MANAGED RETREAT

Managed retreat is a collective term for the application of coastal zone management and mitigation tools designed to move existing and planned development out of the path of eroding coastlines and coastal hazards. This strategy is based on a philosophy of moving out of harm's way, and is proactive in recognizing that the dynamics of the coastal zone should dictate the type of management employed (e.g., identify and map the hazards as a basis for establishing regulations to move property and people away from migrating and/or storm-impacted coastlines).

The term "managed retreat" also is used in a more restrictive sense where shore-protection structures are removed selectively to allow natural coastal environments to be reestablished. For example, Viles and Spencer (1995) describe the creation of a small marsh on Northey Island, Blackwater estuary, Essex, England, by lowering a 200 m section of seawall and building a spillway to allow tidal inundation to be reestablished. This approach of letting parts of a coastline erode in a controlled way to create habitat and manage the coast in a way sympathetic to nature also is known as *managed realignment* (French, 1997). Managed realignment has the advantage that the sediment budget is reestablished.

Need for managed retreat

The Second Skidaway Conference on America's Eroding Shoreline concluded:

> ... the American shoreline is retreating. We face economic and environmental realities that leave us two choices; (1) plan a

NEAL, W.J., BUSH, D.M., PILKEY, O.H., 2005. IN ENCYCLOPEDIA OF COASTAL SCIENCE. SCHWARTZ, M.L. (ED.). THE NETHERLANDS: SPRINGER, PP. 602-606.

strategic retreat now, or (2) undertake a vastly expensive program of armoring the coastline and, as required, retreating through a series of unpredictable disasters. (Howard *et al.*, 1985)

That conclusion applies to developed coasts globally. The recommendation for strategic retreat is synonymous with managed retreat.

The 15 years following the Skidaway Conference proved their predictions to be accurate with the exception that beach nourishment replaced armoring as the preferred engineering method of stabilizing coastlines. Armoring has increased globally (Nordstrom, 1994), and is still a common response to coastline erosion at the individual-property level in the United States. Beach nourishment is proving costly (US Army Corps of Engineers, 1994; Valverde *et al.*, 1999). In the Caribbean and along the Atlantic and Gulf Coasts, the damage from hurricanes is rising (e.g., Hugo, 1989; Andrew, 1992; Opal, 1995; Georges, 1998). Their impact has induced random retreat at the individual-property level, and forced communities to reexamine their coastal zone management strategies. And, although the greenhouse effect is a subject of debate, sea level is rising for most of the world's coastlines, and the rate of rise is increasing.

At the close of the 20th century, a report by the Heinz Center for Science, Economics and the Environment estimated that 10,000 coastal structures in the United States were within the estimated 10-year erosion zone (Leatherman, 2000). As of 1998, coastal counties in the United States exclusive of the Great Lakes, had a total flood insurance coverage of $466,874,000,000 (H. John Heinz III Center for Science, Economics and the Environment, 2000). The best option for many of these properties and their communities is managed retreat. Although "retreat" strikes a negative cord for some, elements of the strategic retreat option increasingly are being incorporated into coastal zone management.

The shift from engineering to "Soft" solutions

Historically, the method of choice to protect beachfront buildings and property was to hold coastlines in place through engineering by armoring (Table M1). By the 1950s and 1960s the realization that coastal buildings were subjected to higher winds and flooding (even those behind seawalls) led many states and communities to adopt more stringent building codes to strengthen buildings in the coastal zone. Coastal management was segmented both in locale and application (e.g., each community or agency focusing on a limited coastal reach or single problem). On barrier islands, the focus was often on the high-tide shoreline rather than a holistic management approach for an entire island or chain of islands. By the 1970s, the US national experience dictated that something be done to control the losses incurred from hurricanes and great storms like the 1962 Ash Wednesday Storm. The tremendous loss of habitat also was being recognized as salt marshes and shell fisheries were lost or closed. The results were two-fold: the National Flood Insurance Act of 1968 (also the result of persistent property loss on riverine floodplains), and the Coastal Zone Management Act of 1972. Building requirements were upgraded, and many coastal states began to define critical environments and control development through permit processes. Communities and states adopted approaches such as zoning and set back requirements. By the early 1980s, Integrated Coastal Zone Management (ICZM) (Clark, 1995) or simply Integrated Coastal Management (ICM) defined strategies in which a variety of management tools were being combined (Table M1). Cincin-Sain and Knecht (1998) define ICM "as a process by which rational decisions are made concerning the conservation and sustainable use of coastal and ocean resources and space" and "is designed to overcome the fragmentation inherent in single-sector management approaches ..."

