Chapter 6

Control of Erosion, Inundation, and Salinity Intrusion Caused by Sea Level Rise

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INTRODUCTION

The most important direct physical effects of a significant rise in mean sea level are: coastal erosion, shoreline inundation owing to higher normal tide levels plus increased temporary surge levels during storms, and saltwater intrusion primarily into estuaries and groundwater aquifers (see Ippen, 1966; Komar, 1976; Sorensen, 1978; and Todd, 1980, for basic discussions of these phenomena). With a few exceptions, a significant sea level rise will increase the normally adverse effects of these phenomena.

In many coastal areas, economic considerations will not justify a response to these sea level rise effects. Where a response is justified, it may be political (zoning to prevent growth in areas of potential inundation and erosion), structural (building of coastal dikes to control inundation or saltwater intrusion barriers for aquifers) or, most likely, a combined political/structural response.

This chapter describes structural methods for controlling erosion, inundation, and salinity intrusion caused by sea level rise, including typical costs and the expected general effectiveness of these methods (in light of the anticipated sea level rise scenarios).[1] Both "hard" and "soft" structural responses are presented. The term hard structures refers tostructures such as seawalls and levees. Soft structural responses include artificial beach nourishment to counter erosion and flooding or injection of water into a well along the coast to develop a saltwater intrusion, barrier in an aquifer. Both the cost and the effectiveness of any structural control method are extremely site dependent and quite variable from site to site.

The next section of this chapter covers methods for the control of erosion and inundation, while the third discusses control of salinity intrusion. Inundation is a major cause of, and is difficult to separate from, shore erosion where erosion is active; thus the two are presented together. Each section discusses, as necessary, the processes involved in coastal erosion, inundation, and salinity intrusion; the basic approaches used to control these phenomena; and details of the specific control methods including their costs and effectiveness. The final section of the chapter summarizes the key points and suggests how these control methods might be applied at a given site.

CONTROL OF EROSION, INUNDATION, AND STORM SURGE

This section discusses the effects of sea level rise on erosion and inundation, and then on storm surge, in terms of both their processes and control. Specific methods for erosion, inundation, and storm surge control are then presented.

Sea Level Rise Effect on Erosion and Inundation

Processes. The processes involved in, and the resulting extent of, shore erosion depend largely on the type of shore being eroded. The discussion of erosion processes is thus presented according to the more common types of shoreline found in the United States. Komar (1976) and Sorensen (1978) provide a general discussion of shore erosion processes.

Beaches. Except near tidal entrances, sand transport on beaches is controlled primarily by wind wave action and secondarily by wind generated currents. Wave action can move sand in both the onshore offshore direction and in the alongshore direction.

During storms, waves break higher up the beach profile and cut the beach face back, depositing the sand offshore. When smaller waves follow a storm, sand is moved back onto the beach face from offshore. Thus, a cyclical change in beach profile occurs due to onshore-offshore sand movement. Net recession of the shoreline is possible if sand is carried too far offshore by storms or if a sequence of above-average stormy seasons moves more sand offshore than can be returned by the milder waves during the interlude seasons.

Alongshore transport of sand occurs when waves approach the shoreline at an angle. Sand is moved along the coast in the direction of the alongshore component of wave energy. If insufficient sand is available to satisfy the transport capacity of the waves, sand will be taken from the beach to satisfy that transport capacity. Groins, jetties, and other works of man that trap sand on the beach can cause erosion in the down-coast direction from the structure.

Thus, the erosion of beaches during an essentially static sea level is caused primarily by waves carrying sand offshore during storms and by the alongshore transport of sand not being satisfied by available sand. The latter typically dominates. Winds generating currents that move sand alongshore and offshore contribute to the erosion.

With a significant rise in sea level there will be an acceleration of beach erosion in areas already eroding and possibly a start of erosion in areas not previously subject to erosion. There are several reasons for this.

1. The main reason for increased erosion is simply that the higher water level allows wave and current erosion processes to act farther up on the beach profile and cause a readjustment of that profile, which results in a net erosion of the beach and deposition on the nearshore bottom.

2.Beach profiles are concave, increasing in steepness nearer to shore. At higher sea levels, waves can get closer to shore before breaking and cause increased erosion.

3. Deeper water also decreases wave refraction and thus increases the capacity for alongshore transport.

4. Higher sea level could change the source of sediments, for example, by decreasing river transport to the sea as the mouth is flooded. However, higher sea level can also act to diminish erosion by making more material available to alongshore transport by allowing wave attack on previously untouched erodable cliffs.

In summary, the general effect of shoreline rise on a beach profile is to move the profile shoreward.

Cliffs. Cliffed coasts often, but not always, have a thin protection beach, which may be temporarily removed during a storm, allowing wave attack at the base of the cliff and undermining of the cliff face, in turn causing a recession of the cliff. Cliffs vary in composition from extremely resistant rock that, under constant exposure to waves, shows little change in a century to loose materials that can be cut back tens of feet when attacked during a single storm. A rapidly rising sea level greatly increases both the exposure of the base of cliffs and the resulting erosion rate of erodable cliffs.

Estuaries. Estuary shorelines are typically exposed to much milder wave action and consist of fine materials and very flat shore profiles. Rising sea levels will flood the shoreline causing greater land loss owing to inundation than that owing to erosion.

Reefed Coasts. Many tropical coasts, for example, Oahu, have thin fragile beaches protected by offshore reefs that cause wave breaking and milder wave action on the beach. A rapidly rising sea level would increase the water depth over the reef and wave action on the beach or cliff inside the reef, resulting in increased erosion.

A rise in sea level will cause coastal inundation, an effect that is difficult to separate from the effect of shore erosion where erosion is occurring. At the water line, typical beach profiles have a slope that can vary from 1:5 to 1:100, so a 1 ft sea level rise can move the shoreline from 5 to 100 ft landward in addition to any landward movement of the profile owing to erosion.

Inundation by sea level rise will also require the raising and/or waterproofing of structures already inundated by virtue of having been built in the water. Examples include jetties built at the entrance to a navigation channel; bulkheads, docks and launching ramps in coastal marinas; and causeways across coastal embayments. Storm drainage, sewerage, and other liquid discharges to the sea by pumped or gravity flow through pipelines will have to be assisted in many areas by the installation of additional pumping capacity.

Deeper coastal waters will increase the tidal range along the coast, which will compound the above-mentioned effects of inundation and possibly change tide-induced flow and sedimentation patterns in coastal waters. Also, deeper coastal waters will permit the penetration of higher waves into coastal waters so that structures needing to be raised may also have to be strengthened to withstand increased levels of wave attack.

Control. To prevent shoreline erosion one must keep waves, particularly storm waves, from attacking the shore by intercepting them seaward of the surf zone or by armoring that portion of the shore profile where erosion occurs. Where longshore transport is significant, erosion can be prevented by reducing the ability of waves to transport sand or by increasing the supply of sand available for transport by the waves so that sand is not removed from the beach to satisfy the sand transport capacity. Most erosion control methods act in more than one way.

Economics will justify erosion control only at selected locations, such as densely populated areas, defense installations, or sites of historic significance, many of which will already have some works to control .erosion. Where shore erosion control works already exist, a response to *sea* level rise will often require building up the cross-sectional size and/or the stability and durability of the existing works.

Of the political responses to erosion, the eroded position could be continuously rebuilt or abandoned. New efforts to respond to erosion might include controls on further site development by appropriate agencies and abandonment of existing development. These approaches also generally apply to inundation.

In coastal regions, inundation caused by a rise in sea level and the increased tide range can be prevented by constructing a water-tight continuous structure such as the dike systems in the Netherlands; or if the inundated area is not too large, fill can be placed and held by a retaining structure. For areas of high wave attack, the dike or retaining structure will also have to be an erosion control structure. With a dike system, interior drainage canals and pumps to remove water that seeps into the areas below sea level will likely be needed.

Increased wave attack owing to higher water levels or wave attack at higher elevations because of the raised sea level will require many coastal structures to be stabilized by the addition of more or larger armor material and the armoring of areas not previously exposed to wave attack.

Higher sea levels will diminish the functionality of certain structures. For example, breakwaters that become more easily overtopped by waves would have to be raised to maintain their effectiveness; many marina and harbor appurtenances, such as fender systems and docks and walkways, would have to be raised.

Sea Level Rise Effect on Storm Surge

Processes. A storm with high sustained winds can cause a storm surge along several types of coastline. Depending on the configuration of the coast, different mitigation techniques are used. In the discussion that follows, three types of coastline or coastal feature are discussed: long narrowing bays or estuaries, open coastlines, and wide bays or sounds.

Each class of coastal feature is subject to different types of damage when storm surge occurs. Hence, mitigation measures must be used that are best suited to the damage potential. Some solutions are common to all areas.

Long Narrowing Bays and Estuaries. Storm surge causes much damage in funnel shaped bays, such as Narragansett Bay, Rhode Island. Water elevations can be dramatically higher at the head of the bay than those along the open coast. The hurricane of 1938 caused a surge almost 5 ft higher in Providence than at the mouth of the bay.

This phenomenon occurs in estuaries that narrow in the direction of the strongest winds. Thus, on the east coast of the United States, where damaging hurricanes move generally northward, estuaries that narrow northward such as Charleston harbor are susceptible to large surges. If the storm center passes to the west of the estuary, the counterclockwise blowing winds of the hurricane can move directly up the estuary. Typically, an urban area is situated at the head of the bay.

The high water in the bay caused by storm surge produces a backwater effect that in turn causes flooding in the tidal rivers that drain into the bay or estuary. This backwater effect can cause urban stormwater drainage systems to malfunction. Because of the heavy rain associated with most hurricanes, the backwater problem can cause extensive flood damage.

Open Coasts. An open coast, such as the barrier islands that run along much of the East and Gulf coasts of the United States or the unobstructed shoreline of the West Coast, is subject to both flooding and severe wave action during a storm surge. Although bluffs or cliffs would not flood, a wave attack at these high elevations could accelerate their erosion.

Bays, Sounds, and Harbors. In a semi-enclosed basin, such as the sounds between barrier islands and the mainland, storm surge at the open coast forces water through tidal inlets; the surge can also overtop the barrier islands. However, the limited distance over which the waves could build up over a small body of water limits the wave size. Hence, the structures can be designed for smaller waves.

Some bays and sounds may be subjected to a surge during an ocean storm if the barrier island is breached during the storm. This surge happens if the beach dune system erodes away. The storm surge moves as a wave across the sound to the mainland. A healthy wetlands or marsh system may help attenuate this storm surge.

Control. *Long Narrowing Bays and Estuaries.* Two structural mitigation methods are used to prevent flooding at the head of bays and estuaries. Usually the damage potential of waves is not as great as along the open coast. The two control techniques are a dam or tidal barrier and levees and/or floodwalls around flood-prone areas.

A tidal barrier prevents the storm surge from moving up the estuary into an urban area and also prevents the backwater effect in streams that run into the estuary. The barrier usually contains gates that are opened to allow navigation during normal weather and closed when a storm approaches. Levees and floodwalls are built in association with a tidal barrier to prevent flanking by the floodwater.

