Chapter 4

The Physical Impact of Sea Level Rise in the Area of Charleston, South Carolina

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INTRODUCTION

This chapter reports on a pilot study to determine the shoreline impact from accelerated rises in sea level due to anthropogenic (man induced) factors. The methods developed have been applied to the coastal city of Charleston, South Carolina, to determine the effects of various accelerated sea level rise scenarios for the years 2025 and 2075.

In the last few decades, there have been numerous studies on the trends and rates of both eustatic and local sea level changes. Eustatic changes are global in nature due to a general rise of the sea level compared to local changes for a specific area due to the relative rise or subsidence of the land surface with respect to a stationary, general sea level. There has been an overall rise in sea level of about 40 m (130 ft) since the last glacial epoch, called the Wisconsin ice age, which ended about 14,000 years ago. From 7,000 to 3,000 years ago, sea level along the east coast of the United States rose at a rate of about 0.3 cm (0.1 in) per year (Kraft, 1971). Studies of sea level over the last two centuries have estimated that global sea level is rising at a rate of 0.10-0.12 cm/yr (0.04-0.05 in/yr). For the Charleston case study area, Hicks and others (1978, 1983) have estimated that the total sea level rise since 1922 has been 0.25 cm/yr (0.1 in/yr).*

Table 4-1. Sea Level Rise Scenarios for the Charleston Case Study Area (in cm, ft in parentheses)

	Year		
Scenario[a]	*1980*	*2025*	*2075*
Baseline	0	11.2 (0.4)	23.8 (0.8)
Low	-	28.2 (0.9)	87.0 (2.9)
Medium	-	46.0 (1.5)	159.2 (5.2)
High	-	63.8 (2.1)	231.6 (7.6)

Source: Global sea level rise scenarios are from Chapter 3, modified to reflect local conditions based on the historical trend for Charleston. (S.D. Hicks et al., 1983, *Sea Level Variations for the United States, 1855–1980,* technical report, Rockville, Md.: NOAA, Tides and Water Levels Branch.)

[a]Baseline scenarios for each year reflect present trends. Other scenarios reflect accelerated sea level rises at various rates.

*Based on a global (eustatic) rise of 0. 12 cm/yr (0.05 in/yr) plus local subsidence of 0. 13 cm/yr (0.05 in/yr).

For our analysis, the local rate was assumed to be 0.25 cm/yr (0. 10 in/yr), and the eustatic rates used were a baseline of 0.12 cm/yr (0.05 in/yr) and the low, medium, and high scenarios discussed in Chapters 1 and 3. These scenarios are outlined in Table 4-1 for the years 2025 and 2075.

This chapter describes the physical responses of coastal land forms in Charleston to accelerated sea level rise. Three types of response are addressed: shoreline changes due to landward displacement of the water line after a sea level rise (in some geomorphic settings, where sediment supply is great, the shoreline may accrete or keep pace with a sea level rise.); storm surges that affect new or higher elevations after a sea level rise; and groundwater changes caused by the intrusion of seawater to higher levels in aquifers.

The chapter is organized as follows. First, the Charleston case study area is described. Then, in turn, we discuss the methodology used in the study: modeling shoreline changes, mapping methods, historical shoreline trends, and storm surge and groundwater analyses. Finally, the results and an analysis of the methodology used are presented.

CHARLESTON CASE STUDY AREA

History of Human Development

The first European settlers arrived in Charleston around 1670. Since that time, the peninsula city has undergone dramatic shoreline changes, predominantly by landfilling of the intertidal zone. Early maps show that over one-third of the peninsula has been "reclaimed." Much of the landfilling occurred on the southern tip of Charleston, behind a high seawall and promenade, known as the Battery. Many of the buildings on the lower peninsula are of historic value and play an important role in the area's major industry-tourism. These areas already experience frequent flooding during intense rainstorms and unusually high tides and would high priority for any protection/mitigation actions to prevent further flooding due to sea level rise.

The port of Charleston, which dominates the eastern shore of the city, has an active merchant ship port, along with a large U.S. Navy base along the Cooper River (Figure 4-1, the area described is in the vicinity of station number 29). Maintenance of the ship channels to the port has generated large volumes of dredge spoil, which have been disposed of at every possible nearby site. There are only two sites currently

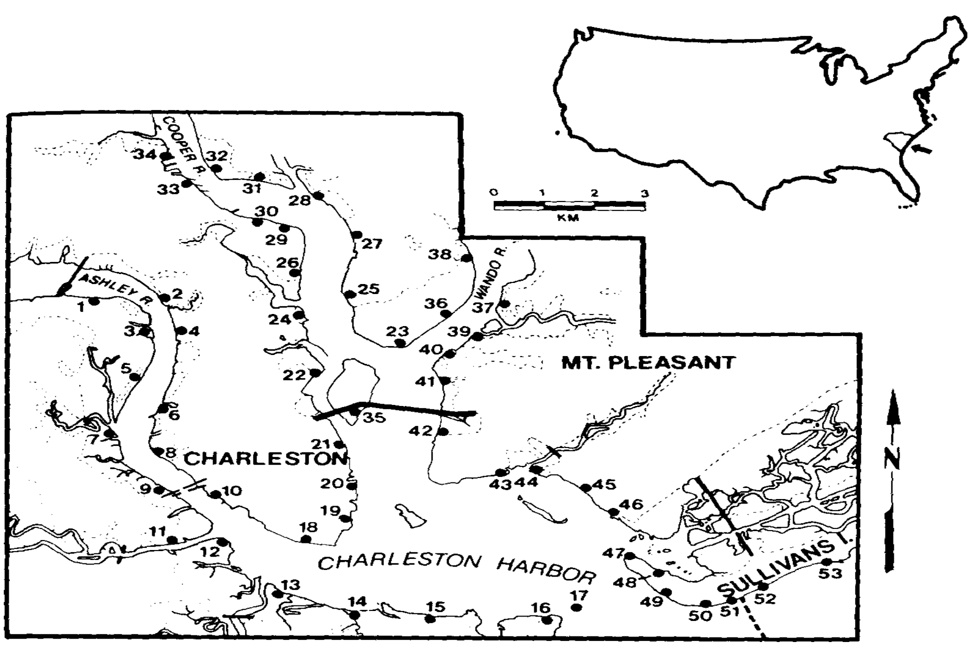

Figure 4-1. Location map of the Charleston case study area and 53 shoreline stations used in the historical trend analysis.

authorized for spoil disposal, and the addition of other sites is unlikely. Plans call for construction of dikes as high as necessary to retain spoil in the designated sites.

The mainland to the east and west of Charleston is primarily residential; much of it is of low density. The trend has been toward slow encroachment on farmland with more intensive development near the harbor, along the Intracoastal Waterway, or on the larger creeks. Sullivans Island and Isle of Palms, developed before World War II, have a large year-round population. These barrier islands northeast of Charleston Harbor are also the principal recreational beaches for the metropolitan area.

Site Description

The Charleston area has a complex coastal plain morphology which has been significantly altered by man in the last 100 years (Figure 4-1). The outer shore to the north is composed of geologically young, developed barrier islands (e.g., Sullivans Island) which are relatively flat; elevations typically average less than 3 m (10 ft) above mean sea level (MSL) on the islands in the study area. Sheltered by the barrier islands is an extensive, intertidal salt marsh/tidal creek system. At the edge of the marsh/ mainland contact (Figure 4-1, dashed line beginning at station number 46 in Mount Pleasant), there is a break in slope and a distinct change to terrestrial vegetation. Elevations on the lower Charleston peninsula are generally 3 m (10 ft), with small areas up to 5.5 m (18 ft). The study area west of the Ashley River is very flat, with elevations generally about 3 m (10 ft). The Charleston shoreline has a characteristic dendritic drainage pattern typical of drowned coastal plain areas.

