation plantings; sand lost from the upper beach is replaced by beach grading; and nourishment projects are implemented to restore the width and volume of the beach (Bush, 1991; Katuna, 1991; Nelson, 1991; Stauble *et al.*, 1991). The new seaward-most construction line is often at the same location it was prior to the storm, and damaged communities are often rebuilt at larger proportions (Fischer, 1989; Meyer-Arendt, 1990; Nordstrom, 1994). Each major storm engenders a new suite of shore-protection projects (Watanabe and Horikawa, 1983; Nordstrom, 1994). The take-home messages about the vulnerability of human structures to natural processes are the same each time storm damage occurs (Podufaly, 1962), but warnings are rarely heeded.

Climate change and associated changes in sea level are other natural factors that have important implications for the way landforms will evolve in the future. There is a considerable body of literature on the effects of past changes in the coastal zone, particularly in Europe (e.g., Klijn, 1990; Tooley, 1990; Carter, 1992), and studies of future changes are proliferating (e.g., van der Meulen *et al.*, 1989; van Huis, 1989; van der Meulen, 1990). A simulation of the impact of future climatic change in the Coto Doñana National Park in Spain indicates an extension of the dry season, a decrease in summer soil moisture and an increase in potential evaporation in the winter that are expected to lead to an increase in sand drifts; climate in Slowinski National Park in Poland may change from a subcontinental climate to a more Atlantic-type climate, accompanied by an increase in winter temperatures, a decrease in occurrence of frost and an increase in rainfall, resulting in extension of the vegetation cover over barren parts of the dunes that are expected to lead to a decrease in wind erosion (van Huis, 1989; van der Meulen, 1990). Although the effects introduced by climatic change and future sea-level rise may cause coastal habitats to be reduced or eliminated (Carter, 1992) or result in abandonment of coastal settlements and a return to more natural coastal characteristics (Corre, 1989), these effects may be obscured in developed areas by human efforts to protect property and maintain a stable or predictable resource base (Titus, 1990, Nordstrom, 1994).

VII Models of evolution of developed coasts

Human-altered landforms and natural landforms respond to energy inputs according to the same physical laws, but differences occur between the two landform types in terms of the mechanisms of change, freedom of movement, locations of sources and sinks for sediment, internal structure, outward appearance and spatial and temporal scales of evolution (Nordstrom, 1990). Undeveloped dunes, for example, are characterized by considerable variety, and they have great local variability due to alongshore differences in distance from inlets, sediment sources, beach widths and kinds of vegetation, and they are characterized by rapid mobility and a variety of shapes and sizes within short distances (metres to kilometres). Human-altered landforms evolve at a variety of temporal and spatial scales, but the boundaries and time it takes them to evolve are inevitably defined by human values. Thus spatial differences in landform characteristics along the shoreline may conform to jurisdictional boundaries reflecting sociopolitical differences at the local scale (Mauriello and Halsey, 1987; Guilcher and Hallégouët, 1991) or even international scale (De Raeve, 1989) rather than to geographical variation in natural processes or sediment budgets (e.g., Davies, 1972; Psuty, 1992).

A variety of temporal scales is also visible in the cyclic changes that occur in human-modified coastal foredunes. Dunes that are eliminated by earth-moving equipment to provide a wide recreation platform or a clean beach in the summer and are then recreated in the autumn to prepare for winter storms, follow a seasonal cycle. Cycles of construction of dunes following losses from major storms are determined by the recurrence interval of storms of that magnitude, although the time it takes for reconstruction of the dune may last a few days (using earth-moving equipment), a season (for use of sand fences) or several years (using artificial vegetation plantings).

Scenarios of change for eroding developed coasts that do not include beach nourishment as a management option are driven by limitations in sediment availability and describe a closed system of evolution. The ability of these sediment-starved human-altered systems to adjust their forms and dimensions to major process changes is impaired relative to natural systems; low-magnitude, high-frequency self-maintaining systems are changed to high-magnitude, low-frequency systems where self-maintenance may not occur (Carter, 1980). Low-magnitude, high-frequency events on developed shorelines eventually convert wide beaches and wide and topographically varied dunes to truncated forms and convert multiple dune crest lines to single ridges that decrease in width and eventually are eliminated as erosion proceeds (Pilkey, 1981; Nordstrom *et al.*, 1986; Nordstrom, 1988b). Models of change for beaches and coastal foredunes on a transgressing natural shoreline, in contrast, include a landward shift of these features, with retention of their form and cross-sectional area as they are displaced inland. The foredune may maintain its characteristics by either continuous migration (Psuty, 1988) or through breaching of weaker portions of the dune by storm waves, followed by buildup of the dune landward of the former crest line (Godfrey *et al.*, 1979).

Rejuvenation of naturally functioning landforms can occur on developed coasts with massive inputs of beach nourishment or changes in land-use regulations that prevent reconstruction of buildings and protection structures damaged during coastal storms. At present, rejuvenation by beach nourishment is the more likely of these adjustments, given human reluctance to abandon development sites, but abandonment occurs in locations where regulations are in place (Psuty, 1989). These human adjustments re-establish the potential for an open system (cyclic) model of beach change for developed coasts

(Nordstrom *et al.*, 1986; Titus, 1990; Nordstrom, 1994).