In an estuary where no tidal barrier is built, levees can be constructed to protect a flood-prone area, In either case, pumping facilities are essential to drain runoff from upland areas or water trapped inside a ring levee.

Providence, Rhode Island, and New Bedford, Massachusetts, have tidal barriers and associated levees, floodwalls, and pumping facilities to mitigate storm surge flooding (see Childs, 1965, and U.S. Army

Corps of Engineers, New England District). The Thames River, east of London, also has a $1 billion tidal barrier to prevent storm surge flooding of London.

Nonstructural alternatives for storm surge mitigation in bays and estuaries include zoning, floodproofing, and abandonment of high risk areas.

Open Coasts. Where flooding must be mitigated and wave action is severe, protective structures must be designed to withstand the forces associated with large storm waves. Also, the height of the structure must be built to an elevation that prevents frequent overtopping by the runup of breaking waves.

Open coastlines can be categorized as natural or urbanized. A natural reach of coastline typically has a beach, a line of dunes, and perhaps some roads or structures behind the dunes. Mitigation of storm surge along a natural coastline can employ beach nourishment and dune building or dune stabilization techniques.

In highly urbanized areas where the dunes and beaches no longer exist or do not offer adequate protection, seawalls and revetments must be used. These structures are designed to reflect or dissipate wave energy and are high enough to protect inland areas from flooding.

Seawalls and revetments are found at various locations along the East and Gulf coasts. The Galveston seawall, for example, was built in response to a hurricane surge that occurred at the turn of the century and killed 6,000 people.

Bays, Sounds, and Harbors. Mainland areas behind barrier islands or land areas surrounding harbors and bays are protected from flooding by levees and floodwalls. Examples of such areas are the Galveston Bay, Matagorda, and Corpus Christi areas of Texas (see U.S. Army Corps of Engineers, Galveston District, 1979) and East Coast bays such as the Chesapeake, Delaware, and Raritan bays.

A rise in sea level in these areas will allow storm surge to flood land areas previously immune to coastal flooding or to affect some land areas more frequently. Existing structures will have to be strengthened and made more effective against a higher static water level and waves. Areas that are not now protected against storm surge flooding and wave attack will be forced to decide between abandonment and initiation of engineering works.

Specific Erosion, Inundation, and Storm Surge Control Methods

Although a rising sea would require some change in application, the methods for controlling the effects of coastal erosion, inundation, and storm surge from sea level rise would be the same as the methods employed today. These methods can be broadly classified as hard, soft, and miscellaneous. The letters in parentheses below indicate whether the method is employed primarily against erosion (E), inundation (I), and/or storm surge (S).

Hard structures include: offshore breakwaters (E), perched beach (E/I), groins (E), revetments (E/I/S), dikes (E/I/S), seawalls (E/l/S), bulkheads (E/I/S), and dams (I/S).

Soft structures include: artificial beach nourishment (E/I/S), dune building (E/l/S), and marsh building (E/l/S).

Miscellaneous inundation responses include: elevation of structures (I/S), strengthening of structures (I/S), and expanding water collection and pumping systems (I/S).

As erosion, inundation, and storm damage occur, economic considerations would dictate that the most lightly inhabitated coastal areas be abandoned. Control of erosion, inundation, and storm damage would not be attempted in uninhabitated and lightly inhabitated coastal areas unless a site has value for some other reason, for example, an historic site or a potential defense site.

When it is apparent that a significant sea level rise is occurring, coastal political authorities will have to limit and direct development to locations that can most economically and effectively be defended. This would have to be accomplished through zoning, penalties to construction in undesirable areas (such as higher insurance rates), and perhaps even condemnation of existing development that cannot be protected.

Raising and strengthening existing structures or expanding flow discharge systems involves an enormous variety of efforts, including determining their costs, application, and effectiveness. A discussion of these methods is beyond the scope of this chapter.[2]

Offshore Breakwaters. One or more breakwaters, with intervening gaps, have been built parallel or nearly parallel to shore in water depths of a few to 20 or 30 ft to stabilize a shoreline. They function by intercepting a large portion of the incident wave energy and thereby decrease the offshore and alongshore transport capacity of waves.

Where significant alongshore transport occurs, offshore breakwaters will trap a portion of that transport to augment the original beach. If the original beach is inadequate and the potential for trapping a significant volume of sand from alongshore transport does not exist, the area in the lee of the breakwater(s) can be filled with sand. Figure 6-1 shows a section of nourished beach at Lakeview Park, Ohio, protected by three offshore detached breakwaters and a groin.

Offshore breakwaters are usually constructed when a new beach is to be developed or an existing beach is to be stabilized. A shoreline without a beach of any consequence is more likely to be stabilized by construction of a structure at the land-water interface such as seawalls, revetments, or bulkheads rather than an offshore breakwater. A tradeoff can be made between the size, length, and crest elevation of breakwaters and the resulting level of transmitted wave energy versus resulting beach shape, erosion, and consequent need for periodic renourishment. Most offshore breakwaters are built with a low crest elevation to minimize cost, maximize water circulation in their lee, and minimize beach planform irregularity.

Offshore breakwaters are quite effective in stabilizing shorelines, but, particularly on exposed coasts having higher waves, their capital cost can be quite high. The structural aspects of their design are reasonably well understood theoretically, but their functional layout, length, gap width, distance offshore, and crest elevation are generally based on empirical evidence.

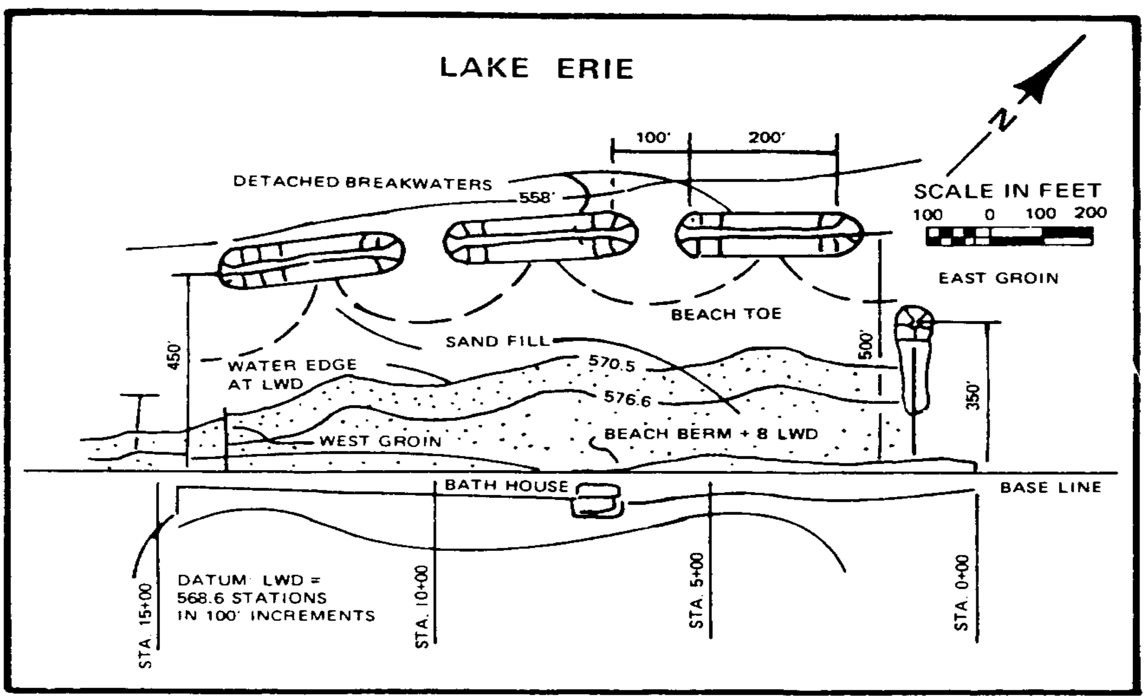

Figure 6-1. Three offshore (detached) breakwaters, a groin, and beach nourishment at Lake View Park, Ohio.

Figure 6-1. Three offshore (detached) breakwater, a groin, and beach nourishment at Lake View Park, Ohio.

Offshore breakwaters, like other breakwaters, are typically stone rubble mounds, but they have been built with steel or concrete sheet piling, sand filled bags and rubber tubes, and wooden cribs filled with stone. To allow some wave transmission through the structure, some have been constructed from large armor stone only.

Table 6-1 lists the cost per foot of breakwater length and cost per foot of beach protected for recent offshore breakwaters. The first three sites are on the Great Lakes and the fourth is in more protected waters in Delaware Bay. No recent cost data were obtained for offshore breakwaters on the open ocean. Economic considerations diminish their use for beach protection in high wave environments. An estimate of the cost per foot of structure in the open ocean can be obtained by looking at cost figures for jetties with similar cross sections. The proposed 1,280 m (4,200 ft) long rubble mound jetty at Barnegat Inlet, New Jersey, has an estimated cost of $25,800,000 (see U.S. Army Corps of Engineers, Philadelphia District, 1981) or an average cost of $20,139/m ($6,140/ft) in 1981. Typical dimensions for this jetty are a 7 m (23 ft) height, 24 m (80 ft) base width, and 6m (18 ft) crown width. A similar offshore breakwater protecting a beach might have a cost of $9,840-$13,120/m ($3,000-$4,000/ft) of beach. Thus, the cost of offshore breakwaters in 1980 dollars could vary from $656-$9,840/m ($200-$3,000/ft) of beach depending on the level of wave attack, nearshore beach slope, and level of protection desired.

As sea level rises, the crest elevation of an existing offshore breakwater would have to be raised to maintain the same level of shore protection. Higher waves would approach the gaps owing to the deeper water, so gap widths may have to be decreased. Also, higher sea levels will increase the distance between the breakwaters and the shoreline and allow more wave energy to reach the protected area owing to wave diffraction at each end of the line of offshore breakwaters. Thus, the two end breakwaters may have to be extended. Beach fill and/or shoreline structures might be constructed landward of the breakwaters to keep the shore from being inundated. Because rubble structure costs vary geometrically with crown elevation, a 10 ft rise would generally cost much more than five times the cost of controlling a 2 ft rise.

Perched Beach. Related to offshore breakwaters but functioning **in** a different way is the concept of a perched beach. A continuous well-submerged structure is built offshore and parallel to shore, and a beach is built between the structure and shore by artificial nourishment. The structure retains the toe of the beach and perhaps diminishes incident wave energy somewhat by causing larger waves to break. Being submerged, the structure is not exposed to large wave forces.

A perched beach was proposed for the coast of California at Santa Monica (see Dunham, 1968) but not built. As part of a shore erosion control demonstration project in sheltered waters, Longard Tube, sand bag, and wood sheet pile structures were built at Slaughter Beach, Delaware (see U.S. Army Corps of Engineers, Philadelphia District, 1978a). Structure crests were about 0.6 m (2 ft) above the bottom in water averaging about 1.2 m (4 ft) deep and sand fill was placed behind the structures. Structure costs were $279-$515/m ($85-$157/ft) in 1978. Structure costs for a perched beach might be roughly one-fourth to one-half those of an offshore breakwater on a per foot of structure basis or one-half to three-quarters on a per foot of beach basis.