The highly populated Charleston peninsula is formed by the junction of three rivers which discharge into Charleston Harbor: the Cooper, Ashley, and Wando Rivers (shown in Figure 4-1). The Cooper River dominates the discharge into the harbor, with an average flow of 450 m?/s [15,600 ft?/s (cfs)], which includes flow from the Santee River (a large river originating in the mountains) diverted for hydroelectric power in 1942. The diversion has reportedly caused a significant increase in sedimentation in Charleston Harbor, requiring increased dredging from 400,000 m^3 (525,000 yd^3) per year to over 7,500,000 m^3 (10,000,000 yd^3) per year (S.C. Water Resources Commission, 1979). Studies have shown that diversion is responsible for 85 percent of the sedimentation in Charleston Harbor (U.S. Army Corps of Engineers, 1966). To alleviate this problem, the flow will be rediverted back to the Santee River by 1985, reducing discharge to one-fifth its present volume. The natural harbor shoreline is dominated by fringing salt marsh from several meters to over a kilometer wide. As will be shown from the historical shoreline trend data, most of the marshes have accreted since diversion of the Santee into Charleston Harbor.

The entrance to Charleston Harbor has also been modified by the construction of jetties in the 1890s to stabilize the navigation channel. The jetties have caused large-scale changes in sediment transport patterns, producing up to 300 m (1,000 ft) of deposition along the barrier islands (Sullivans and Isle of Palms) to the north. Concomitant with accretion north of the harbor, extensive erosion has occurred south of the jetties, including over 500 m (1,700 ft) of erosion along Morris Island (Stephen et. al., 1975). Another man-made change in the system is the Intracoastal Waterway, dredged to 4 m (12 ft), which has altered flow patterns in the marsh behind the barrier islands.

Physical Processes

South Carolina's climate is mild, with an average temperature for the coastal region ranging between 10.1EC (50.2E) in December and 27.2EC (81.0EF) in July. An average of 1.4 hurricanes and tropical storms affect the coast annually- Winds are somewhat seasonal, with northerly components dominating in fall and winter and southerly components dominating in spring and summer (Landers, 1970). The tidal range increases considerably from north to south along the state's shoreline, from approximately 1.7 m (5.5 ft) at the northern border to 2.7 m (8.8 ft) at the southern border. The increasing tidal prism (volume of water flowing in and out of a harbor or estuary with the movement of the tides) has several effects as one moves southward along the South Carolina coast: tidal inlets become more frequent and are larger in order to accommodate greater tidal flow, salt marshes are more extensive, and the ebb-tidal deltas (seaward shoals at inlets) become much larger (Nummedal et al., 1977). Charleston's mean tidal range is 1.6 m (5.2 ft); spring tides average 1.9 m (6.1 ft); and the highest astronomic tides of the year exceed 2.1 m (7.0 ft) (U.S. Department of Commerce, 1981). The spring tidal elevation represents the limit of human development because the land surface is inundated every 14 days to that elevation, and it is the upper limit of high marsh vegetation on which development or any alteration is strictly regulated by South Carolina Coastal Zone Management laws (U.S. Department of Commerce, 1979).

The wave climate at Charleston is dependent on offshore swell conditions but is diurnally modified by the seabreeze/landbreeze cycle typically occurring in the area. The prevailing winds are from the south and west in these latitudes, but the dominant wind affecting the coastline is from the northeast, originating in extratropical storms travelling parallel to the coast (Finley, 1976). Breaking wave heights along the outer beaches average approximately 60 cm (2 ft) high in the Charleston area. Predominant wave-energy flux is directed south along the beaches, accounting for net longshore transport rates of approximately 100,000 m^3yr (135,000 yd ^{3}/yr) (Kana, 1977).

The relatively large tidal range produces current velocities at all tidal entrances and creeks that often exceed 1.5 m/s (5.0 ft/s) (Finley, 1976). With three major tidal rivers within the study site, a diverse set of estuarine processes influences circulation, flushing, and sedimentation patterns in Charleston Harbor.

The subtropical climate of the southeast produces high weathering rates, which provide large fluxes of sediment to the coastal area. Suspended sediment loads, which dramatically increased in Charleston Harbor because of diversion of the Santee River, provide significant inputs to the study area and may account for growth of some marsh shorelines. Marshes accrete through the settling of fine-grained sediment on the marsh surface as cordgrass *(Spartina alterniflora)* baffles the flow adjacent to tidal creeks. Marsh sedimentation has generally been able to keep up with or exceed recent sea level rises along many areas of the eastern U.S. shoreline (Ward and Domeracki, 1979).

Hydrogeology

The water table aquifer is composed of surficial sands and clays of Pleistocene age and, in the study area, extends to 10-20 m (30-65 ft) below sea level. It is heavily used by the Mount Pleasant and Sullivans Island water districts; both have over 20 wells or well-point systems, each tapping the shallow aquifer. Although the exact position of the freshwater/saltwater interface is unknown, there have been reports of shallow wells close to shore being moved because of unsuitable water quality. The next geologic unit is the Cooper Marl, a calcareous clay, which acts as a confining layer on top of the Santee Limestone-Black Mingo aquifers. These aquifers have not been used for drinking water in the area since about 1950 because of saltwater intrusion. The present freshwater/saltwater interface in this aquifer system is thought to be near Summerville, about 40 km (25 mi) inland (Drennen Parks, 1983, South Carolina Water Resources Commission, personal communication).

The Black Creek aquifer of Late Createaceous age is an important water source. Although there is no saltwater currently in the Black Creek aquifer in the study area, the U.S. Geological Survey (USGS) has measured chloride contents of 390-534 mg/l in the lower half of the aquifer on Kiawah and Seabrook Islands, about 30 km (20 mi) to the southwest. The position of the freshwater/saltwater interface in the Black Creek offshore of Charleston is unknown. The deepest aquifer used in Charleston is the Middendorf Formation; deep wells down to 700 m (2,200 ft) have not encountered saltwater in the study area. However, on Kiawah and Seabrook Islands, freshwater (62-160 mg/l chloride) was found to 700 m (2,200 ft), and saline water (1,440 mg/l chloride) was encountered at 790 m (2,400 ft).

The main users of groundwater are the municipalities of Mount Pleasant, Sullivans Island, and Isle of Palms, which use several million gallons per day. Groundwater demand is expected to grow rapidly, as these areas are projected to experience rapid population growth. The city of Charleston uses surface water and services the peninsula and west Ashley areas. The present position of the freshwater/saltwater interface for the shallow and deep aquifers is unknown, except 30 km (20 mi) to the southwest, and the middle aquifer is already too salty to use. As water usage increases, saltwater intrusion due to overpumpage alone is predicted to be a serious problem in the future, eventually resulting in abandonment of the shallow aquifer for potable water.

MODELING EFFECTS OF SEA LEVEL RISE

Shoreline Changes

With respect to retreating or eroding shorelines, there are several different shoreline response concepts that can be used to model the resulting shoreline reconfiguration as a function of sea level rise. The simplest to quantify is the inundation concept (Figure 4-2), whereby preexisting contours above shorelines are used to project new shorelines. Here, slope is the controlling factor. Shorelines with steep slopes will experience little horizontal displacement of the shoreline.

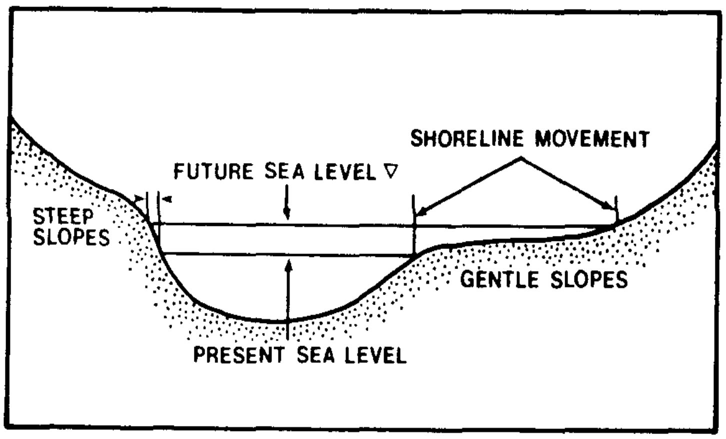

Figure 4-2. Schematic cross-section of inundation concept of sea level rise. The shoreline movement greatly depends on the land slope.

Gently sloping shores, on the other hand, will experience a much broader area of inundation for a given sea level rise. The inundation concept, in fact, is the preferred methodology to apply for immobile substrates or rocky or armored shorelines, or where the shoreline is not exposed to wave action or strong currents.