Continued beach loss and the associated losses of storm protection, recreational use, aesthetics, and beach economy, led to greater interest in "soft" solutions such as beach nourishment to combat erosion. Beach nourishment, however, is a modern equivalent of the engineering "fix" to hold the line, and does not recognize the natural dynamics of coastline retreat in areas where sea level is rising. This approach has proven drawbacks including ongoing costs, diminishing sand supplies, shorter half-lives of nourished beaches, and environmental impacts from dredging and sand placement.

Common regulatory methods, such as building codes, requirements for structures to be elevated, and controls on development density and type through land-use planning and most zoning, may lessen the impact of storms, but these methods do not remove development from the hazard zone. In some cases, vulnerability to hazards is increased. Furthermore, these approaches do not recognize coastline retreat as coastal adjustment takes place in response to sea-level rise, changes in sediment supply, variable wave regime, and other controls of coastline equilibrium. High-density development along shores all over the world demonstrate that land-use planning either has not worked or coastal management has come after the fact.

Table M1 General property damage mitigation options on the beachfront (modified after Bush *et al.*, 1996)*

Hard stabilization
Shore-parallel
Seawalls
Bulkheads
Revetments
Offshore breakwaters
Shore-perpendicular
Groins
Jetties[a]
Soft stabilization
Adding sand to beach
Beach replenishment
Beach bulldozing/scraping
Increasing sand dune volume
Sand fencing
Raise frontal dune elevation
Plug dune gaps
Vegetation
Stabilize dunes (oceanside)
Marsh (soundside)
Modification of development and infrastructure (control through zoning, building codes, insurance eligibility requirements)
Retrofit homes
Elevate homes choose elevated building sites
Lower-density development
Curve and elevate roads
Block roads terminating in dune gaps
Move utility and service lines into interior or bury below erosion level
Managed retreat
Abandonment
Unplanned
Planned
Relocation
Active (relocate before damaged)
Passive (rebuild destroyed structures elsewhere)
Long-term relocation plans (zoning, land use planning)
Setbacks
Fixed
Rolling
Acquisition
Avoidance: recognize hazard areas and avoid
Tidal inlets (past, present and future)
Swashes
Permanent overwash passes
Wave-velocity zones

* These management options are listed in increasing order of preference for Integrated Coastal Management (ICM). Historically, early management usually focused on shoreline stabilization, relying on a single mode of armoring. Various mitigation tools have been added to management plans, often in response to deficiencies in earlier plans that were revealed by the impact of the most recent storm.

[a] Jetties are built specifically to protect harbor entrances or maintain inlets, and are not constructed to protect coastlines. They are listed here because they impact adjacent shorelines, and that impact must be considered in management schemes.

Methods of managed retreat

"Retreat" is sometimes used for setbacks (e.g., Clark, 1995), or has been viewed simply as denying property owners the right to construct shore-hardening structures, forcing abandonment (Sturza, 1987). Managed retreat, however, implies applying an appropriate management strategy from a menu of tools, including stabilization techniques in some cases (e.g., particular urban coastlines). Specific retreat mitigation techniques include: abandonment, relocation, setbacks, land acquisition, and avoidance.