As sea level rises, the crest elevation of an existing perched beach structure would be raised, and more sand would be placed behind it. An offshore breakwater system being submerged by a rising sea level could be converted to a perched beach system by building a structure in the gaps and placing additional fill. Further laboratory and field evaluation of this concept is needed; however, it could prove to be an effective way to maintain a shoreline exposed to rising sea levels.

Table 6-1. Offshore Breakwater Cost Data

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Site	Cross-section dimensions	Cost/ft Structure	Cost/ft Beach	Remarks
Presque Isle Erie, Pennsylvania	15' vertical 65' base 13.5' crown width rubble mound	$1,728	$585	Project also calls for beach fill; groin field exits at site
Lakeshore Park Ashtabula, Ohio	10' vertical 45' base 9.5' crown width rubble mound	622	330	Breakwater is all armor stone; beach fill provided
Lake View Park Lorain, Ohio	(see Figure 6-1)	890	700	Beach fill and terminal groin
Kitts Hummock Delaware	69'' Ø Longaard tube with sand fill	188	91	Structure crests at mean sea level; structures part of demonstration project and probably somewhat underdesigned
	Six 4' × 20'' × 12' sandbags	216	105	
	5' vertical 20' base 5' crown width rubble mound	228	111	

Sources: For Presque Isle: U.S. Army Corps of Engineers, Buffalo District, 1980, "Construction Cost Estimate: Beach Erosion Control Project, Presque Isle, Erie, Pennsylvania."

For Lakeshore Park: U.S. Army Corps of Engineers, Buffalo District, 1982, "Construction Contract Cost Bidding Schedule: Beach Erosion Control and Shoreline Projection Project, Lakeshore Park, Astabula, Ohio."

For Lake View Park: U.S. Army Corps of Engineers, Buffalo District, 1977, "Construction Contract Cost Bidding Schedule: Beach Erosion Control Project, Lake View Park, Lorain, Ohio."

For Kitts Hummock: U.S. Army Corps of Engineers, Philadelphia District, 1978b, "Kitts Hummock, Delaware, Pre-construction report, Shoreline Erosion Control Demonstration Program."

Sources: For Presque Isle: U.S. Army Corps of Engineers, Buffalo District, 1980, "Construction Cost Estimate: Beach Erosion Control Project, Presque Isle, Erie, Pennsylvania." For Lakeshore Park: U.S. Army Corps of Engineers, Buffalo District, 1982, "Construction Contract Cost Bidding Schedule: Beach Erosion Control and Shoreline Projection Project, Lakeshore Park, Astabula, Ohio."

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Groins. Groins are built perpendicular to the shore to trap sand transported alongshore by waves and/or to hold existing sand from being transported away (see Figure 6-2). Many people mistakenly call these structures jetties. They have little effect on the offshore transport of sand during storms, unless the angle of wave attack is extremely oblique. Typically, groins extend from the beach berm crest to the outer edge of the surf zone. Groins are most commonly rubble mound structures, but they have been built of concrete or wood sheet piling, concrete blocks, or timber cribs filled with stone.
Because they are perpendicular to shore and located mostly in shallower water than offshore breakwaters, the cost per unit length of structure for groins is typically less. For example, the groin extension at Lake View Park, Ohio, cost approximately $1,476/m ($450/ft) of structure (see U.S. Army Corps of Engineers, Buffalo District, 1977) compared to $2,919/m ($890/ft) for the offshore breakwater at the same site.

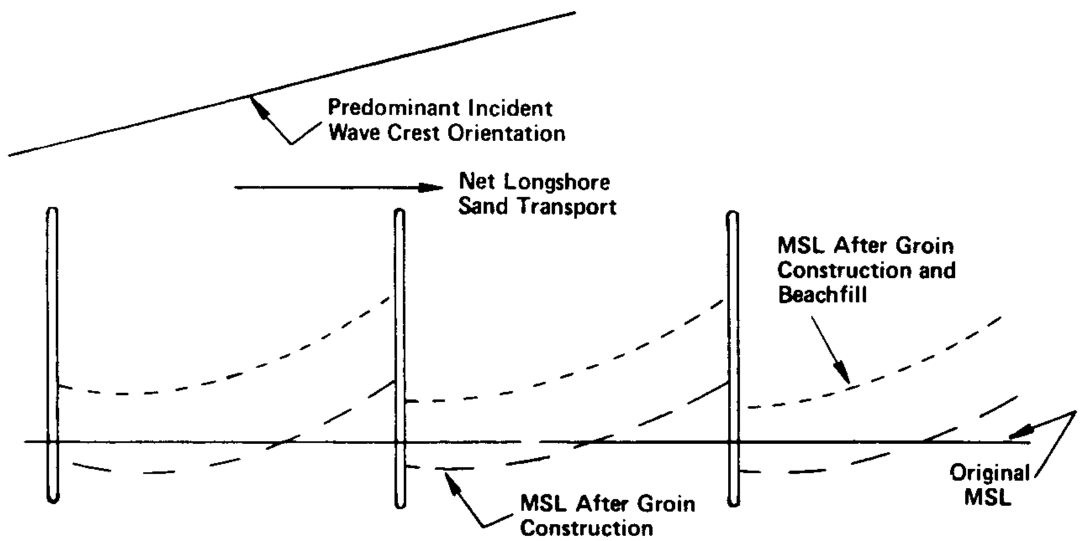

Figure 6-2. Schematic plan view—typical groin field.

Figure 6-2. Schematic plan view-typical groin field.

Wood pile groins on the Atlantic Coast of Delaware had an estimated cost of $984/m ($300/ft) in 1975 (see U.S. Army Corps of Engineers, Philadelphia District, 1975). In a groin field, the ratio of groin length to distance between groins can vary from 1:1.5 up to 1:4. Using a typical value of 1:2 and assuming groins cost half as much as offshore breakwaters on a per foot of structure basis, typical 1980 costs per foot of shoreline for groins could vary from $100 to $1,500 depending on level of wave attack, whether or not beach fill will be placed, and beach slope.

With a significant sea level rise, existing groins would have to have their crest raised, and unless beach fill is provided to counter inundation, they would have to be extended inland. Groins would not directly control shoreline recession in response to sea level rise. However, where there is a substantial alongshore movement of sand, they can help control erosion from sea level rise.

Revetments. A revetment is a structure typically consisting of loose armor material, stones, and concrete blocks laid on a relatively flat slope to protect an embankment from wave attack (see Figure 6-3). Revetments are used in locations where there is little or no protective beach and low to moderate wave climate, such as the Chesapeake Bay. They would rarely be used on open ocean shorelines. Important considerations in their design include: a filter, finer stone, or cloth to keep embankment soil from being removed, and toe protection, sheet pile cutoff wall, or larger stone to prevent failure from scour at the toe. An adequately designed revetment is an effective means of stabilizing a shoreline subject to low-moderate waves. Fill can be placed behind the revetment to raise ground levels along the shore. A flat near-shore slope and adequate sand to satisfy alongshore transport greatly improve their performance.

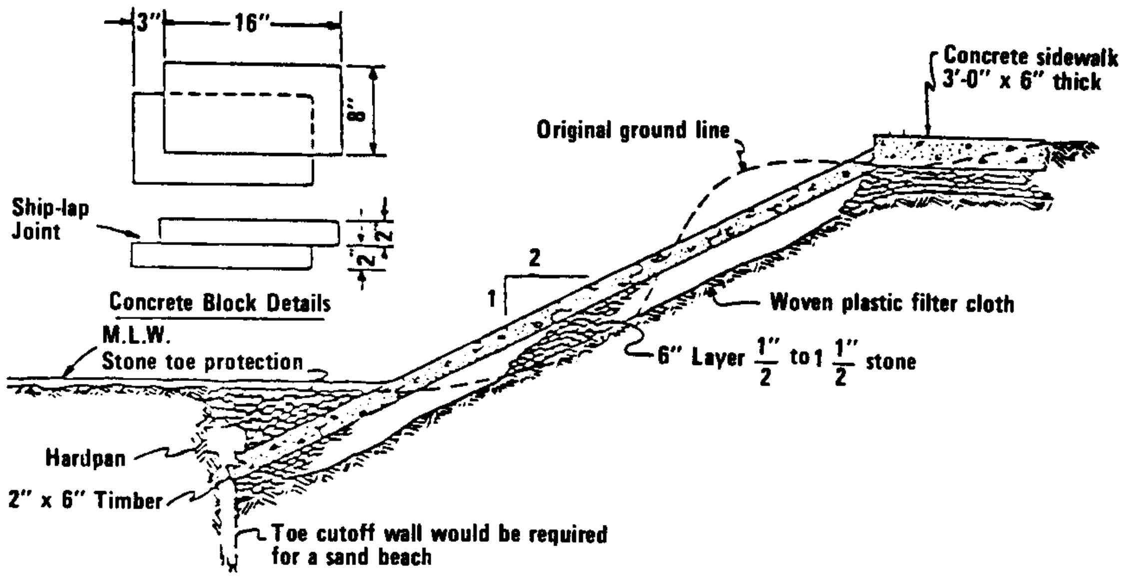

Figure 6-3. Profile of concrete block revetment showing the most basic features of a typical revetment.

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Table 6-2. Cost Estimates for Bluff Protection Revetment

Armor Material	*Length along Slope (ft)*	*Cost/Ft*
Stone riprap	52	$225
Gabion mat (wire cover filled with stone)	54	$136
Lok-Gard concrete blocks	71	$201
Car tire mat filled with cement	61	$125

Source: Data from B.L. McCartney, 1976, *Survey of Control Revetment Types*, CERC MR 76-7, Fort Belvoir, Va.: Coastal Engineering Research Center.

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Source: Data from B.L. McCartney, 1976, Survey *of Control Revetment* Types, CERC MR 76-7, Fort Belvoir, Va.: Coastal Engineering Research Center.

McCartney (1976) estimated the costs for a bluff protection revetment on Lake Superior having a 20 year design life. The bluff slope is about 1:3, no special toe protection was required, and no overtopping by wave runup was allowed. The results for four revetment types (1975 cost figures) are presented in Table 6-2. McCartney's cost estimates are probably somewhat low, as can be seen by comparing some of his unit costs with those in other sources (see U.S. Army Corps of Engineers, Philadelphia District, 1980). Thus, in 1980 figures, these revetments might cost $984-$1,640/m ($300-$500/ft) of beach for an exposure similar to Lake Superior's. Designing for a longer project life at a site having a different embankment slope could raise the cost per meter of beach to, say, $1,640-$1,968 ($500-$600/ft).

Because of higher waves reaching the revetment, higher sea levels will require that revetment crests be raised and, at some point, armor units sizes be increased and toe scour prevention works be improved. For any given sea level rise, the structure and landward supporting embankment can be appropriately raised to continue control of erosion and inundation. Quoted structure costs do not include any costs for enlarging the embankment that supports the revetment.