The analysis becomes more complicated when dealing with mobile sediments, such as sand-sized material along beaches. As Chapters 1 and 5 describe, Bruun (1962) introduced a model to predict the equilibrium adjustment of shoreline profiles during a sea level rise. Bruun hypothesized that a typical concave-upward profile in the nearshore zone will maintain its configuration, but the profile will be translated landward and upward as sediments erode near the old water level and settle in deeper water, building up the bottom. This offshore displacement of sediments theoretically maintains the same depth at a given distance from the new shoreline compared to that distance and depth combination from the old shoreline. Hands (1981) presented a relationship based on Bruun's model, which is a practical way to predict this profile adjustment:

$$y = \frac{rX}{Z} (R_A)$$

where (= shoreline change; *r* change in water level; *X* = average, representative width of adjustment in the profile; Z = height of responding profile or vertical relief of active beach; and R_A = overfill ratio to account for loss of suspended load from the eroded material.

Nearshore surveys along Charleston's beaches (RPI, unpublished) indicate the depth of active movement in the profile (i.e., wave base) is typically at depths of 10-15 m (33-50 ft). This yields values of Z between 15 and 20 m (50-66 ft) when the mean dune elevation is added. Based on existing slopes, these values for Z yield a typical range of X between 1,000 and 3,000 m (3,300-10,000 ft) for Charleston's outer beaches. Factor R_A is 1.0 if no fine-grained suspended sediment losses are expected. We assumed this to be the case for the outer beaches since existing dune sediments essentially match the beach and nearshore sediments in the project area (Brown, 1976). Hands' model, illustrated in figure 4-3, was tested against sandy shorelines of the Great Lakes, which responded to changes in water level. Although the formula has been shown to apply under field conditions and uses generally available information, it only applies to erodable substrates, such as sand beaches or unconsolidated bluffs.

The model for shoreline changes along beaches that we believe is presently the most realistic and feasible for widespread application combines projections of new equilibrium shorelines using historical shoreline movement patterns and the erosion/inundation effects due to sea level rise according to Hands. Once the sea level has exceeded the dune elevation, onshore movement of beach sediments occurs by washovers (Leatherman, 1977). The rate of shoreline retreat, once in the washover mode, can be estimated from retreat rates along existing washover islands north and south of the study area (Stephen et al., 1975). Thus, we project additional erosion due to sea level rise for shorelines on barrier islands. We do not project accelerated erosion along riverine (cohesive sediment) shorelines due to sea level rise.

In summary, the model for shoreline change that has been applied to Charleston consists of drowning the shoreline by each particular sea level rise scenario, then applying a shoreline correction factor for particular coastal geomorphic types that considers: historical erosion/accretion rates for beaches and active cutbanks on rivers, mobility of sediments, likelihood of the profile to respond rapidly to sea level rise and maintain its general shape, and locus of sediment movement (offshore, alongshore, or onshore) for a given site. The first factor is quantifiable, based on historical data; sediment mobility is greatest in the sand-size ranges, decreasing as sediments get coarser or very fine and cohesive. Major sediment transport patterns can be deduced from geomorphic features and man-made coastal structures.

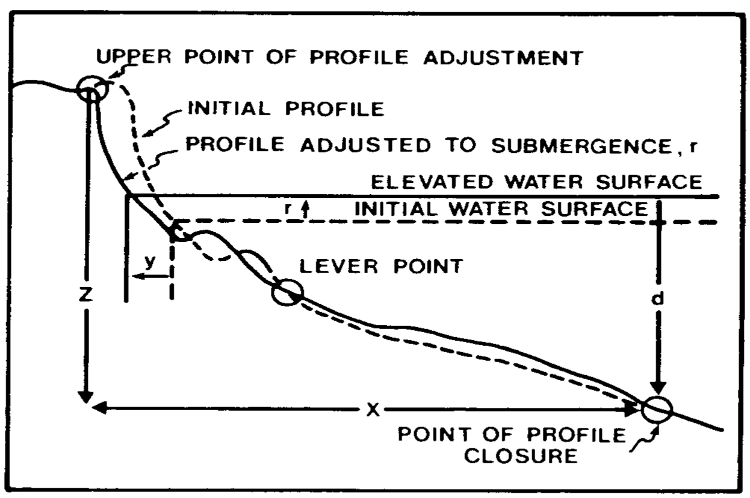

Figure 4-3. Sketch of predicted shoreline profile adjustment to a change in water elevation. *(After E.B. Hands, 1981, Predicting Adjustments in Shore and Offshore Sand Profiles on the Great Lakes, CERC technical aid 81-4, Fort Belvoir, Va.: Coastal Engineering Research Center.)*

Storm Surge

The term storm surge refers to any departure from normal water levels due to the action of storms. This can take the form of a set-up or rise in the sea surface due to excess water piling up against the shore or a set-down if water is removed from the coastal region. For obvious reasons, a super-elevation of coastal waters is of most concern because of its potential for causing property damage from flooding.

Storm surges are generally reported as a deviation in height from MSL. The magnitude of this deviation at any point along the coast is a function of several factors, including: the energy available to move excess water toward the coast (wind and waves), the width of the continental shelf, the shape of the basin, and the phase of the normal astronomic tide.

The most widely applied model for predicting open-coast hurricane-surge elevations is the National Oceanic and Atmospheric Administration's (NOAA) SPLASH [Special Program to List Amplitudes of Surges from Hurricanes (Jelesnianski, 1972)]. Recently, a model called SLOSH (Sea, Lake, and Overland Surges from Hurricanes), which "routes" the surge inland, has been developed by NOAA (Jelesnianski and Chen, 1984) and is considered the state of the art for inland surge computations. Unfortunately, this model was not complete for the Charleston study area at the time the study was undertaken.

Designers and engineers have set standard recurrence intervals such as 1, 10, 25, 50, or 100 years to compare flood elevations from one place to another. This can be restated as the percent chance of occurrence for a particular flood level in any year. For example, a 10-year flood elevation has a 10 percent chance of occurring each year, whereas a 100-year flood has a 1 percent chance of occurring. The relative increase in flood levels from a 10-year to a 100-year storm is generally less than 25 percent (U.S. Army Corps of Engineers, 1977). In most regions, this holds true for inland, as well as open-coast, surges. The generally accepted standard for safe design is the 100-year flood level. This is the basis for delineating flood-prone areas used by the Army Corps of Engineers, NOAA, and the Federal Insurance Administration (FIA).

Two different probability storms were used in the present study to evaluate the effect of sea level rise on flooding frequency: the 100-year storm and the threshold storm. (Threshold storm is that storm with the greatest probability of initiating significant damage in the study area.) The 100-year storm elevations ranged from 4. 2 m (14 ft) on the outer beaches to 2.7 m (9 ft) inland. For Charleston, the threshold storm was selected to be the 10-year storm. It was determined by sequentially raising water levels until significant inundation of developed areas occurred. The 10-year storm elevations ranged from 2.1 m (7 ft) on the outer beaches to 1.4 m (4.5 ft) inland. Intermediate storm-surges can be selected from frequency curves on the historical tidal-storm elevations for Charleston (Myers, 1975).

Groundwater Analyses

Saltwater intrusion is the most common and serious pollutant of fresh groundwater in coastal aquifers. Although many complex mathematical models have been developed to predict saltwater intrusion, a simple concept, the Ghyben-Herzberg principle (Herzberg, 1961), can be used as a conservative estimate of the position of and change in the freshwater/saltwater boundary.

The Ghyben-Herzberg principle predicts that the depth of the freshwater/saltwater interface is 40 times the elevation of the water table above MSL. Therefore, if the water table is 1 m above MSL, the freshwater/saltwater interface is predicted to be at 40 m below MSL at that point. For artesian aquifers (aquifers which are confined by overlying, relatively impermeable beds), the freshwater/saltwater interface can be predicted by using the elevation of the piezometric surface, which is the artesian pressure or level of water in the aquifer analogous to the water level in unconfined aquifers. A later section on results includes an explanation of our assumptions regarding the modeling of groundwater impacts from sea level rise.

MAPPING METHODS

The first step required in the analysis was to establish a method for contouring new shoreline positions and storm surge elevations for each sea level rise scenario. New positions and elevations could be plotted by manual interpolation between closest contours on standard USGS topographic maps. This procedure is appropriate for simple shorelines or small geographic areas. However, for the Charleston case study, an automated interpolation scheme was necessary for two reasons: first, the 5 ft contour interval on the existing topographic maps did not provide the necessary detail for accurate interpolation, especially between 0 and 5 ft; and second, there were well over 800 km (500 mi) of shoreline to interpolate.