Abandonment

Abandonment may be unplanned, or part of a planned strategy of retreat. Historically, abandonment is often an unplanned, post-storm response to destruction of buildings and land loss (e.g., bluff retreat so that reconstruction is impossible). Fallen houses in the water or on the beach are a common sight along open-ocean coastlines after hurricanes and northeasters. Similar scenes are common in the Great Lakes and large embayments like Chesapeake Bay. Destruction may be so complete that the property is abandoned. Ruins of houses destroyed in Hurricane Gilbert in 1988 remained 12 years later along Mexico's Yucatán coast. Entire villages on barrier islands and along eroding bluffed shores have been abandoned. The village of Broadwater, Hog Island, VA, was abandoned in 1933 after losses to storms and shore erosion, although in part it was a short-term planned abandonment as houses were relocated off the island. Earlier, Cobb Island, VA, and Edingsville Beach, SC, had met similar fates. West coast abandoned towns include Bayocean, OR, and Cove Point, WA. Over the last century, 29 villages have been abandoned (lost) to the sea along England's Yorkshire coast.

Planned abandonment can be incorporated into managed retreat in several ways. Long-term planned abandonment can follow what is sometimes called the "do nothing" approach. Buildings are regarded as having a fixed life span, and when their time comes to fall into the sea, bay, or lake, no attempt is made to protect them. Buildings are razed either just before or after failing. Planned abandonment can be achieved by prohibiting post-storm reconstruction, or by requiring relocation landward of the revised post-storm setback control line. The original South Carolina Beachfront Management Act would only allow habitable structures damaged beyond repair (two-thirds or greater damaged) to be rebuilt landward of the no-construction zone (Beatley *et al.*, 1994). In part because of a poorly written law, post Hurricane Hugo enforcement led to the famous court case of *Lucas v. South Carolina Coastal Council* in which the plaintiff prevailed, resulting in the law being rewritten and softened. Rebuilding after storms can be discouraged by other methods as well, such as denial of flood insurance and other subsidy programs.

Relocation

For an existing building, the most obvious way to avoid a hazard is to move away from it! For developed coasts relocation is an essential component of managed retreat. So it is with an eroding or shifting high-tide shoreline.

Active relocation is undertaken by moving a building back either before it is threatened, or, if threatened, before it is damaged.

Passive relocation is achieved by rebuilding a destroyed structure in another area, away from the shore and out of the coastal hazard zone.

Long-term relocation usually implies a broader strategy through community zoning or land-use plans that identify a frontal zone of buildings likely to be impacted by known erosion rates or predicted flood levels from storm surge and coastal flooding. These building are then scheduled for relocation over an extensive period (assuming they will not be lost in coming storms). In effect, this is an engineered retreat, and on a barrier island the plan may include creation of new land on the soundside of the island for relocating the structures (Viles and Spencer, 1995). Artificial island migration is achieved, however, because barrier islands are usually backed by sensitive marshes and wetlands, the approach is questionable and raises complicated issues of property rights and changing ownership. This approach is more easily achieved in moving communities off of riverine floodplains and non-barrier coasts.

Even where setbacks are used, a retreating coastline will catch up with the property, and relocation will again become an option. Relocation is often the best economic option (Table M2) even though the up-front cost may be high. One can find examples along almost every coastline where armoring is used in which the cost of seawalls, groins and breakwaters, or nourishment, over the lifetime of the property, exceeds the value of the property, and greatly exceeds the cost of moving the structure.

The 1987 Upton–Jones Amendment to the National Flood Insurance Program (NFIP) allowed owners of threatened buildings to use up to 40% of the Federally insured value of their homes for building-relocation purposes (Wood *et al.*, 1990). The law recognized relocation as a more economical, more permanent, and more realistic way of dealing with long-term erosion and flood problems. The NFIP would pay a relatively small amount to assist relocating or razing a threatened house, rather than paying a larger amount to help rebuild it; only to see the rebuilt house destroyed in a subsequent storm, and paying to rebuild again. By March 1995, North Carolina had claims for over 70 relocations and 168 demolitions, and accounted for over 60% of all coastal claims under the program. The National Flood Insurance Reform Act of 1994 ended the Relocation Assistance Program as of September 23, 1995, replacing the Upton–Jones program with the National Flood Mitigation Fund.