Dikes. A dike or levee is an earth fill mound, usually having a trapezoidal cross-section, that is placed along the land/water edge to prevent water from flooding the lower dry land area. The side exposed to waves and currents is often reverted with rip rap, asphalt or concrete pavement, and special flexible matting. An impervious core, for example, a clay layer, is desirable to limit seepage through the dike during raised water levels. To control water overtopping the dike by wave action, it is desirable to have water collection channels and sump pumps to remove the water. Some of these features are demonstrated in Figure 6-4, which shows a typical levee section for proposed flood control works wherestrong wave attack is not anticipated.

When space is available (base width required is about five times the structure height) and fill can be found, a dike system is the best way to control flooding, except where there is strong exposure to wave action such as the open ocean. For a given sea level rise, greater wave action requires a more massive revetment system and a higher structure crest to control increased wave runup. Both features can significantly increase the cost of the dike. All important advantage of a dike system for controlling sea level rise is that it can be easily raised by placing additional fill on the top and backside and extending the revetment. As sea level rises and the land landward of the dike is now continuously below sea level, a canal/pump system will be needed to remove water that seeps into the area as well as normal runoff from rainfall. Lock systems would have to be constructed to connect interior navigation channels with the sea.

The cost per foot of a dike can vary widely depending on its dimensions, availability of fill and impervious core material, need for revetment of the exposed side, accessibility of the work site, length of section being constructed, and other factors. In 1980 prices, a small nonrevetted levee with the dimensions shown in Figure 6-4 might cost $492-$656/m ($150-$200/ft) of structure. A 6.09 m (20 ft) high revetted levee, on the other hand, could cost $3,280-$3,936/m ($1,000-$1,200/ft). These cost estimates are typical, but actual costs at a given site can vary substantially.

Floodwalls. Floodwalls, usually made of concrete, are used in urban areas where broad earthen structures such as dikes would use too much valuable land. The function of a floodwall is to protect a land area flooding. As with levees, riprap is often added in front of a dike, as shown in Figure 6-5. This could be done with existing walls as sea level rises.

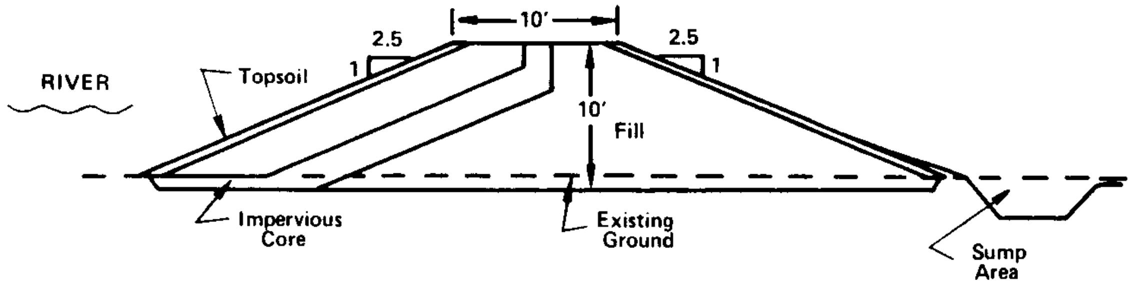

Figure 6-4. Typical dike or levee section to prevent inundation where strong wave action is not anticipated.

Figure 6-4. Typical dike or levee section to prevent inundation where strong wave action is not anticipated.

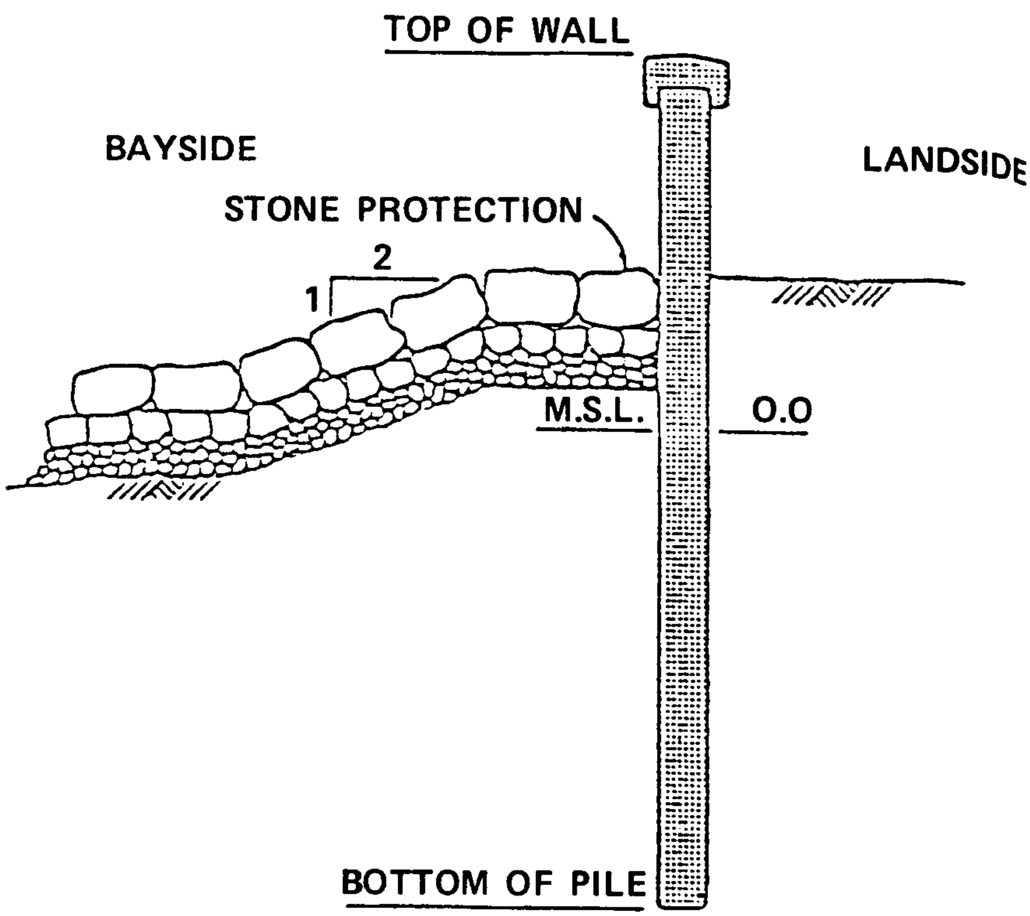

Figure 6-5. Wall and levee section.

Figure 6-5. Wall and levee section.

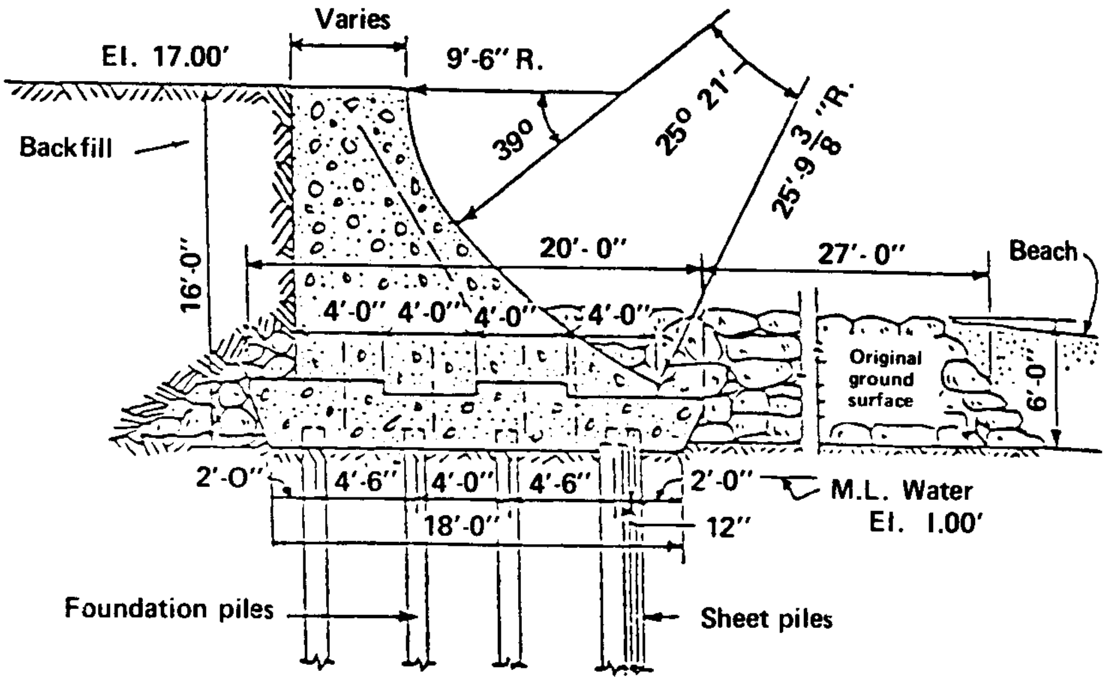

Figure 6-6. Massive concrete seawall, Galveston.

Figure 6-6. Massive concrete seawall, Galveston.

Seawalls. In areas of extreme wave action where shore erosion and inundation due to sea level rise and storm surge are to be completely controlled, a concrete seawall may be constructed. Figure 6-6 shows the massive concrete seawall built in Galveston to resist storm surge and wave action. Note the sheet piling driven at the toe to resist scour at the base of the structure, bearing piles to support the structure, a curved or stepped face to limit wave overtopping, and backfill to raise the land elevation behind the structure. Seawalls require less space than dikes or levees.

A seawall is much more costly than a revetment or bulkhead and consequently would only be used in areas of strong wave attack or where valuable property is to be protected. Because of the necessary concrete form work, reinforcing steel, and bearing and support piles, seawalls cost $9,840 or more per meter ($3,000/ft) of structure.

If appropriately designed, a seawall could be extended vertically at a later time, in response to a rising sea. This would entail, for example, providing adequate bearing and cutoff piles, since deeper water would typically mean greater scour, and designing the top so a uniform strong connection can be made as the structure is raised. Also, the original section should be designed to withstand the larger and more frequent waves that will attack the structure during higher sea levels.

Seawalls have also been built at the base of erodable cliff sections to prevent cliff retreat caused by storm wave attack. Since their purpose here is erosion control, not prevention of inundation, they may be made of rubble mounds containing large breakwater-size armor units.

Bulkheads. Typically, a bulkhead is a vertical wall constructed at the land-water interface and having the primary purpose of retaining fill (see Figure 6-7). Bulkheads are commonly found in areas where strong wave and current action are not likely, such as marinas and harbors, and along inland waterways. When they must resist wave attack, they are more massive and fronted by a beach and/or rubble toe scour protection.

Bulkheads can be built from steel, aluminum, timber, or concrete sheet piling. Anchor piles or "tie-backs" are usually required to keep the bulkhead from falling into the water because of the pressures exerted by the fill the bulkheads retain.

As sea level rise and coastal inundation occur, much of the shoreline requiring protection from inundation will be in sheltered or semi-sheltered bays and estuaries and thus appropriate for protection by bulkheading. As deteriorated bulkheading is replaced and a significant sea level rise is anticipated, the replacement bulkheading length should anticipate this rise. Typical projected lives for quality timber and steel bulkheading is 25 years; concrete bulkheading might have a projected life of 50 years.