Topographic maps were made by the translation of map contours using a digital map data base. Computer-generated maps were produced from digital terrain data (point elevations located on a geographical coordinate system). The maps consisted of interpolated contours generated by numerical averaging within grid squares. For example, the most accurate map would be one that has digital data plotted every few meters so that contour plotting interpolation would take place over a very small grid cell. Unfortunately, few surveys ever contain "field" data this closely spaced. Also, for practical reasons, grid spacings of a few meters would be inappropriate for a geographical area such as Charleston, which covers over 20 km ^{2} (75 m ^{2}). Instead, a compromise grid-cell spacing was required that was appropriate to the scale of the map and concentration of original contour data.

Programs using a digital terrain model (DTM) are limited to mapping with grids that fit within a designated number of rows and columns on the computer matrix. For example, if the largest matrix for a particular system is 500 rows by 500 columns, map resolution will be proportional to the scale of the map. Each grid unit on a 500 X 500 km map would represent one km^2, whereas one unit on a 500 X 500 m map could represent one m^2. The system used in the present study allowed for a 240 X 256 matrix with a grid cell for the case area of 30 m^2(375 ft^2). This translates to map dimensions of 7.31 X 7.79 km (4.54 X 4.84 mi). The study area was approximately 3.2 times these dimensions.

Base Maps

Two types of source map were used to extract topographic/bathymetric control points. First, control points were selected from the USGS 7.5 minute topographic maps at a scale of 1:24,000 with 1.5 m (5 ft) contour intervals. Control points from this source were measured to the nearest foot. The control points were obtained by periodically sampling the contour lines and using existing benchmarks. All contours and benchmarks from -1.8 m (-6 ft) MSL up to +5.8 m (+19 ft) MSL were sampled.

An additional map source covering the city of Charleston (1:2,400 planimetric maps with 1ft contour intervals) was used to supplement the digital topography data. Only benchmark data (no contours) were used in this data set. Control points from the large-scale maps were digitized at a resolution of 0.03 m (0.1 ft), substantially improving the quality of the DTM-computer-generated map, compared with using only data from the 1:24,000 scale USGS quadrangles. This procedure is recommended wherever additional, more accurate map sources are available.

Digitization

The spatial resolution of the DTM was chosen to be 30 m (100 ft) on the 1:24,000 base map. The elevation matrices for the study area were generated with dimensions of 240 rows by 256 columns [7.31 X 7.79km (4.54 X 4.84mi)] . A total of 3.5 maps was required (2,000-2,500 data points each) to cover the entire project area. A two-phase interpolation algorithm was employed to estimate the elevation values for all 900-m ^{2} (9,700-ft ^{2}) cells. The first phase performed a quadrant search around each cell in question to ensure that control points would be obtained from at least two of the compass directions. A nearest-neighbor method then automatically selected, from the subset of control points generated initially, the n nearest neighbors to estimate the elevation of each cell. The interpolation was to the nearest 0.03 m (0.1ft), resulting in a DTM with relatively accurate elevation data.

Contour maps were generated and overlaid onto the 1:24,000 base map to determine the planimetric and topographic accuracy of the interpolated grid matrix. When discrepancies occurred, additional control points were located and digitized, and a new grid matrix was created by the same interpolation method described above. This procedure was repeated several times to improve resolution as much as possible within the size limits of each grid cell.

Within the case study area, the largest sections of questionable map data are the marsh shorelines. In general, few elevation data are given on maps to illustrate the marsh topography. USGS quadrangles typically show only the MSL and 1.5m (+5 ft) MSL contour. A computerized interpolation of intermediate elevations within the marsh would produce an unrealistic profile of the marsh surface. During previous field surveys by our research group, it was found that a marsh has a characteristic elevation that varies with local tidal range and type of marsh vegetation (Ward and Domeracki, 1979). Figure 4-4 illustrates a typical marsh/tidal creek system for the Charleston area (a shoreline type representative of over 75 percent of the study area).

Typical elevations range from +0.5 to +1.0 m (+1.5 to +3.1 ft) MSL. Note the profile of the "typical" marsh in comparison to a hypothetical profile generated by straight interpolation between the

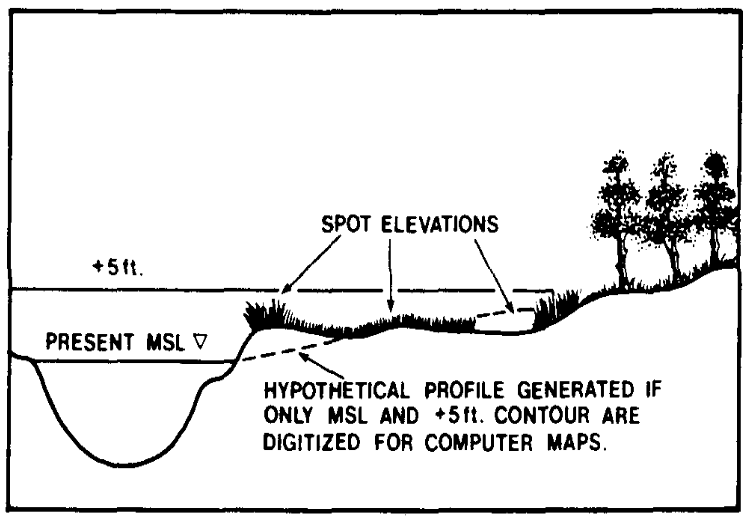

Figure 4-4. Typical South Carolina marsh transect illustrating need for spot elevations on marsh surface to improve contour interpolation.

MSL and + 1.5 m (+5 ft) MSL contour. By means of aerial photographs, seaward edges of the marsh were identified and additional data points were added for the computer maps in order to account for this characteristic morphology. This gave the computer additional geomorphic data to produce more realistic shoreline interpolations.

Although efforts to add extra detail in the digital terrain model were time consuming, high concentrations of elevation data substantially improved the accuracy of the computer-generated map and allowed resolution of subtle changes in topography, a key factor for some of the smaller sea level rise scenarios. Once the digital map data base was established, the computer easily performed contour interpolation for any specified elevation. The system used is capable of plotting contour maps showing only those contours of interest. It also can display color maps on a high resolution raster CRT (Cathode Ray Tube monitor), which allowed easier visualization of the effect of sea level changes.

Computer-Generated Maps

Contour/bathymetric maps displaying the desired contours and contour intervals were prepared, scaled to overlay the original 1:24,000 scale base map. Various combinations of contours and contour intervals were plotted, depending upon the sea level rise scenario selected. These computer generated maps became the new base maps for final determination of shoreline position using geomorphic data and increased storm surge elevations. Vertical resolution of contours was to the nearest 0.03 in (0.1 ft), whereas spatial resolution was " 15m (50 ft).

The color CRT allowed viewing various sea level rise scenarios applying the simple inundation concept. By choosing colors illustrative of water, intertidal, and land areas, it was possible to obtain a preliminary picture of the effect of each sea level scenario. The digital terrain elevation values were converted to 8 bit (byte) data ranging from values of 0 to 255. Selected elevation class intervals were assigned different colors to represent baseline and predicted changes in sea level and storm surge elevations. Although the CRT screen does not offer permanent hard copy for detailed analysis, it can be photographed directly for illustrative purposes. This is one of the most useful modern tools for applications of this kind.