Table M2 The advantages and disadvantages of relocating buildings back from a retreating shoreline (modified after Bush *et al.*, 1996)

Advantages

- building moved out of hazard zone, or is less vulnerable to hazards
- natural shoreline processes allowed to continue
- preserves the beach and associated value to community
- high probability of one-time-only cost (economical in the long term)
- cost savings because no public or private money spent on stabilization

Disadvantages

- high initial cost
- politically difficult
- building site must be deep enough to allow suitable moveback, or an alternative site must be purchased
- structure must be of a type and design/construction that allows it to be moved (e.g., a wood-frame house is easier to move than a cinder-block house on a poured concrete slab)
- coastal land is lost

Demolition and relocation activities are eligible for grant assistance under the program, but now compete with other mitigation approaches, including elevation and flood-proofing programs, acquisition of flood-zone properties for public use, beach nourishment, and technical assistance. Some states have encouraged relocation with similar programs (e.g., Michigan) (Platt *et al.*, 1992), or require houses to be moveable through the building permit process (e.g., New York).

The relocation alternate often is regarded as too expensive or technically impossible, but the move of the famous Cape Hatteras, NC lighthouse in 1999 again proved the feasibility and economic wisdom of this alternative (Pilkey *et al.*, 2000). Relocation is not a new mitigation strategy. Lighthouses have been relocated in North America since the 19th Century. Entire communities have relocated by choice or by necessity when they can no longer defend against the ravages of nature. Discouraged by continual hurricane damage, the citizens of Diamond City, NC relocated in 1899, disassembling their houses and barging them to their new locations. Rice Path, NC relocated because of encroaching sand dunes. FEMA's web site gives examples of recent success stories of relocation. Moving houses and communities off of riverine floodplains is not uncommon (e.g., English, IN; Rhineland, MO; Glasgow, VA).

Deep property lots are an important element in planning for future relocation Deep lots allow homeowners to relocate houses threatened by erosion to another location on their own property. In effect, lot depth determines possible future on-site relocation. While relatively deep lots are found in some coastal communities, new developments are often designed to maximize the number of dwelling units, resulting in small lots. Despite this trend, some communities, such as Nags Head, NC, are now requiring deep lots (oceanside to soundside on barrier islands) in order to provide for relocation.

Setbacks

Setbacks as the name implies are a management tool to keep structures out of extreme-to-high hazard zones, or at least at a distance from the hazardous processes (e.g., coastal erosion, v-zone flooding, storm surge). Klee (1999) reviews two types: "stringline" and "rolling" setbacks. A stringline setback simply requires that new construction be a fixed distance inland from a reference line (e.g., the back of the beach, the vegetation line, the crest of the dune line). The regulatory line is not adjusted for changes such as storm impact. A rolling setback is one in which the regulatory line shifts landward as the high-tide shoreline erodes (e.g., as the bluff edge, back beach, or dune toe retreats).

Although setbacks often are defined as creating zones in which no buildings or structures are allowed, in reality most setback regulations allow for variance application, and in some jurisdictions, liberal granting of variances circumvents management intent.

How far back is a "safe" building setback? The answer is difficult and will vary from place to place according to erosion rates and state and local regulations. No uniformity exists between coastal states' setback regulations in terms of how they are defined or applied (see Leatherman, 2000, table 4.4 for state-by-state summary).

While setbacks put some distance between buildings and the shore, that distance does not remain constant. When high-tide shoreline retreat catches up to the buildings, the original setback distance is of no consequence. Once again, the relocation or abandonment options must be considered.