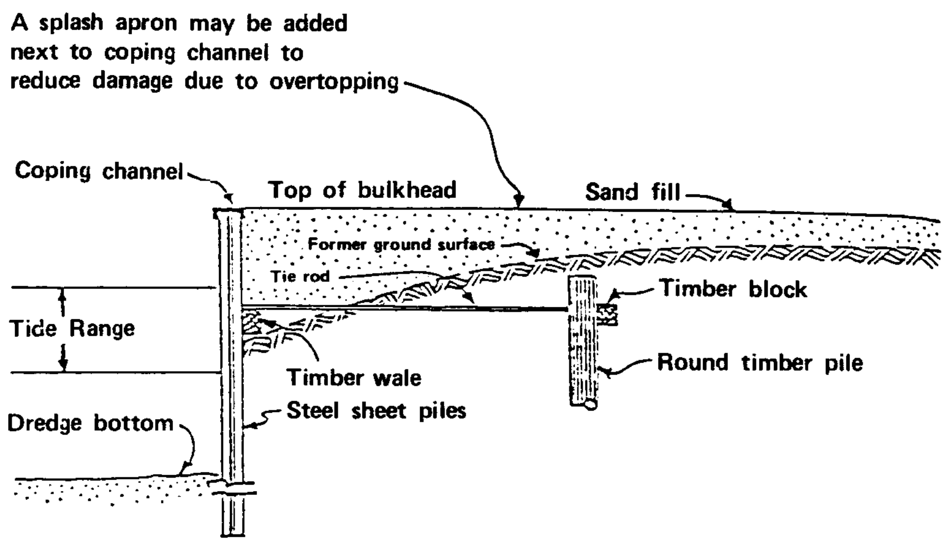

Figure 6-7. Steel sheetpile bulkhead, Nantucket Island, Massachusetts.

Figure 6-7. Steel sheetpile bulkhead, Nantucket Island, Massachusetts.

Where damage from vessel impact, ice, and so on is expected or when the original structure quality is not the best, shorter projected structure lives can be expected.

Steel and timber bulkhead designs and their costs for Great Lakes usage are given by the U.S. Army Corps of Engineers, North Central Division (1978). The cost per foot for bulkheads including steel piling with cable tiebacks, sandfill, and stone toe protection are found in Table 6-3. Timber bulkheading, which has a shorter design life, costs $230, $312, and $492/m ($70, $95, and $150/ft) for the same conditions.

Prestressed concrete (7 m/long, 0.3 m thick; 23 ft long, 1 ft thick), timber (8 m long, 3 m thick; 27 ft long, 10 in thick) and Z-27 steel (8 rn long; 27 ft long) piling bulkheads were designed for the Atlantic coast of Delaware (see U.S. Army Corps of Engineers, Philadelphia District, 1975). They were part of a beach erosion control/hurricane flooding protection project that included groins and beach nourishment. The costs per meter (1975) were $2,162 for prestressed concrete ($659/ft), $2,775 for timber ($846/ft), and $2,060 for steel ($628/ft), plus $577/m ($176/ft) for riprap toe protection.

From the above figures, typical costs per meter for bulkheading in 1980 could be expected to vary from $492 to $984 ($150-$300/ft) in sheltered harbor/waterway areas and from $3,280 to $3,936/m ($1,000$1,200/ft) on the open coast with a protective beach that might be removed only during heavy storms.

Table 6-3. Bulkhead Costs.

Table 6-3. Bulkhead Costs

Water Depth 50 Ft Offshore (ft)	Piling Length (ft)	Cost/Ft
3-4	13	$290
5-6	20	$460
7-8	25	$580

Source: Data from U.S. Army Corps of Engineers, North Central Division, 1978, "Help Yourself: A Discussion of Erosion Problems on the Great Lakes and Alternative Methods of Protection," pamphlet.

Source: Data from U.S. Army Corps of Engineers, North Central Division, 1978, "Help Yourself: A Discussion of Erosion Problems on the Great Lakes and Alternative Methods of Protection," pamphlet.

Dams. Dams or tidal barriers are concrete or earthfill structures built across an estuary or tidal river to prevent a storm surge from moving up river and causing flooding in tributaries and in the main stem. A levee system along the river or estuary and running inland is used in conjunction with the dam to prevent flanking by floodwaters. Gates are provided through the barrier to allow navigation vessels to move through and to allow drainage to the sea during normal tidal elevations. The gates must be closed at the approach of a storm and a pumping facility must then pass the river flow over the barrier.

The cost of such dams is very site specific. Some information is given by Childs (1965) for New England tidal barriers.

Artificial Beach Nourishment. Eroding shorelines can be stabilized by the placement of suitable (adequate particle size) sand, usually a large initial fill followed by periodic renourishment to make up for losses. Beach nourishment, by raising beach surface elevations, will also act to limit inundation. Many beach fills are stabilized by groins and/or offshore breakwaters to reduce renourishment requirements. In turn, beach nourishment is used to stabilize some shore protection structures, for example, bulkheads, dikes. For example, groins with beach nourishment are used at critical areas of the Dutch coast to protect the base of potentially erodable dunes. To be feasible, a good source of sand located near the nourishment area is required. Typical sources included offshore deposits, deposits at the ebb and flood deltas of a tidal inlet, and occasionally, if adequate quantities can be found, onshore or in nearshore embayments. Mechanical bypassing of sand past an obstruction to alongshore transport such as an inlet is a form of beach nourishment; sand is taken from the site that is accumulating and taken to the site that is accumulating and taken to the site that is eroding.

Numerous beach nourishment projects have been completed in the United States during the past few decades. Hobson (1977) discusses 20 of these including cost data. At a given date, the cost per cubic yard of sand in place on a beach can vary widely depending primarily on the volume of fill required and the transport distance to an adequate source. This is demonstrated in Table 6-4. The typical cost per cubic meter for beach fill could vary between $7 and $13 ($5 and $10/yd^3), with the former figure being for large fills and nearby sources and the latter for smaller fills and more remote sources.

Table 6-4. Beach Nourishment Costs

Table 6-4. Beach Nourishment Costs

Site	*Fill Period*	*Volume (Yd^3)*	*Cost/Yd^3*
Rockaway Beach, N.Y.	1975-1977	2,145,000	\$4.38
Caroline Beach, N.C.	1971	447,000	\$8.73
Hunting Isle, S.C.	1968	436,000	\$1.40
Presque Isle, Pa.	1980	500,000	\$7.56
Lake View Park, Oh.	1977	111,000	\$7.49
Lakeshore Park, Oh.	1982	36,700	\$12.08

Source: Data from R. D. Hobson, 1977, *Review of Design Elements for Beach-Fill Evaluation*, CERC 77-6, Fort Belvoir, Va.: Coastal Engineering Research Center.

Source: Data from R. D. Hobson, 1977, Review of *Design Elements for Beach-Fill* Evaluation, CERC 77-6, Fort Belvoir, Va.: Coastal Engineering Research Center.

To determine the cost of beach nourishment per unit length of beach, one needs to know the volume placed per unit length. Typical volume per unit length values cannot be stated, as they vary too widely depending on the desired widening of the beach, the initial beach profile and the resulting stable fill profile, and whether or not frontal dunes are to be constructed with the fill.

As sea level rises, beach fill can be placed along with stabilizing structures to maintain the location of mean sea level in critical areas. The fill would prevent inundation, and structures would control erosion of the fill. Nourishing a beach to retain a pre-sea level rise location steepens the beach face, making it more prone to erosion and more in need of stabilization by structures. In many areas where beach nourishment is practiced, supplies of suitable sand are limited, and continuous extensive placement of fill on beaches to control shoreline retreat would not be practical.

Dune Building. A line of continuous coastal dunes located just landward of the active beach profile can help limit storm inundation and beach erosion. For the former, the dune field acts like a dike and for the latter, it provides a reservoir of sand to overcome the erosive effect of waves. If an inadequate dune field exists, it may be raised and widened rapidly by the mechanical placement of sand or more slowly by trapping wind-blown sand with fences and/or vegetation. Vegetation is generally more appropriate. The cost of the mechanical building of dunes can be estimated from the volume of sand required and the costs per cubic meter reported above. For example, a dune built to 3 m (10 ft) above a given elevation may have 14 m^3 of sand per meter of beach (500 ft^3 or about 18 yd^3 of sand per ft). At \$10/m^3 (\$8/yd^3), dunes would cost \$472/m (\$144/ft) of beach plus the costs of stabilizing the dune. The latter would include planting of vegetation and periodic chemical fertilization. In some circumstances, it may pay to revet the seaward face of a natural or artificial dune to increase its resistance to erosion by storm waves.

Marsh Building. In salty or brackish estuarine areas, salt marshes are common. A shallow flat marsh can provide some protection to adjacent land areas by dissipating incident wind and vessel waves. Also, vegetation in the marsh encourages trapping and stabilization of fine sediments and upward growth of the marsh surface (at quite a slow rate). If insufficient vegetation exists, marsh growth and stabilization can be encouraged by the planting of vegetation. Woodhouse (1979) presents the techniques for building salt marshes with vegetation, and Knutson and Inskeep (1982) discuss the use of salt marsh vegetation for controlling shore erosion in sheltered coastal areas.

Depending on marsh width, plant density, soil characteristics, and shoreline geometry, marshes can be stabilized against wave attack if wave generation fetches are typically a few miles or less. Planting of a 9 m (30 ft) wide strip of marsh would cost $16-$33/m ($5-$10/ft) in 1980.

With a sufficiently slow sea level rise, marsh growth may keep pace with increasing sea levels and resist erosion/inundation effects. However, significant inundation and related higher waves would soon destroy a vegetated marsh.

SALTWATER INTRUSION

The Process of Saltwater Intrusion

Many investigations have been conducted to determine the movement and extent of saltwater intrusion. A brief summary of the principles is presented here.

Saltwater Intrusion Into Aquifers. The Ghyben-Herzberg principle provides an initial estimate of the inland extent of saltwater intrusion in a simple unconfined aquifer of infinite depth (see Figure 6-8). This theory assumes two fluids separated by a sharp interface and ignores many of the complexities found in real aquifers (see Figure 6-9). The principle assumes that an equilibrium condition exists between the saltwater offshore and a freshwater flowing from the upland area down toward the ocean. As shown in Figure 6-8, because the saltwater is 1.025 times denser than the freshwater, the saltwater/freshwater interface lies a distance *below* mean sea level (H) for a given height of the freshwater above mean sea level (h). The product of the density of saltwater times its height is balanced by the density of freshwater times its height. In equation form:

$$1.025 \text{ x } H = 1.0 \; x \; (h + H)$$

or solving for H, the interface location below mean sea level in terms of h, the freshwater head above mean sea level is $H = 40\ h$. At any point in time, for every foot that the freshwater table lies above mean sea level, the depth to the saltwater is 12 m (40 ft) below mean sea level.

Where coastal aquifers are strongly influenced by the withdrawal of water, the location of the saltwater front is controlled by the pumping pattern and intensity rather than the density balance predicted by the simplistic Ghyben-Herzberg principle (see Figure 6-8). Aquifers with complex geometries or heavy groundwater pumpage may require the application of models that are more sophisticated than the Ghyben-Herzberg model, as addressed by investigators such as Pinder and Gray (1977) and Contractor (1980). The mixing or diffusion zone between the saltwater and freshwater is taken into account in many of these models. However, it is often relatively small, and for an initial study a relatively simple model is recommended that assumes that a sharp interface exists between the freshwater and saltwater.