HISTORICAL SHORELINE TRENDS

The computer-generated contour maps were used to project the shoreline position due to simple inundation by each sea level rise elevation. The next step was to adjust shoreline positions based on geomorphic factors, such as historical trends of erosion and accretion, and accelerated erosion of the beach shorelines due to accelerated sea level rise, applying Hands' (1981) model. Shorelines composed of mobile sediments, such as the beaches along the case study area, change in response to many factors. Storms, hurricanes, and sand bypassing at inlets can cause short-term erosional and depositional trends along the shore. Long-term trends result from changes in sediment supply (such as damming or diversion of rivers) and sea level. An analysis of the net effect of accelerated sea level rise on shoreline position must exclude existing erosional/depositional trends, including those due to recent sea level rise. To accomplish this, "baseline" maps for the years 2025 and 2075 were produced that represent the predicted shoreline position at that time without any effects from accelerated sea level rise. The baseline maps were constructed through an analysis of historical shoreline trends using aerial photographs and topographic maps available for the period 1939-1981. A total of 53 selected reference points, identifiable on successive photographs or maps, were established throughout the Charleston study area (see Figure 4-1). The distance from the reference point to the shoreline was measured on each available photograph, making the necessary scale corrections between photo sets taken at different altitudes. The trends in changes between successive photographs were used to evaluate the validity of the net change and excursion rate (shoreline movement per year) for each reference point for the years 1939-1981. Table 4-2 lists the shoreline change rates determined for each station. Annualized excursion rates were then projected into the future to compute the position of the shoreline for the reference years 2025 and 2075. The computed position was finally adjusted considering several factors:

Table 4-2. General Description of Stations and Historical Trends

Station Number	*Historical Trend ft/yr (yrs of record)*[a]	*Geomorphic Type*	*Slope (MSL±5ft)*
		Ashley River	
1	+ 1.6 (40)	Marsh	001
2	− 3.4 (42)	Cutbank	06
3	+19.4 (42)	Marsh/Point Bar	.0004
4	− 2.3 (42)	Cutbank	.032
5	+ 0.9 (34)	Exposed Marsh	.0006
6	+ 6.4 (34)	Marsh/Tidal Flat	.006
7	− 0.1 (34)	Marsh/Cutbank	.001
8	+11.1 (34)	Marsh/Point Bar	.001

[a]Accretion = +; erosion = −

(continued)

Table 4-2. *(continued)*

Station Number	Historical Trend ft/yr (yrs of record)[a]	Geomorphic Type	Slope (MSL±5ft)
9	+17.5 (34)	Marsh	.002
10	+15.8 (34)	Marina	.083
	Charleston Harbor		
11	+13.8 (34)	Marsh	.005
12	+ 8.8 (34)	Marsh	.0005
13	− 3.9 (42)	Exposed Marsh	.001
14	− 0.3 (42)	Exposed Marsh	.002
15	+ 2.3 (42)	Exposed Marsh	048
16	+37.5 (8)	Marsh/Tidal Flat	.001
17	0 (42)	Armored	Vertical
18	0 (42)	Armored	Vertical
19	+ 2.6 (34)	Armored	Vertical
20	0 (42)	Armored	Vertical
21	0 (42)	Armored	Vertical
	Cooper River		
22	+ 3.8 (42)	Marsh/Spoil	008
23	0 (42)	Spoil Dike	24
24	+16.0 (42)	Marsh	.004
25	+40.2 (4)	Marsh/Spoil Island	.008
26	+ 4.8 (42)	Marsh/Spoil	.006
27	+28.8 (4)	Marsh/Spoil	.009
28	+ 1.4 (4)	Sandy Marsh	.048
29	0 (42)	Armor/Bulkhead	Vertical
30	0 (42)	Armor/Riprap	.048
31	+ 6.1 (38)	Marsh	.007
32	+ 1.5 (38)	Marsh/Spoil	.012
33	0 (42)	Armor/Bulkhead	Vertical
34	0 (42)	Armor/Bulkhead	Vertical
	Wando River		
35	+ 2.0 (42)	Marsh/Spoil/Flat	.032
36	0 (4)	Spoil Dike	.24
37	0 (42)	Armor	Vertical
38	+ 0.5 (4)	Marsh	.003
39	+ 3.0 (10)	Armor/Fringe Marsh	.048
40	+ 3.0 (10)	Fringing Marsh	.016
41	+24.5 (4)	Fringing Marsh	.003
	Charleston Harbor		
42	− 5.1 (42)	Exposed Marsh	.003
43	+19.3 (42)	Exposed Marsh/Spoil	.007
44	+ 8.7 (42)	Marsh Spit	.048
45	+ 3.4 (40)	Fringing Marsh	.01
46	+ 3.4 (40)	Fringing Marsh	012

[a]Accretion = +; erosion = −

(continued)

Table 4-2. *(continued)*

Station Number	Historical Trend ft/yr (yrs of record)[a]	Geomorphic Type	Slope (MSL±5ft)
		Sullivans Island	
47	− 0.3 (40)	Armor/Wall	Vertical
48	− 0.2 (40)	Fringing Marsh	.008
49	− 0.5 (34)	Pocket Beach/Channel	.029
50	+21.1 (40)	Beach/Recurved Spit	.015
51	+ 1.6 (34)	Beach/Recurved Spit	0.17
52	+ 1.0 (34)	Beach/Recurved Spit	.012
53	+ 5.7 (34)	Barrier Beach	.02

[a]Accretion = +; erosion = −.

nearshore slopes, proximity to channels (if accreting),proximity to highland (if eroding);
types of sediment (e.g.,cohesive marsh clays compared to unconsolidated sand deposits);
proximity to open fetches or commercial waterways; dredge and fill (i.e., artificial changes) during the period of record, if known;
presence of unprotected development that likely would not be allowed to erode past a certain point, at which time armoring would be placed along the shoreline;
large-scale changes in sediment input that are expected to occur during the interval under consideration, such as rediversion of the Santee River.

Discrete shoreline data points were used as the basis for interpolating continuous contours for each baseline map. Because these maps were based on historical trends, they inherently include effects from recent changes in sea level. Figure 4-5 shows the 50-year trend in sea level along the Charleston shoreline with respect to adjacent land, based on tidal data for selected east coast cities (Hicks and Crosby, 1974). The sea level rise scenarios used in this study range from 2.5 to 10 times the previous rates for Charleston.

Treatment of Man-Made Shorelines

The geomorphic approach to determining historical shoreline trends is inappropriate to certain developed or man-made shorelines. Within historical times, man has manipulated shorelines to suit requirements for waterborne commerce and port development. The city of Charleston has been an active port for over 200 years and contains numerous waterfront areas "armored" with seawalls, bulkheads, or riprap (a mat of stone along the bank) that preclude virtually all shoreline movement. Areas such as these will experience little or no change in shoreline position until a sea level rise or possible storm surge overtops the shoreline armoring. For the present analysis, maps for each scenario assumed that no alterations of the existing elevations of man-made structures occurred and that no storms would significantly erode backshore areas. All elevations used throughout this study are existing elevations. Thus, once sea level topped the structures, inundation of the backshore area proceeded according to the land slope.