Acquisition

Land acquisition can be an important component of a managed retreat plan. Land in the public trust through federal, state, and local ownership usually provides benefits in terms of conservation, providing public access to the shore, contributing to recreational and tourism needs, preserving aesthetics, and protecting habitat. Most coastal states have land acquisition programs and governments can purchase land through negotiated purchases where owners voluntarily sell land, or, less common, by eminent domain (condemnation proceedings). Other strategies include tax incentives, donations of conservation easements, trading of land, and transference of development rights. Condemnation usually results in a much higher cost for the land. Most land acquisition programs are hampered by a lack of funding. Florida and California are states with fairly successful programs. Just how well a publicly owned urban coastline can serve its citizens is demonstrated by Chicago's 18-miles of continuous public parkland.

Avoidance

The best way not to experience a hazard is to avoid it! Although the decision not to locate in a hazardous area may not seem like retreat, including areas where no development is allowed because of specific hazards, critical habitats, or sediment sources, is usually part of managed retreat. In this case, zoning can contribute to safe siting of structures away from coastal hazards. In part, setbacks reflect an avoidance approach, however, as noted, setbacks are temporary because coastline retreat will eventually reach buildings that met the original setback requirement. An eroding coastline may be more than just a hazard. Sacrificial coastline may be necessary to preserve the down-drift sediment budget, and Hooke (1998) gives an example in which the South Wight Borough Council (England) does not allow coastal defense works so a cliff-line will continue to erode and provide sediment to the beaches of Sandown Bay.

Again, disincentives may be used in an effort to encourage people not to build in high-hazard zones or in areas of critical habitat. Federal laws such as the 1982 Coastal Barriers Resources Act (COBRA) and the 1990 Coastal Barriers Improvement Act (CoBIA) have designated areas in which development is allowed, but buildings are not eligible for federal flood insurance or any post-storm federal assistance such as small business loans and funding to rebuild infrastructure. After Hurricane Fran in 1996, however, such assistance apparently did go to the community of North Topsail Beach, NC which is located in a COBRA unit.

Nags Head, North Carolina: managed retreat at work

The managed-retreat approach has been successfully implemented by the town of Nags Head, NC. This mitigation strategy stems from a desire to protect Nags Head's family beach atmosphere that attracted the residents in the first place (Bush *et al.*, 1996). Recognizing that hurricanes are inevitable, the Nags Head Repetitive Loss Plan and Floodplain Management Plan's implementation includes an extensive list of pre-storm mitigation measures, town response during a storm event, and post-storm mitigation and reconstruction measures (Nags Head, 1995).

The town adopted building standards more restrictive than required by either FEMA or the North Carolina Coastal Area Management Act (CAMA). Incentives are used to encourage development to be located as far back from the ocean as possible, including strict setbacks (minimum standard of 150 ft (45.7 m) setback from mean high water). Because small, single-family structures are much easier to move, the town has limited the development of oceanfront hotels and condominiums. Deep lots running perpendicular to the shore provide considerable room for relocation. Prior to rebuilding after a storm the Town may require adjoining lots in common ownership to be combined into a single lot. New construction of wood frame, multi-story, multi-family, buildings is not permitted. Strict limits are set on the amount of impervious surfaces within the oceanfront zoning districts that further reduces the amount of real property at risk. The post-storm measures include building moratoriums, policies on reconstruction, and a program for rapid acquisition of land.

The general theme of Nags Head's mitigation plan is based on the recognized history of coastline retreat, and that it is far better to adopt a policy of planned retreat than to wait for a disaster to force retreat. That philosophy is not new to residents of North Carolina's Outer Banks. A landmark property in Nags Head is the Outlaw House, named for the Outlaw family. This structure has been moved back 600 ft (183 m) from the retreating high-tide shoreline in five separate moves over 100 years.