Fortunately, moderately sophisticated models, which are not over-simplified and do not require an unrealistic effort to apply, exist. Many investigators such as Harbaugh et al. (1980) have employed such models to predict the movement of the saltwater front in aquifers for various pumping schemes without resorting to the extremely complicated convection-dispersion transport models. Existing saline water levels obtained by field measurements are converted to equivalent freshwater levels. Along with saltwater velocities computed by the model, useful initial estimates of saltwater movement can be obtained. However, these methods will not provide detailed description of the location of the saltwater equilibrium surface. In many instances, the choice of the proper model is crucial.

The following initial data are required to employ such models properly: an existing water level map, an existing chlorine concentration map based upon field data, the physical properties of the aquifer, and current, past, and projected groundwater withdrawals. Then, a predictive model should be chosen which can model the projected impact of the rise sea level.

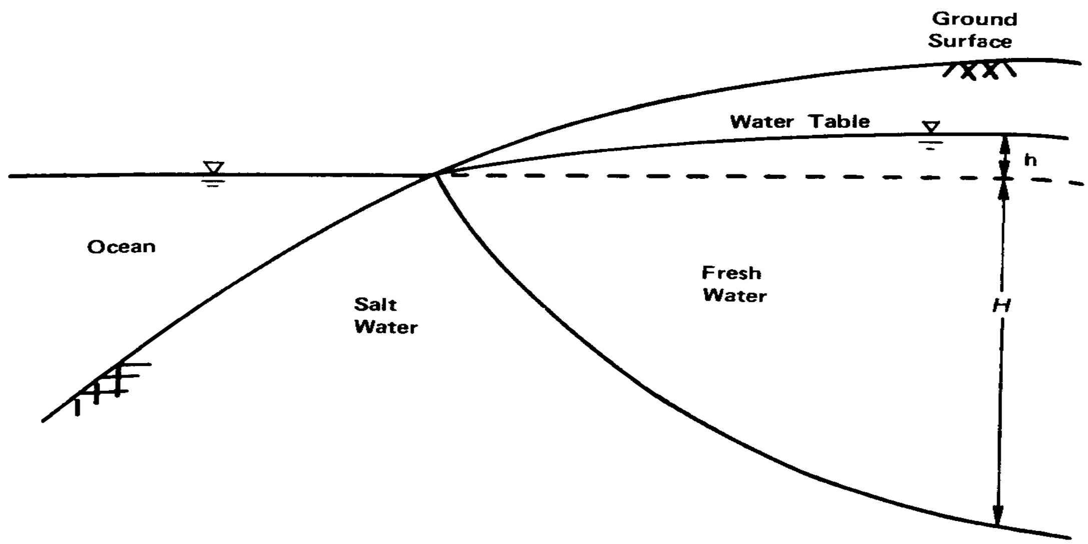

Figure 6-8. Saltwater intrusion in a coastal aquifer according to d'Andrimont.

Figure 6-8. Saltwater intrusion in a coastal aquifer according to d'Andrimont.

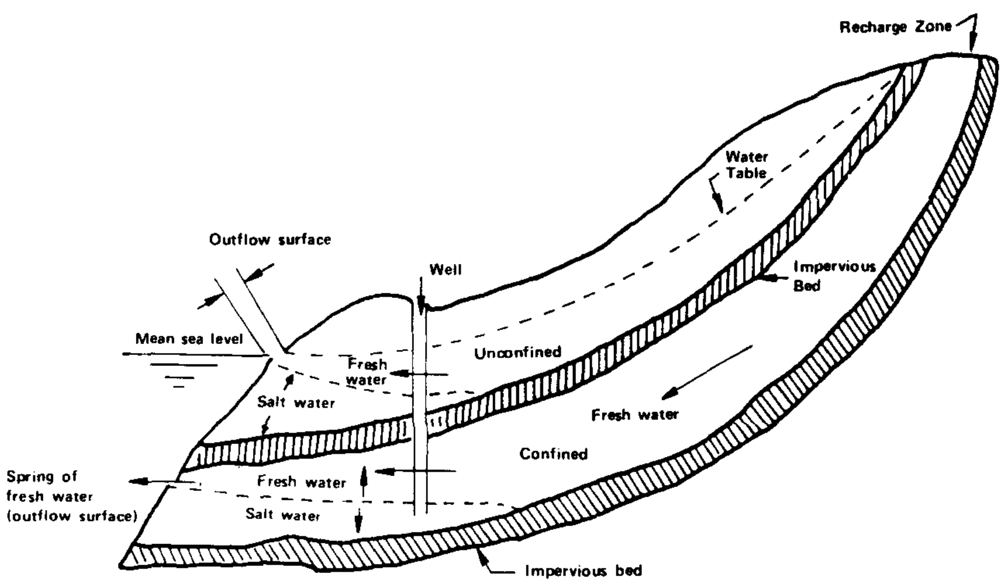

Figure 6-9. Saltwater intrusion into two-aquifer system. *(After J.S. Brown, 1925, Study of Coastal Groundwater With Special Reference to Connecticut, U.S. Geological Survey Water Supply Paper 537.)*

Figure 6-9. Saltwater intrusion into two-aquifer system. *(After J.S. Brown, 1925, Study of Coastal Groundwater With Special Reference to Connecticut, U.S.* Geo*logical Survey Water Supply Paper* 537.*)*

Saltwater Intrusion into Estuaries. During extended droughts, decreased river flow allows the saline water to migrate up the estuary. A rise in sea level will also cause saltwater to migrate upstream. The general methods of preventing saltwater intrusion up estuaries are similar for sea level rise, drought conditions, and storm surge. As discussed previously, storm surge elevates the ocean in relation to the estuary water level, causing saltwater intrusion. A major difference is that storm surge and drought conditions last for a limited duration, whereas the sea level rise is expected to last much longer.

In order to minimize saltwater migration, river basin commissions provide low-flow augmentation and water conservation requirements during periods of low flow. Water from rainfall and snowmelt are stored in large surface reservoirs and released continuously during droughts to maintain a flow that helps repel the saltwater from migrating upstream. These planning agencies recognize the need to sustain stream flows to protect freshwater intakes, instream uses (including fish migration and fish production), and shellfish beds, as well as treated-waste assimilation, recreation, and salinity repulsion. An economic justification is usually necessary, showing that the cost of the mitigation is less than the anticipated benefits.

The prevention of saltwater intrusion can be provided by other options including:

Barriers. Dams can be constructed that physically prevent the saltwater from moving past a certain point in the estuary. Injection barriershave also been employed successfully.

Restrictions on pathways for saltwater intrusion. Construction of canalsallow saltwater to migrate into inland areas and allow a pathway forsaltwater intrusion to occur.

Alternate sources of water. Water users may be able to obtain water fromother sources that are not endangered by saltwater intrusion.

Restrictions on use of water. During periods of higher sea level or drought, stricter conservation and restrictions on export of water fromthe river basin may be considered for short durations.

The Delaware River Basin Commission (DRBC) is one of the planning agencies responsible for managing the surface waters and groundwaters within the drainage basin of the Delaware River. The DRBC has included sea level rise projections through 2000 in its planning (DRBC, 1981) and is currently working on a cooperative program with Dr. Gerard Lennon of Lehigh University and the Environmental Protection Agency in esti*mating* the salinity intrusion into the Delaware Estuary for the sea level rise scenarios discussed in Chapter 3.

Control of Saltwater Intrusion

Control methods for saltwater intrusion have been employed or seriously considered only in areas where withdrawals of water have caused water levels in aquifers to fall significantly below mean sea level. Because of the very slow velocity with which the saltwater moves, many localities with serious overdrafts have not yet lost their aquifers as sources of water. However, they must solve this problem eventually because once saltwater has invaded an aquifer, it could take hundreds of years to regain the salinity levels of the virgin aquifer.

Where the existing water levels in principal aquifers are already several tens of meters below sea level, a rise in sea level of less than 1 m would be of less consequence than a slight increase in the withdrawal rate. However, in areas where the existing water levels are within a few meters of mean sea level, the impact could be significant. If sea level rises more than 1 m, all coastal aquifers will be affected to some degree.

The greatest danger to freshwater aquifer supplies could be the migration of saltwater up an estuary that recharges an aquifer. If the water levels in the aquifer are below mean sea level because of withdrawals, the saltwater would recharge the aquifer.

Several control strategies can be used to prevent or retard saltwater intrusion into aquifers. They include:

Physical subsurface barriers. Options include driving sheet pile, installing a clay trench, or injecting impermeable materials through wells.

Extraction barriers. The saltwater that moves inland is collected and removed. The pumping encourages further intrusion and may inadvertently withdraw freshwater.

Freshwater injection barriers. Freshwater from another source isi njected into the aquifer, raising water levels in the area and reversing the saltwater intrusion.

Increased recharge. Spreading of water on the land in upland recharge areas allows more percolation (infiltration of water into the aquifer), which retards saltwater intrusion.

Modified pumping patterns. Reducing withdrawals or moving the pumping locations further inland can substantially reduce the intrusion.

Direct surface delivery to replace groundwater use. Groundwater can be replaced by surface water through the use of direct surface delivery.

Combinations of these techniques can also be employed. A combination of an extraction and an injection barrier or increased recharge with injection barrier are particularly effective combinations.

Physical Barriers. Subsurface physical barriers such as sheet pile, cutoff walls, clay slurry trenches under earth dams, and impermeable clay walls are routinely used by engineers in the field to control the movement of water and other liquids including the containment of hazardous waste materials. It is also possible to inject materials that form a zone of low permeability. Figure 6-10 illustrates a cross-section of a typical physical barrier.

Kashef (1977) indicates that, although the construction methods are technically well established, the cost is usually too high because the required depths are substantial. Even in the uppermost layers where the cost may not be prohibitive, Kashef points out that the backwater effect could cause coastal lowlands to become waterlogged. Unit cost estimates for slurry walls range between $20 to $40 per square meter of surface area. Thus, for a wall as wide as the standard trenching equipment and 10 m, deep, the cost is $200-$400 per linear meter of wall. The cost is highly dependent on depth of cutoff, length of wall, and specific material availability costs. Barriers require complete depth of cutoff to be effective.

Impermeable walls can be almost 100 percent effective at preventing saltwater intrusion. However, in actual practice, some limited penetration will occur.

Extraction Barriers. Extraction barriers have been used in various locations in order to prevent or reduce saltwater intrusion. In 1965 a 0.5 mi (0.8 km) long extraction barrier was employed in the Oxnard aquifer, Oxnard Plain, Ventura County by the California Department of Water Resources (CDWR), as summarized by Stone (1978). The five-well experimental extraction barrier was discontinued in 1968 because of corrosion and proved to be inadequate at preventing the intrusion. Figure 6-11 illustrates a typical extraction type barrier where the saltwater intrusion is halted by the withdrawal of saltwater relatively close to the shoreline.