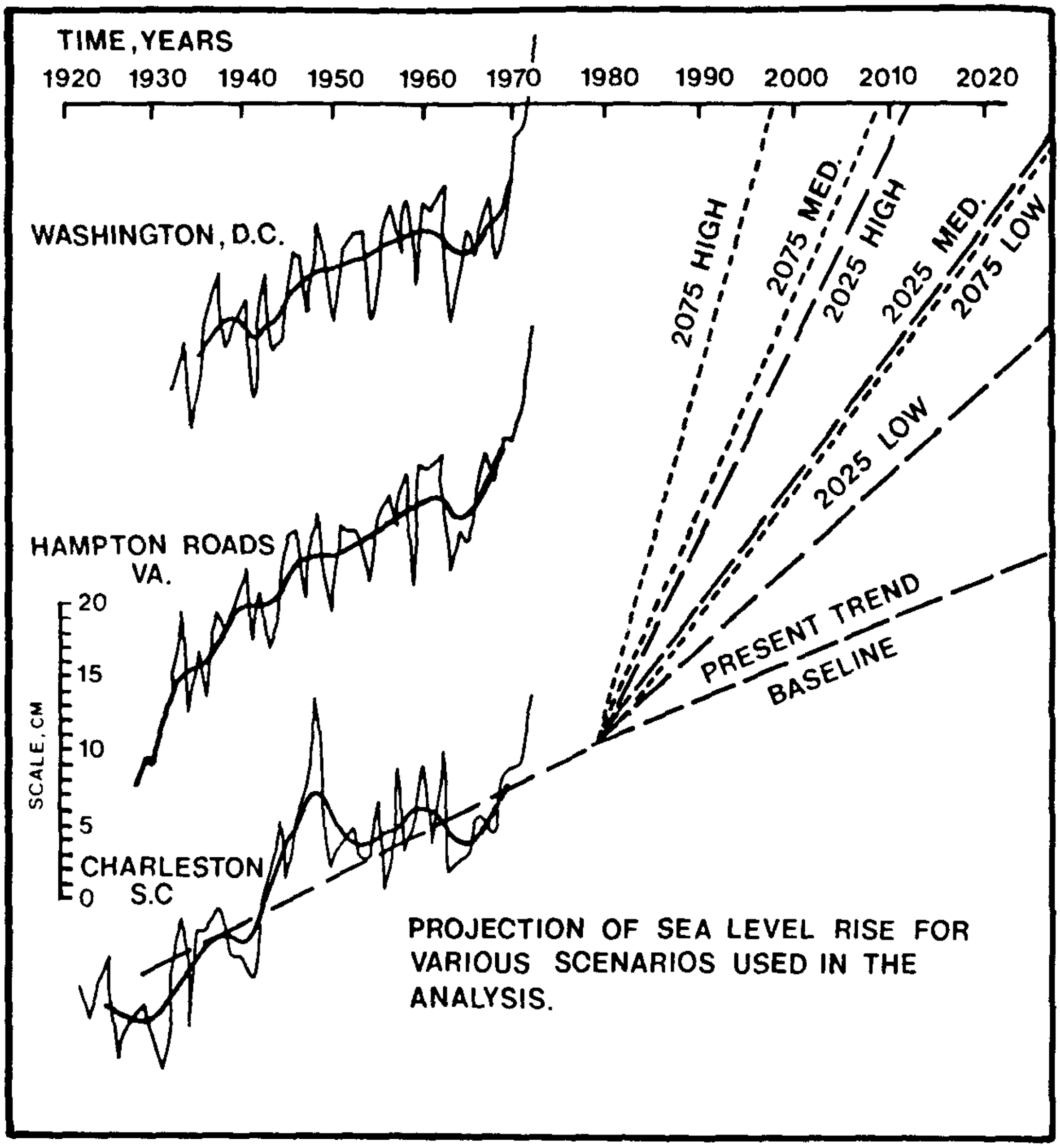

Figure 4-5. Change in sea level with respect to adjacent land for stations from the District of Columbia to South Carolina. The projected changes of the accelerated sea-level rises for 2025 and 2075 (low, medium, and high scenarios) are shown for comparison with baseline. *(After S. D. Hicks and J. E. Crosby, 1974, Trend and Variability of Yearly Mean Sea Level, 1893–1972, NOAA technical memorandum NOS-13, Rockville, Md.: Department of Commerce.)*

Treatment of Marsh Shorelines

Shorelines fronted by marshes were treated differently than sand beaches because they do not maintain an equilibrium profile with sea level changes. Marsh surfaces accrete through the deposition of fine-grained, suspended sediment when water flow is baffled by marsh vegetation. Erosion of marshes is a slow process of wave erosion at the seaward edge of the marsh or at cutbanks of meandering streams. As shown in Table 4-2, most of the marsh stations in Charleston have been accretionary since 1939. However, the rediversion of the Santee River is expected to reduce the sediment input by 85 percent, and the marshes are not likely to continue accreting as in the recent past.

Our analysis did not assume that marsh sedimentation would keep pace with sea level rise in the (low to high) scenarios. Therefore, a sea level rise would result in significant flooding of areas that are now marshes. Where marshes exist, there tends to be a critical elevation range for the majority of the deposit. In Charleston, that range is from +0.5 m (1.5 ft) to the highest normal level of tidal inundation, referred to as mean spring high water (MSHW).

An incremental rise in MSL is expected to have less effect on the MSL shoreline position (since it generally occurs along steep, tidal creek banks) than on the position of MSHW because of the local slopes involved. MSHW is a critical elevation in Charleston because it establishes the contact between marsh and upland forests as well as the practical limit of development. Table 4-3 indicates the typical zonation of marsh/tidal flat habitats by elevation in the Charleston study area.

Table 4-3. Typical Elevations of a Marsh/Tidal Creek System in Charleston

Elevations	*Zone*	*Species*	*Elevation (MSL) m (ft)*
Highest	High marsh	*Spartina patens, Distichlus sp.*	+0.8–+1.2 (+2.5–+4.0)
	Low marsh	*Spartina alterniflora*	+0.3–+0.8 (+1.0–+2.5)
	Mud flat/oysters	*Crassostrea virginica*	−0.4–+0.3 (−1.5–+1.0)
Lowest	Channels	Benthic fauna	Less than −0.8 (Less than −2.5)

Source: Research Planning Institute, Columbia, S.C., unpublished survey data.

The response of marshes to rapid sea level rise would be by inundation, shift in vegetation zones, and creation of new intertidal habitats, rather than alteration of the substrate topography. Therefore, shoreline changes along marshes were made by showing the area of inundation using the change in MSHW for each scenario. We do not anticipate that there would be any other factors causing changes in the position of marsh shorelines, even considering the larger sea level rises that would flood the fringing highland areas. Marsh vegetation is very rapidly established and will always occupy the niche between MSL and spring high tide in sheltered areas, even in sandy substrate. Marsh vegetation would shift from high marsh to low marsh with sea level rise and would produce a wide, shallow platform that would attenuate wave energy in much the same manner as existing shorelines. Studies of shoreline changes of sheltered environments of Pleistocene sea level rises have shown that there is an upward and landward shift of environments as opposed to a one-dimensional shoreline retreat (Colquhoun et al., 1972).

Determination of Shoreline Change

The shoreline position (at mean high spring tide) for each of the 53 stations in the study area was computed for all scenarios at the years 2025 and 2075, respectively. Because of the large reduction in sediment input anticipated when the Santee River is rediverted, the marshes were assumed to go into a stable phase with no change projected from the historical trends, which are accretionary. The only shoreline change in the marsh stations for the baseline maps was assumed to be by inundation due to the continued historical rise in sea level at 0.25 cm/yr (0.1 in/yr). The total baseline change in the position of sandy shorelines (station numbers 49-53) for each scenario year included both extrapolation of historical trends (in ft/yr O number of years) and inundation. Discrete station data were used to produce the baseline maps for the years 2025 and 2075.

The changes in shoreline location by scenario for each year are estimated as the net change caused by accelerated sea level rise, measured from the baseline for that year, and total change, measured from the 1979 USGS 7.5 minute topographic maps. The net and total change included only inundation for marsh shorelines. The net change on sandy beaches included inundation and erosion (projection of historical trends using Hands' (1981) relationship) due to the higher sea level. After sea level topped the current elevation of the dunes, the shoreline retreat was projected as a washover process, using averaged rates from existing washover islands along the South Carolina coast (as determined by Stephen et al., 1975). The total change was a summation of the historical trends and the sea level rise-induced changes. Therefore, rather than project the total disappearance of the barrier island, it was assumed that waves would build washover ridges to the spring tidal level for a uniform width which would migrate landward. The appendix tables at the end of this chapter show predicted shoreline changes for all scenarios and stations, giving a breakdown of the various components contributing to the change.

Example Analysis. As an example, the analysis for one station (52 on Figure 4-1) follows (see also appendix). The historical trend at that station for the last 40 years has been +0.3 m (1.0 ft/yr) of accretion. (It is a beach along a recurved spit on Sullivans Island.) To determine the change in the position of the shoreline for the year 2025 without accelerated sea level rise (the baseline position), the yearly depositional rate was multiplied by 45, equal to 14 m (45 ft) of accretion. Historical sea level rise rates were also projected to the year 2025 to determine the elevation of MSHW at that time, under the baseline scenario, which was a rise of 11 cm (0.4 ft). This placed MSHW for the year 2025 (baseline) at 1.0 m (3.5 ft) above present MSL. Computer-plotted maps of the present and 2025 baseline shoreline positions were overlaid and the change in position measured. For Station 52, there was a change of -6 m (-20 ft) due to inundation along the existing beach slope. The total change in the 2025 baseline position, compared to the present, was the sum of both the historical trend and inundation, which in this case was equal to +7.6 m (+25 ft). The change in shoreline position for the 2025 low scenario can be measured from both the present shoreline (called total change) or from the projected baseline position (called net change), which is due solely to accelerated sea level rise. Net change was determined by summing the inundation component (from the comparison of contour positions for each MSHW elevation), which was -15 m (-50 ft) for Station 52, and a component for additional erosion due to the higher sea level, using Hands '(1981) model, which was -14 m (-45 ft). The total change from the present also included the change from the present due to historical trends in erosion or deposition. Thus, the total change for Station 52 under the 2025 low scenario was equal to -21 m (-70 ft), which is the sum of the projected baseline [+8 m (+25 ft)], plus changes due to inundation [-15 m (-50 ft)], plus the effect of accelerated erosion [-14 m (-45 ft)].