The cost of moving buildings is the best economic strategy because the solution is long-term compared with relying on beach nourishment with an estimated cost of approximately $2 million per mile (1.6 km). The area's relatively high wave energy would require additional nourishment every three years resulting in an average annual cost of $3 million. This expenditure would continue as long as replenishment was the chosen mitigation technique. By comparison, the cost of removing structures from the threatened areas is much less. As of the early 1990s, Nags Head had accounted for 78 of the 379 (21%) Upton–Jones petitions submitted nationwide, 55 of which had been approved (Williams, 1993). Of these 55, 35 petitions requested funds for demolition at an average cost of $74,409, and 19 requested funds for relocation at an average cost of $30,211 (Williams, 1993). Similarly, an estimated cost for a beach nourishment program along a 4.5 (7.6 km) mile reach of South Nags Head shoreline was about $9 million every 3 years compared with the retreat option estimated at about $2 million every 20–25 years.

Relocation is a viable coastal management tool, and need not be considered only for single-family houses. When a structure is moved, the danger is reduced (Table M2).

The 10/100-year relocation concept

The difficulty of applying a managed retreat strategy is exemplified by areas such as the Myrtle Beach Grand Strand, SC, Miami Beach, FL, and other great oceanfront resort communities where a vast number of high-rise condominiums and hotels are right on the high-tide shoreline. At present, beach replenishment is economically feasible for these communities because of the large number of people that use the beaches and the significant revenue generated. The Miami Beach replenishment project, the most successful on the east coast in terms of replenished beach lifetime, has lasted for over 20 years. Along parts of the Grand Strand, SC, replenishment has to be repeated almost yearly. A time will come, however, when the economics of replenishment will no longer be acceptable. The increasing sand volumes needed, the declining sand supplies, and escalating project costs will make nourishment a less acceptable management tool. The time is approaching when serious consideration will have to be given to managed-retreat alternatives such as relocation and land acquisition.

Although the argument is that development along urban coasts is either not feasible or too entrenched to consider managed retreat, the alternative is both feasible and, perhaps, preferable for some communities. The International Association of Structural Movers says that moving large structures is technologically feasible, though expensive. Recall also that relocation can mean demolishing a building and rebuilding its replacement elsewhere. The unanswered question is economics.

Urban communities and owners of large buildings should not exclude managed retreat as a management tool, and need to begin researching the economics of this option. One possibility is a *10/100-year relocation plan* in which a relocation strategy is developed within 10 years and implemented as necessary over the following century (Bush *et al.*, 1996). Cost comparisons of traditional relocation or relocation by demolition and rebuilding should be evaluated against the long-term feasibility of continuing the replenishment option (e.g., the projected sea-level rise, financing requirements, identifying and acquiring distant sand resources, a timetable for obtaining necessary permits, etc.). Whether buildings can be relocated on the present property or off property, within the community or outside must be ascertained. What are the options and questions yet to be raised? A 10-year planning window should set the stage for implementation. Plans will vary by community and coastal type, and will take decades to implement. Virtually all coastal communities will need such programs of managed retreat over the next 100 years, or they will fulfill the prediction of retreating as the result of a series of coastal calamities.

The need for long-term managed retreat

In summary, to hold the line against the sea-level rise for all of the world's developed coasts is unrealistic. Managed retreat may provide the best set of tools for mitigating coastal hazards and reducing property losses. Avoidance remains the best solution for undeveloped and lightly developed areas, while various forms of relocation are the long-term solution for even urbanized shores. Coastal land acquisition is one method of meeting both of these goals, however, greater funding will be needed for future acquisition to succeed. Setbacks are a temporary solution, even when redefined periodically as rolling setbacks. In order for managed relocation to work, integrated land-use planning and zoning efforts will have to take a broader, holistic approach. For example, barrier-island management policies must consider the entire island, moving from a focus on site-specific and linear (island front) regulation to a whole-island perspective, and from shore hardening/hold-the-line programs to approaches which concentrate on preservation, augmentation, and repair of the natural systems.