Extraction barriers may withdraw some freshwater that would otherwise be useful and thus may not be a valuable option where water supplies are scarce. In addition, problems with saltwater corrosion must be overcome.

Again, experiences by Kashef (1977), Stone (1978), and others have generally indicated that the saltwater intrusion caused by pumping overdrafts can be technically controlled by extraction barriers but are usually more expensive than injection barriers. Although extraction barriers have not proven to be economically justifiable for saltwater intrusion in most localities that have considered them, certain special considerations may result in the economical use of extraction barriers. Such sites might include the prevention of saltwater intrusion into a limited area such as a hazardous waste site or a coastal aquifer with a relatively narrow connection to the ocean.

However, a major problem with the extraction barriers are that withdrawal of saltwater and the inadvertent withdrawal of some freshwater cause the water levels to fall substantially throughout the basin. The increased lift and the cost of wells going dry often become costly in time. Furthermore, although a complete cutoff extraction barrier does not have to be completed all along the coast, saltwater intrusion can around the barrier. The lower levels also encourage saline water from above or below to move vertically into the aquifer. For a 1-3 m sea level rise scenario over the next 120 years, extraction barriers can be up to 100 percent effective along the length of coast being protected. However, vertical leakage may occur from above or below.

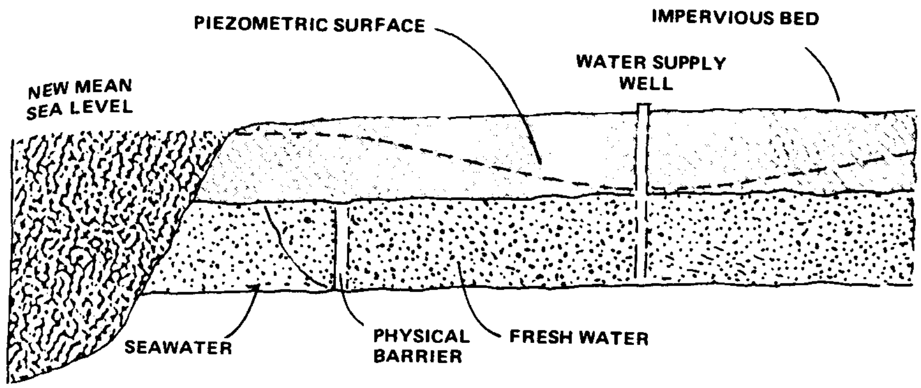

Figure 6-10. Physical seawater intrusion barrier. *(After Wayne L. Stone, 1978, "An Assessment of Alternate Sea Water Intrusion Control Strategies for the Oxnard Plain of Ventura County, California," report submitted in partial satisfaction of the requirements for the degree of Doctor of Environmental Science and Engineering, Berkeley: University of California.)*

Figure 6-10. Physical seawater intrusion barrier. *(After Wayne L. Stone, 1978, "An Assessment of Alternate Sea Water Intrusion Control Strategies for the Oxnard plain of Ventura County, California," report submitted in partial satisfaction of the requirements for the degree of Doctor of Environmental Science and Engineering, Berkeley: University of California.)*

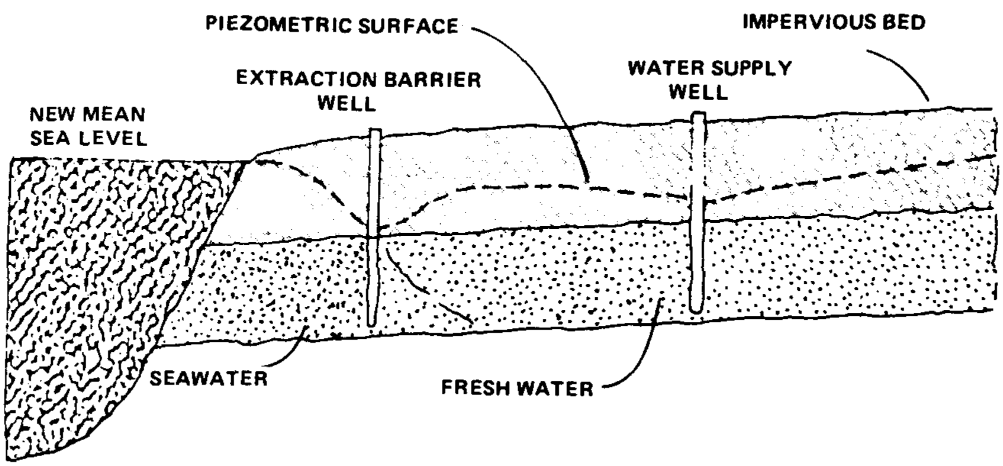

Figure 6-11. Extraction-type seawater intrusion barrier. *(After Wayne L. Stone, 1978, "An Assessment of Alternate Sea Water Intrusion Control Strategies for the Oxnard Plain of Ventura County, California," report submitted in partial satisfaction of the requirements for the degree of Doctor of Environmental Science and Engineering, Berkeley: University of California.)*

Figure 6-11. Extraction-type seawater intrusion barrier. *(After Wayne L. Stone,* 1978, 'An Assessment *of Alternate Sea Water Intrusion Control Strategies for the Oxnard Plain of Ventura County, California, " report submitted in partial satisfaction of the requirements for the degree of Doctor of Environmental Science and Engineering, Berkeley: University of California.)*

Freshwater Injection Barriers. Figure 6-12 illustrates a typical injection barrier in operation to control the saltwater intrusion for cases where the sea level is in excess of freshwater levels. In contrast to the extraction barrier, with an injection barrier, freshwater is injected int, the aquifer through a line of wells along the coastline. The higher groundwater levels along the injection barrier prevent saltwater intrusion from occurring. A proper design of well spacing and location must be performed to ensure that saltwater does not intrude around the injection barrier, in between individual wells, or move vertically from above or below.

The problems with injection wells include the fact that a relatively large number of wells is required,

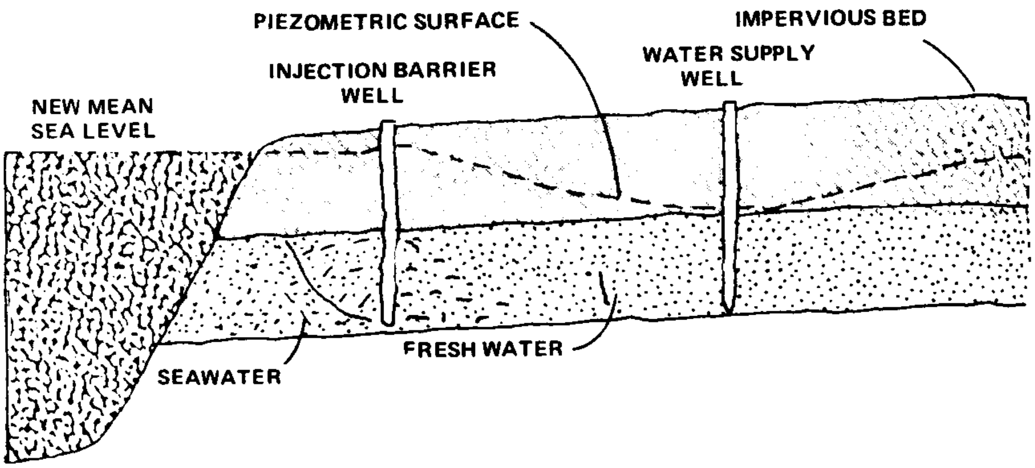

Figure 6-12. Injection-type seawater intrusion barrier. *(After Wayne L. Stone, 1978, "An Assessment of Alternate Sea Water Intrusion Control Strategies for the Oxnard Plain of Ventura County, California," report submitted in partial satisfaction of the requirements for the degree of Doctor of Environmental Science and Engineering, Berkeley: University of California.)*

a high maintenance cost will be necessary to prevent plugging of wells, and most important, a source of freshwater will be needed.

Figure 6-12. Injection-type seawater intrusion barrier (After *Wayne L. Stone,* 1978, 'An Assessment of *Alternate Sea Water Intrusion Control Strategies for* the *Oxnard Plain of Ventura County, California," report submitted in partial satisfaction of the requirements for the degree* of Doctor *of Environmental Science and Engineering, Berkeley: University of California.)*

The Los Angeles County Flood District injection barrier construction costs were approximately $20 million from 1953 to 1973, not including the cost of purchasing the water to be injected and not adjusting for inflation (DRBC, 1981). The annual maintenance and operation cost of the 32 km (20 mi) barrier was approximately $1.5 million in the period 1978-1980, and the annual cost of filtered injection water was $5,684,375 ($0.086/m^3 or $106.25/acre-foot-see Bookman-Edmonston Engineers, 1982). An acre-foot is a unit of water equal to 1,234 m^3 (326,000 gal).

The 1978-1980 operation averaged $44,000 per km ($70,000/mi); figuring 6 wells/km (10 wells/mi), this is $7,000 per well for an estimated 3.8 x 10^5 m^3 (100 million gal) per day of injection.

The operation cost depends upon the length of the barrier, the geometry and physical properties of the aquifer, differences in water levels in the aquifer relative to mean sea level, and the volumes of water injected, being recharged to the aquifer, and being withdrawn.

Stone (1978) summarized the capital costs ($18.3 million) and annual operation costs in 1980 ($430,000) for the Oxnard Plain Study. For the 13 km (8 mi) barrier, the 1980 capital cost is $1.4 million/km ($2.3 million/mi) and the annual maintenance cost is $34,000/km ($54,000/mi).

Also, because 1.5 x 10^7 m^3 (12, 100 acre-feet) of water are to be injected annually, expressing unit costs in terms of volume of injection water rather than miles protected may be useful where the injection is to prevent intrusion due to a rise in sea level of 1 or 2 m. The unit capital cost per acre-foot of water injected annually is $1,512, with an operational cost of $0.028/M3 ($35/acre-foot) injected.

Because the injection of water raises the water levels in the vicinity of the barrier, a complete cutoff all along the coast is not required. If the cutoff barrier is maintained at 1 or 2 in above mean sea level (continuously increasing the barrier water level as sea level increases), the injection barrier will provide 100 percent effectiveness in preventing saltwater intrusion along its length. In addition, the freshwater mound will tend to flow inland toward the lower water levels there. Also, freshwater from the injection barrier will flow along the coast for a limited distance, extending the effective length of barrier slightly. The effectiveness of the injection barrier will be maintained if the water levels in the vicinity of the barrier are increased as sea level increases to always maintain them at 1 m (3 ft) above mean sea level.

Increased Recharge. In many coastal locations in the United States, sufficient amounts of freshwater are available for recharge during periods of high precipitation. Although some water is captured during these periods and stored in surface reservoirs, very little water is recharged groundwater reservoirs for use in drought periods. This extra water which is "wasted" to the ocean could be used to replenish the aquifer, build up groundwater levels, and repel the saltwater intrusion. If the natural plus additional recharge exceeds the groundwater withdrawals he stable saltwater line would be established.