Shoreline changes due to inundation were measured at each station directly from the computer-generated contour maps for each sea level rise. The shoreline position was then altered where appropriate according to historical trends for baseline maps or erosion due to sea level rise on each scenario map. The shoreline between stations was interpolated using the shoreline type and adjacent stations as guides.

STORM SURGE ANALYSES

The next major impact of sea level rise considered was the alteration of storm surge levels in proportion to the sea level rise scenario. There may be minor factors that would tend to change the incremental rise in storm surge elevations, but these would be dwarfed by the present inaccuracies of inland surge modeling. The approach used was to elevate the selected storm surges (10-year and 100-year storms) by an amount equal to the sea level rise scenario. Although this technique is slightly conservative, by not accounting for displacement of the storm surge inland with sea level rise, there is no available model to estimate what the effects of sea level rise would be on the inland routing of the storm surge.

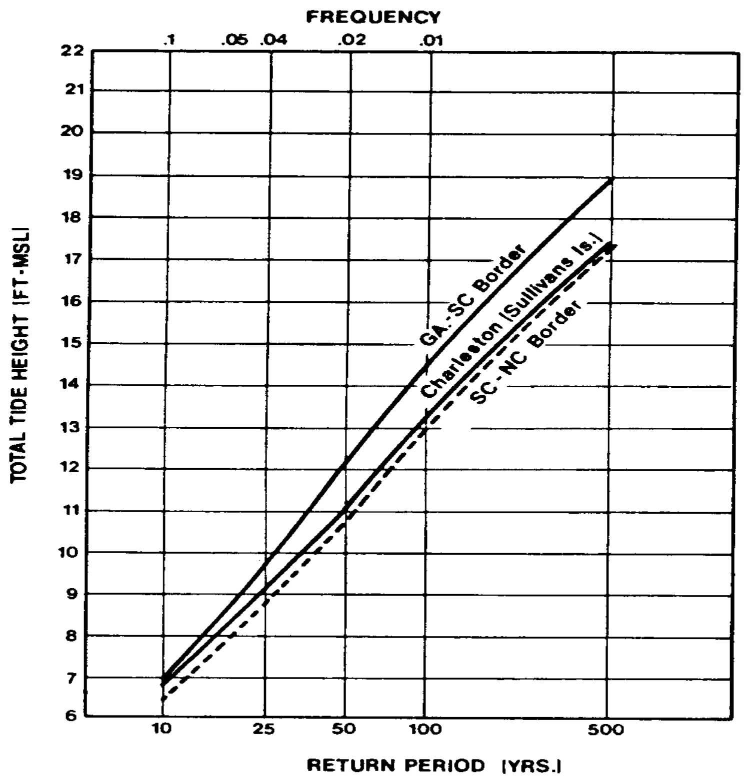

Figure 4-6. Tide frequencies at selected points on the South Carolina coast. *(After V. Myers, 1975, Storm-Tide Frequencies on the South Carolina Coast, Silver Spring, Md.: National Weather Service, Office of Hydrology.)*

Storm surge elevations for the study area were taken from Federal Emergency Management Agency (FEMA) flood maps. These maps, produced for various Charleston sites since the early 1970s, are the basis for Federal Flood Insurance rates and zoning and indicate flooding zones and corresponding surge elevations for the 100-year event (storm with a probability of 0.01). The 10-year storm elevation (with a probability of 0.1) was determined from a summary of storm tide frequencies prepared by Myers (1975) for Charleston (Figure 4-6). This figure shows that for the 10-year storm, total tidal heights would be above 1.5 m (5 ft) MSL.

GROUNDWATER ANALYSES

There have been numerous case studies of saltwater intrusion, which generally occurs from the reversal or reduction of groundwater gradients which causes denser saltwater to displace freshwater or from the destruction of natural barriers separating freshwater and saltwater. Many methods have been developed to calculate the position, simulate the motion, and predict the rate of intrusion of the freshwater/saltwater boundary (Cooper et al., 1964; Mercer et al., 1980; Pinder and Cooper,1970). The most accurate methods involve complex convective-dispersive solute-transport equations, which require specific hydrogeological parameters and are difficult to solve. Also, for many coastal aquifers, hydrogeological parameters are not well known, not even within an order of magnitude.

A simple approach, called the Ghyben-Herzberg principle, was used as a conservative estimate of the position and change of the freshwater/saltwater boundary. The basic principle is that there is a sharp interface between freshwater and saltwater that is in hydrostatic equilibrium (i.e., no flow) due to the different densities of the two solutions. It is known that the interface is actually a broad zone of diffusion, and the saltwater is not static but flows in a cycle from the sea floor into (and creating) the zone of diffusion and back to the sea (Cooper et al., 1964). Figure 4-7 shows how this circulation pattern forms. However, the Ghyben-Herzberg principle is known to be conservative (Kohout, 1960) and can be used only as a first approximation. Only near the shoreline, where vertical flow components become pronounced, do significant errors in the position of the interface occur (Todd, 1980). Using the Ghyben-Herzberg principle, the depth to the freshwater/saltwater interface is equal to 40 times the elevation of the water table (for unconfined aquifers) or the piezometric surface (for artesian aquifers) above MSL.

There are various opinions of the effect of sea level rise on the position of the freshwater/saltwater interface in the water table aquifer using the Ghyben-Herzberg principle. On one side, the opinion

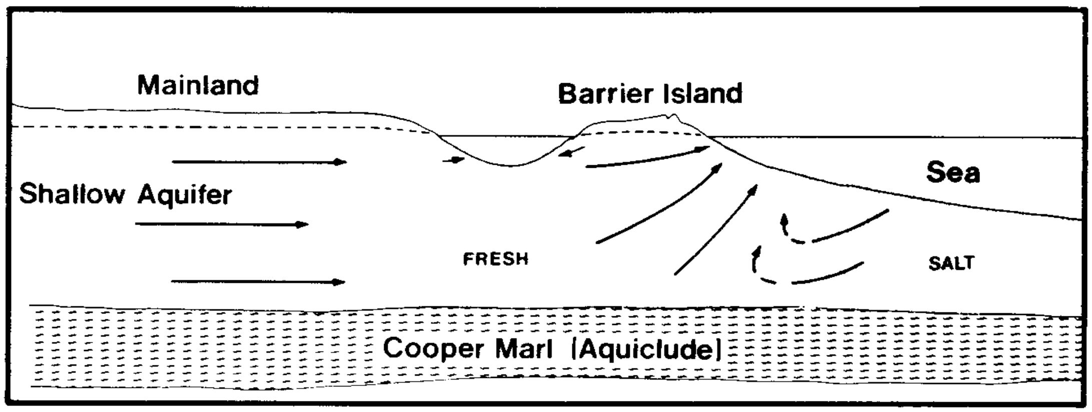

Figure 4-7. Schematic cross-section through the shallow aquifer for the eastern portion of the Charleston area showing the circulation of seawater and the general position of the zone of diffusion between freshwater and saltwater.

is that, even though the saltwater head rises, the freshwater would also rise, and the gradients would eventually reestablish hydrodynamic equilibrium. Therefore, the whole system would shift upward in proportion to the sea level rise and landward in proportion to the shoreline retreat. The slope of the interface would control the inland excursion of the toe of the saltwater wedge beyond the new shoreline position.

On the other side, the opinion is that a rise in sea level would decrease recharge (renewal of groundwater from natural resources) and increase discharge so the freshwater rise would not match sea level rise but would be some fraction of it. The increased discharge would be primarily via streams that would drain off freshwater as the water table rise intercepted the land surface. The land elevation and existing drainage patterns would determine the amount of increased discharge for a given sea level rise.