William J. Neal, David M. Bush and Orrin H. Pilkey

Bibliography

Beatley, T., Brower, D.J., and Schwab, A.K., 1994. *An Introduction to Coastal Zone Management.* Washington DC: Island Press.

Bush, D.M., Pilkey, O.H., and Neal, W.J., 1996. *Living by the Rules of the Sea.* Durham, NC: Duke University Press.

Cicin-Sain, B., and Knecht, R.W., 1998. *Integrated Coastal and Ocean Management: Concepts and Practices.* Washington DC: Island Press.

Clark, J.R., 1995. *Coastal Zone Management Handbook.* Boca Raton, FL: Lewis Publishers.

French, P.W., 1997. *Coastal and Estuarine Management.* London, UK: Routledge.

H. John Heinz III Center for Science, Economics and the Environment, 2000. *The Hidden Costs of Coastal Hazards; Implications for Risk Assessment and Mitigation.* Washington DC: Island Press.

Hooke, Janet, 1998. *Coastal Defense and Earth Science Conservation.* Bath, UK: The Geological Society.

Howard, J.D., Kaufman, W., and Pilkey, O.H., 1985. *National Strategy for Beach Preservation,* Second Skidaway Institute of Oceanography Conference on America's Eroding Shoreline. Savannah, GA: Skidaway Institute of Oceanography.

Klee, G.A., 1999. *The Coastal Environment: Toward Integrated Coastal and Marine Sanctuary Management.* Upper Saddle River, NJ: Prentice Hall.

Leatherman, S.P., Chair, Erosion Hazards Steering Committee, H. John Heinz III Center for Science, Economics and the Environment, 2000. *Evaluation of Erosion Hazards.* Washington DC: The H. John Heinz III Center for Science, Economics and the Environment.

Nags Head, 1995. *Town of Nags Head Repetitive Loss Plan and Floodplain Management Plan.* Nags Head, NC: Town of Nags Head.

Nordstrom, K.F., 1994. Developed Coasts. In Carter, W., and Woodroffe, C.D. (eds.), *Coastal Evolution: Late Quaternary Shoreline Morphodynamics.* Cambridge, NY. Cambridge University Press, pp. 447–509.

Pilkey, O.H., Bush, D.M., and Neal, W.J., 2000. Lessons from lighthouses: shifting sands, coastal management strategies, and the Cape Hatteras lighthouse controversy. In Schneiderman, J.S. (ed.), *The Earth Around Us.* New York, NY: W.H. Freeman and Company, pp. 198–220.

Platt, R.H., Miller, H.C., Beatley, T., Melville, J., and Mathenia, B.G., 1992. *Coastal Erosion: Has Retreat Sounded?* Boulder, CO: Institute of Behavioral Science, University of Colorado, Program on Environment and Behavior, Monograph No. 53, 195p.

Sturza II, R.P., 1987. The Retreat Alternative in the Real World: The Kill Devil Hills Land-Use Plan of 1980. In Platt, R., Pelczarski, S., and Burbank, B. (eds.), *Cities on the Beach.* Chicago, IL: University of Chicago, Department of Geography, Research Paper No. 224, pp. 289–294.

US Army Corps of Engineers, 1994. *Shoreline Protection and Beach Erosion Study: Yearly Cost Data for Constructed Projects (1950–1993),* accompaniment to *Shoreline Protection and Beach Erosion Control Study Phase I: Cost Comparison of Shoreline Protection Projects of the US Army Corps of Engineers.* Institute of Water Resources Report, 94-PS-1, January 1994.

Valverde, H.R., Trembanis, A.C., and Pilkey, O.H., 1999. Summary of beach nourishment episodes on the U.S. East Coast Barrier Islands. *Journal of Coastal Research, 15: 1100–1118.*

Viles, H., and Spencer, T., 1995. *Coastal Problems: Geomorphology, Ecology and Society at the Coast.* London, UK: Arnold.