In many instances, such as Oxnard Plain in California (Stone, 1978), the recharge region of the principal water supply aquifer is far away from, the coast. In these regions, it is possible to recharge the confined aquifer far from the shoreline and prevent saltwater intrusion. For unconfined aquifers, the recharge occurs in an area near the coastline and near the center of withdrawal.

The problems with increased recharge can be a lack of sufficient replenishment water, lack of inexpensive land for the recharge basins shallow injection wells, and costly technical problems of maintaining an adequate inflow rate. However, as mentioned previously, many areas have excess water during wet periods, which can be utilized during dry periods.

In the Oxnard Plain, the capital cost of the replenishment water is $14 million and annual operation costs (1980 dollars) are $64,000, as summarized by Stone (1978). In addition, the cost of purchasing 31 million m^3 (25,000 acre-feet) of water annually at $0.93/$m^3$ ($115/acre-foot) is $2,875,000/year. Considering that the recharge is used in place of a 13 km (8 mi) injection barrier, the unit capital cost is $1.0 million/km ($1.8 million/mi) and $5,000/km ($8,000/mi) of annual operational costs, exclusive of the cost to purchase water. However, the amount of required injection water is very dependent upon the withdrawal of groundwater by users, natural recharge, and basin geometry. A more appropriate unit cost figure is the cost of recharge per unit volume of water. In this case, the capital cost is $0.45/$m^3$ ($560/acre-ft) injected annually plus $0.002/$m^3$ ($2.56/acre-foot) of water recharged.

The saltwater will intrude farther inland than is now occurring unless the amount of additional recharge can push the saltwater equilibrium surface seaward. Hence, significant saltwater intrusion can still occur even with increased recharge for a 3 m sea level scenario. A 1 m sea level rise will probably intrude only slightly with the increased recharge option.

Modified Pumping Patterns. For unconfined aquifers where no pumping exists, an intrusion of saltwater as a result of sea level rise could damage agricultural crops. Either the injection barrier or increased recharge would be viable solutions if substantial crop damage was expected without control of the saltwater advance.

For unconfined or confined aquifers where moderate pumpage already occurs and the effect of a sea level rise is projected to be important, a phased shutdown of wells can be designed as the monitored saltwater intrusion progresses. Instead of a disorganized search for alternate water *as* the chloride concentrations increase, logical permitting of new wells or new economical surface distribution schemes can be implemented.

The cost of new surface distribution schemes may be expensive, as is the abandonment of old wells that are still operational. Cost figures are dependent upon the existing facilities, resulting in site costs that are of little use at other locations. Cost figures prepared by Stone (1978) are very specific to the particular setting in the Oxnard Plain and are presented because costs were available for some of the previous options, thus making them comparable. Pumping plan C, the least costly of the three modified pumping schemes presented by Stone, has a capital cost of $10 million with an annual 1980 operational cost of $180,000. It is difficult to express a unit cost for the case of modified pumping plans.

A modification of pumping patterns will allow water levels to recover in critical areas. This will have an effect of slowing down the saltwater advance. However, the saltwater will intrude until it reaches a new equilibrium. Depending upon the recharge rate, the pumping rates, the net overdraft, water levels, aquifer geometry, aquifer characteristics, and the present status of saltwater intrusion, the effectiveness of the modification of pumping patterns will vary. For a saltwater interface currently in equilibrium, an increase in sea level rise may be counteracted by a modification of pumping patterns. However, it is possible that the intrusion will be retarded, not stopped. A 3 m sea level rise over the next 120 years will allow the intrusion to occur at a faster rate and the equilibrium position will be further inland in general than would occur in a lesser sea level rise scenario.

Direct Surface Delivery. Another method that can be used to prevent saltwater intrusion is direct surface water delivery in lieu of groundwater withdrawal. If a long-term but inevitable sea level rise faces the United States, the gradual phasing out of certain pumpage could be conducted in a very rational manner with the resulting demand for water satisfied by direct surface delivery. The state of New Jersey has approved a bond issue to provide hundreds of millions of dollars to study and improve the distribution of water in the state. If the state managers recognize and properly address the possibility of extreme sea level rises, the protection of water resources and control of saltwater intrusion may be possible at a very reasonable cost, provided they respond to the need in the near future. Unnecessary expense will be incurred if a new freshwater intake is constructed to withdraw freshwater from a river that will be excessively saline during the life of the intake because of saltwater encroachment as a result of a moderate sea level rise in the next 120 years.

The work by Stone (1978) indicates that an initial capital cost of $11.4 million and an annual 1980 operational cost of $70,800 will be required to prevent the saltwater intrusion in the Oxnard Plain. The capital cost per annual cubic meter delivered is $0.76 ($942/acre-foot). Other costs include a 1980 annual unit operational cost of $0.05 1/M3 ($64/acre-foot) and a cost of $0.093/m^3 ($115/acre-foot).

Direct surface delivery allows less groundwater to be withdrawn, which in turn allows water levels in the aquifer to recover. The higher water levels in the aquifer will retard any existing saltwater advances, and in some instances may push the saltwater back. For an aquifer in an equilibrium situation in the face of a 1-3 m sea level rise over the next 120 years, a certain amount of the groundwater withdrawal should be replaced by direct surface delivery in order to maintain equilibrium. For a 3 m sea level rise, more drastic cutbacks would be required to keep the saltwater from intruding. Under any circumstance, 100 percent effectiveness ill preventing saltwater intrusion should not be expected.

SUMMARY

This chapter has presented an overview of coastal engineering methods for controlling the effects of sea level rise. That is, hard and soft structural methods were the focus, rather than political methods. The specific effects considered were shore erosion and inundation, increased storm surge flooding, and salinity intrusion (particularly into groundwater supplies). For each of these effects, the process involved was discussed in general terms and the basic approaches to controlling the effect were discussed. Then, the specific methods that define each approach were described, including a general explanation, situations where the method can be used, typical cost data, and effectiveness of the method in controlling the effects of sea level rise.

With an accelerated sea level rise, the importance of having the best possible forecasts of the expected rate of rise cannot be understated. With this information, planning can be more effectively accomplished by setting aside space for future control works. Control works can be built to the ultimate required size and at the optimum location for sea levels that would occur during their design life (or they can be designed for easy expansion as sea levels rise), and new development that would be flooded or destroyed by erosion can be limited or prevented.

If the rise in sea level during the next century is on the order of magnitude suggested by the high rise scenarios, it is likely that eventually some form of national or state programs will be developed to respond to the crisis. Presumably, any such programs would efficiently and effectively combine political and structural responses. Precise forecasts of future sea levels based on sound scientific analysis would hasten the development of these programs. However, if a much lower but still significant sea level rise occurs, the response will more likely be on a site-by-site, ad hoc basis. This will be particularly true if precise forecasts are not developed. As structures reach the end of their effective life or are in general need of repair, they will be rebuilt or improved to respond to existing (or slightly higher) sea levels. Some marginal coastal developments and some groundwater sources will be abandoned. Developing lowland areas will only have protective works adequate for a short time period. In general, it will be more difficult to develop and operate a coordinated response to rising sea levels.

For a given sea level rise scenario, the type, extent, and cost of structural responses to the rise are extremely site dependent. Particularly important factors are the local tide range and exposure to wave action, the space available, foundation conditions, the nature of existing structures, the length of shoreline to be protected by any particular method, and local construction experience and material availability. In addition to the construction of erosion, inundation, and salinity intrusion control works, existing coastal features such as jetties, piers, marinas, port facilities, bridges, and causeways would have to be modified.

The hard and soft structural responses can vary in effectiveness from location to location. However, if sufficient design information on environmental, foundation, and related conditions is available and if sufficient funding is available for construction, in all but rare situations, an effective structural response can be built. Required concepts and construction techniques to respond structurally to sea level rise are within the state-of-the-art.

In order to develop a meaningful estimate of the cost and physical extent of effort required for the structural response to a given sea level rise scenario, the following investigation is recommended. A well-developed specific estuary/coastal location should be selected where erosion, inundation, storm surge flooding, and salinity intrusion (estuarial and groundwater) are existing or potential problems. An example would be the Raritan Bay in New Jersey and the adjacent shorelines from Sandy Hook to Asbury Park. This region includes coastal urban development, port facilities, small marinas, natural unstabilized shorelines, shorelines strongly fortified by existing structures, heavy marine commerce, and so on. For a particular sea level rise scenario, design tide and storm levels would be determined, design wave climates (with appropriate return periods for the types and locations of structures to be considered) would be forecasted, estuary/groundwater salinity changes would be estimated and potential shoreline erosion/deposition changes would be evaluated. Expected patterns of growth during the duration of the sea level rise scenario would also be projected. Then, the estuary and coastal works required to control the effects of sea level rise would be located, designed, and evaluated for cost, including required modifications to existing, structures. Designs would be preliminary in nature, but they WO d account for local wave, water level, foundation, and layout conditions, the time during the sea level rise when the work was required, and the conditions of existing structures. It is only in this way that the precision, required for accurate estimates of the potential costs of a structure response to sea level rise can be developed.

NOTES

1. The material presented herein was compiled largely from local (Philadelphia and New York) U.S. Army Corps of Engineers district libraries, the U.S. Geological Survey and the Delaware River Basin Commission offices

in Trenton, New Jersey and the Water Resources Archives Library of the University of California at Berkeley. Time, funding, and space constraints prohibit a more thorough survey of the available literature, particularly in regard to examples of the cost and effectiveness of specific control methods.

2. The U.S. Army Coastal Engineering Research Center (1977) provides a general discussion of the structural and functional aspects of these methods.

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23. Land use changes and rates of growth were identified from planning documents from the city of Charleston, city of North Charleston, and Mount Pleasant.
24. Stephen Leatherman, Michael S. Kearney, and Beach Clow, 1983. *Assessment of Coastal Response to Projected Sea-Level Rise: Galueston Island and* Bay *Texas.* URF Report TR 8301; report to ICF under contract to EPA, College Park: University of Maryland.
25. Ibid.
26. The distribution of topographical elevations above mean sea level within each subarea was developed at the University of Maryland by Stephen Leatherman and Beach Clow.
27. Carlton Ruch of the Research Center, College of Architecture, Texas A&M University, provided economic and population data developed in his ongoing research of the effects of hurricanes. The data provided by Dr. Ruch not only, contributed significantly to the Galveston case study but also provided a model after which the development of the data for the Charleston case study was patterned.
28. Expected changes in land use were indicated in the data provided by Dr. Ruch (see note 27). These data were augmented with information in local planning documents from Texas City, Texas.
29. Storm damages were simulated by interpolating between three storm types (a 10 year storm, 50-year storm, and 100-year storm) to calculate a frequency-damage function that is integrated to estimate the expected value of damages in a given year. Protective structures (such as seawalls and levees) produce a discontinuous frequency-damage function. Although the continuous nature of sea level rise produces a continuous shifting of the discontinuity, the use of only three storm types to develop the frequency-damage function results in a large discontinuous jump in damages as soon as one of the three storm types overtops the protective structure. A more sophisticated model of the impact of protective structures on storm surges whose elevations exceed the height of the protective structures would eliminate this problem of discontinuity.
30. The mechanisms via which protected areas become vulnerable to storm surge in the high scenario are described in Leatherman et al. (see note 24).