Models of change for developed coasts may be constructed following several different approaches that may determine, a priori, the extent to which human alterations will be considered an aberration or an integral part of the coastal system. Nordstrom (1994) identifies three basic approaches, including: 1) the overlay approach, that compares and contrasts a developed area with an undeveloped area that is assumed to have the same process controls; 2) the no-action approach, that assumes the kind of shoreline change that occurred in the recent past will continue unabated by local actions (and often implicitly defines a closed system on an eroding shoreline); and 3) the active human-input approach, that bases predictions on probabilities of human action, calibrated with knowledge of physical processes in a multiple scenario format (and implicitly defines an open system). Many geomorphologists may use the overlay approach because they feel that it is necessary to understand undeveloped systems before superimposing the complexities of human modification (Sherman and Bauer, 1993b). It is likely that the active human-input approach, which considers human action endogenic rather than exogenic (Phillips, 1991), is more realistic for intensively developed areas and will have increased usefulness in the future in areas now developing (Nordstrom, 1994).

VIII Implications for future research

Recent research on the geomorphology of developed coasts has provided ample evidence of divergences in the form, surface cover and rate of change of human-altered landforms relative to natural landforms but has largely ignored the conclusions that natural landscapes are a myth, that human agency is not an intrusion into the coastal environment so much as it is now a part of the coastal environment and that human-altered landscapes can and should be modelled as a generic system. The focus on human-altered systems as an aberration is understandable. Many coastal scientists may not think that it is in their interest to underscore the lack of naturalness of the landscape they subject to rigorous objective analysis because this documentation conveys an impression that their results lack universal applicability, that they accept the human-altered condition as the norm or that they accept the human-altered system as a blueprint for future coastal evolution.

Models of geomorphic processes and changes in morphology or sediment characteristics may be tested in developed areas if development does not violate any assumptions of the model (e.g., Kim and Huntley, 1986; Nordstrom, 1989). Incorporation of both developed and undeveloped locations as test sites can be viewed as a better test of the universality of geomorphological or sedimentological principles than use of undeveloped sites alone (Nordstrom, 1989). The availability of documentation from archaeological settings, historical documents and maps (Innocenti and Pranzini, 1993) and the need for support infrastructure to use the kinds of sophisticated equipment that are increasingly employed in field investigations may provide catalysts to direct research to human-altered environmens. Despite these advantages, research on human-altered systems still retains the stigma of applied research. Articles on the geomorphology of developed systems are usually placed in the back of edited volumes, often in sections labelled as applied or as management studies, or they may be listed under headings such as 'environmental' or 'pollution', when listed in abstracts, even when implications for planning or mangement are not part of the original study.

Modelling human-altered geomorphic systems is not an easy task. Models that evaluate humans as en endogenic pocess require a greater number of assumptions and more explicit assumptions about human actions than models that consider humans as an exogenic process. Geomorphic factors must be combined with human factors such as preference and precedent, rights of property owners, legal implications, economic motivation, environmental interests and constraints of government programmes (Nordstrom, in press). The approach requires a more holistic perspective than is often practised by physical geographers and a greater emphasis on social science and humanities, just as is now required for scenario-setting in issues in environmental management (Newson, 1992; Rhoads, 1992). Perhaps the increasing disenchantment of the process paradigm by physical geographers (Newsom, 1992; Rhoads, 1992) and the growing willingness among geomorphologists to reject the concept of a single stable equilibrium condition for a given geomorphic system (Phillips, 1992; Renwick, 1992) may help overcome reluctance to develop complex models for human-altered systems. True progress in the study of coastal evolution requires the development of conceptual and predictive models of landform dynamics that involves an orderly, objective and scientifically informed intellectual process, identifying gaps in understanding and a rational plan of study, followed by a concerted research effort backed by ample resources (Sherman and Bauer, 1993b). At present, there is no groundswell movement to mount such a programme for human-altered shorelines.

It is likely that the impetus for funding projects on developed coasts will still be in an applied research mode, investigating impacts of new buildings or protection strategies. A creative task for geomorphologists operating in an applied mode is to provide guidelines to help maintain beach resources in a way that preserves as many elements of the natural system as possible within the existing management framework by maintaining the natural sediment budgets and preserving the mobility of landforms and their tendency to grow and be altered (Nordstrom, 1990). Nature conservation is now often the protection of a human-made scenery (Klomp, 1989). An integrated nature-management strategy for beaches and dunes can no longer consist of solely striving for a natural situation or evaluating human activities as negative factors in a pristine environment, but it should try to safeguard or promote an optimal diversity of landforms, species and ecosystems, compatible with human values, even while using controlled disturbance (van der Maarel, 1979; Nordstrom and Lotstein, 1989; Roberts, 1989; Westhoff, 1985; 1989).

There is increasing concern that engineering solutions to coastal erosion should be 'soft' or 'geomorphically compatible' alternatives (Rijkswaterstaat, 1990). A new role for geomorphologists is to provide the terrain parameters required to reshape the coastal landscape in a way that is compatible in appearance and function if not in genesis (van der Meulen and Jungerius, 1989b). Ways of maintaining the essential characteristics of depositional coastal landforms include conserving coastal landscapes as large, undivided units where vegetation and landforms can undergo cycles of growth and decay (De Raeve, 1989; Wanders, 1989; Westhoff, 1989); dedicating large portions of the shoreline to conservation; and restricting access and placing buildings and support infrastructure outside the mobile areas in public parks (Nordstrom, 1990).

There is clearly much challenging work that can be done by coastal geomorphologists in human-altered geomorphic systems, both in applied and basic research modes. This review has touched on only a few of the many areas of research required to understand the processes and resulting landforms caused by intentional and unintentional human actions. The direct chain of events leading from human decisions to geomorphic responses and to future changes to the coastal landscape are difficult to assess, but assessments are critical, given the inexorable transformation of the coast to a human artifact.

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