Williams, J.M., 1993. *An Examination of the Risks of Coastal Development and Some Possible Mitigation Methods: A Case Study of Nags Head, North Carolina.* Master's project, Durham, NC: Duke University, School of the Environment.

Wood, W.L., Chairman, Committee on Coastal Erosion Zone Management, 1990. *Managing Coastal Erosion.* Washington DC: National Academy Press.

Cross-references

Coastal Boundaries
Coastal Zone Management
Economic Value of Beaches
Global Vulnerability Analysis
Greenhouse Effect and Global Warming
Sea-Level Rise, Effect
Setbacks

MANAGEMENT—See COASTAL ZONE MANAGEMENT

MANGROVES, ECOLOGY

Introduction

Mangroves have always been considered as marginal ecosystems for at least three main reasons. First, the global mangrove area does not exceed 180,000 km^2 representing less than 2% of the world's tropical forest resources. Second, their discontinuous distribution, at the land and sea interface of tropical and subtropical coastlines, is primarily characterized by tidal regimes, which is a unique forest habitat. Third, the frequent wide fluctuations of environmental factors (dissolved oxygen, salinity, organic, and inorganic suspended matter) have induced in mangrove flora, a complex range of adaptations, lacking in other woody species, unable to compete or to survive in these highly variable and adverse environmental conditions (low oxygen content in soils, sulfate toxicity, high NaCl in water and soils, exposure to hurricanes and surges, muddy soils, instability, etc.). Yet, these ecosystems are highly productive with an average primary productivity often higher than that of neighboring continental forest types.

Many species of invertebrates and vertebrates of commercial value use mangrove habitat for food and shelter during their life cycle. Most mangrove ecosystems around the world have been depleted during the 20th century. Until the 1980s they have been extensively converted to other uses. For the last 20 years, many mangrove areas have come under full or partial protection, and restoration programs are being implemented in almost every one of the 70 countries possessing mangroves.

Most of the mechanisms and processes regulating mangrove ecosystems; primary productivity, food webs, nutrient fluxes, physiological adaptations of plants and animals, etc. are still poorly known, and this fragmentary knowledge is mainly restricted to species of commercial value.

Present distribution of mangroves

Six geographical zones have been recognized (Chapman, 1976; Snedaker, 1982; Rao, 1987; Saenger and Bellan, 1995; Duke *et al.*, 1998).

With rare exceptions, mangroves are restricted to coastal areas where mean monthly air temperatures, in winter, are higher than 20°C and where ground frost is unknown (Figure M2). The tallest (up to 35 m tall) and more dense mangroves are found in bioclimatic conditions with high annual rainfall (>2000 mm) and a short dry season (<3 dry months). They can survive in arid areas (Persian Gulf, Mauritania, Red Sea), in the form of low or dwarf, monospecific stands (Dodd *et al.*, 1999). The largest contiguous surface area of mangroves, covering more than 6,000 sq. km, is located in the upper Bay of Bengal, on the delta of the Ganges.

Recent estimates (Spalding *et al.*, 1997) indicate that the total mangrove area is about 180,000 sq km, most of it being located in South and Southeast Asia (Table M3). A few nations dominate these area statistics. For example, of the approximately 70 countries with this ecosystem, Indonesia, Australia, Brazil, Nigeria have about 43% of the world's mangroves. Indonesia alone has 23% and 12 countries have two-thirds (Table M3). Political and management decisions relating to mangrove stands of these countries will have significant effects on the global status in the future (Hamilton and Snedaker, 1984). It is assumed that at least 30% of these ecosystems are degraded or very degraded.

Productivity goods and services of mangrove forests

Our general knowledge of mangrove structural properties, above ground biomass and litter production (Saenger and Snedaker, 1993) is rather