Without site-specific modeling of the groundwater flow regime, it was assumed that the freshwater/saltwater gradients in the unconfined aquifer will quickly reestablish equilibrium after sea level rise. This assumption should be valid because recharge of the aquifer is from local precipitation and is rapid through the sandy surficial sediments. The position of the saltwater/freshwater interface was calculated from the 1:40 GhybenHerzberg relationship. However, because the aquifer thickness averages about 13 m (40 ft), the interface will always be estimated to occur at the point where the water table is 0.3 m (1 ft) above MSL without interferences due to present water withdrawal. Using existing groundwater slopes, the position of the interface was estimated to be at approximately 60m (200ft) inland of the new shoreline position for each scenario. Thus, for this study, saltwater intrusion after sea level rise can be approximated by the shore erosion/inundation distance for each scenario. For artesian aquifers, the adjustment in the freshwater/saltwater interface can be predicted using the Ghyben-Herzberg principle: that is, *a* 1:40 ratio for sea level rise to freshwater/saltwater interface rise (Henry,1962). The recharge zone for artesian aquifers is generally far removed from the coast, and there would not be a significant increase in discharge. However, the time lag of saltwater intrusion is very large, as discussed in the next section.

Rates of Saltwater Intrusion

The rates of adjustment of the freshwater/saltwater zone of diffusion in groundwater in response to sea level rise will be different for water table compared to confined aquifers. Although a determination of the absolute rates is beyond the scope of this study, there are examples which demonstrate the relative rates to be expected.

There are many examples of very rapid saltwater contamination of water table aquifers due to man's activities. Large-scale construction of canals in south Florida has resulted in the penetration of saltwater into previously fresh areas-an effect somewhat analogous to sea level rise. Dense saltwater gradually replaced fresh groundwater below the canals in several years, including a drought (Parker, 1955). The saltwater zone then moved in response to gradients created by heavy pumping in the area. In New Jersey, construction of the Washington Canal in the early 1940s breached the confining layer of the shallow aquifer. By the 1980s, saltwater had traveled 8-16 km (5-10 mi) inland (Harold Miesler, 1983, USGS, personal communication). There are many other case histories that show that where shallow aquifers come in direct contact with seawater, saltwater intrusion can occur on a scale of several to tens of years. The time necessary to reach equilibrium may be much longer and is generally complicated by local changes in recharge and discharge.

The rates of adjustment in extensive artesian aquifers will be very slow, especially for the deep, stratified aquifers along the east coast. The USGS is developing a digital technique to model the movement of the altwater/freshwater zone of diffusion during the sea level fluctuations throughout the Pleistocene epoch (Harold Miesler, 1983, USGS, personal communication). Although the model is still being developed, they estimate that the time required for stabilization of the zone of diffusion for the New Jersey sections with which they are working is on the order 10^5 and 10^6 years.

These calculated time periods are supported by studies done by the USGS on the Atlantic continental shelf. Hathaway et al. (1979) reported that low-chlorinity water occurs beneath much of the shelf from 16 to 120 km (10-75 mi) offshore. The general pattern was described as a freshwater lens overlain by low-permeability clays, which have a sharp chlorinity gradient increasing toward seawater concentrations. They interpret the freshwater lens as a remnant of fresh groundwater that recharged the shelf sediments during the Pleistocene glacial maximum, when sea level was as much as 100 m (330 ft) lower than present. The impermeable clay has acted as a confining bed, preventing saltwater intrusion during the last flooding of the continental shelf about 8,000 years ago. Hathaway et al. (1979) proposed that the offshore freshwater lens had played an important role in preventing saltwater intrusion into mainland wellfields. The slow rates of adjustment in the freshwater/saltwater zone of diffusion is further supported by reports of remnant saline water that intruded during higher sea level stands into various coastal aquifers (Stringfield, 1966; Wilson, 1982).

RESULTS AND DISCUSSION

Smooth shoreline and flood maps for the various baseline and sea level rise scenarios for the years 2025 and 2075 were prepared from the digital terrain model and methodology already outlined. The following results offer a sampling of the changes expected under selected scenarios. A technical report by Michel et al. (1982) contains a more complete data summary.

The first set of maps prepared illustrate existing conditions, giving the location of the 1980 MSL shoreline, MSHW, and 10-year and 100-year flood zones (Figure 4-8). The maps have been combined in Figure 4-8 to illustrate the entire project area. Because of the scale at which this and subsequent maps are reproduced, it is difficult to appreciate the magnitude of many of the shoreline changes. The results indicate

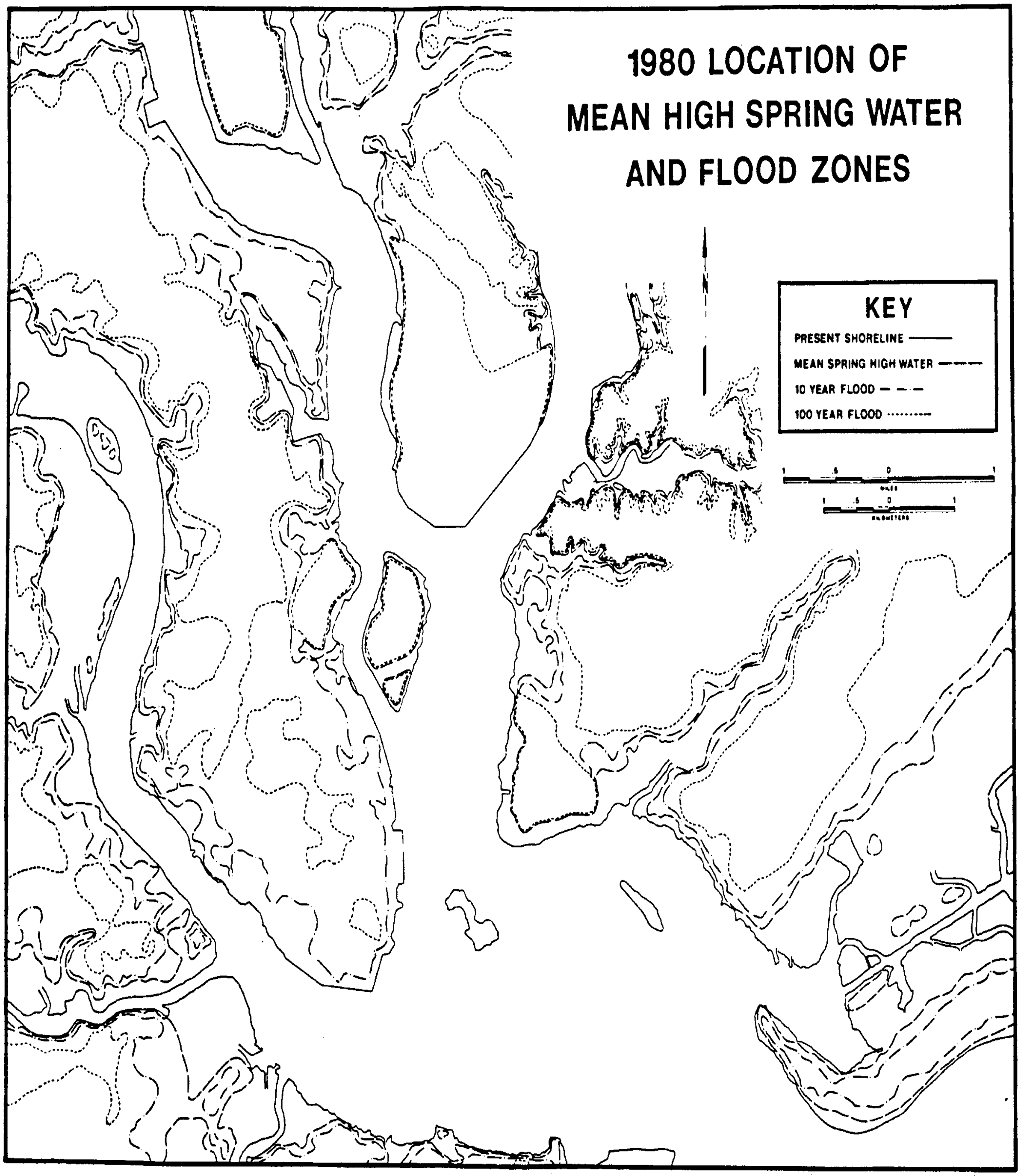

Figure 4-8. Existing (1980) locations of the MSHW, 10-year storm surge and 100-year storm surge in the study area.

future shoreline change is indeed significant under all but the lowest scenarios. At the scale of these maps, a pencil width represents up to 100 m (330 ft) of change, a result that would certainly be of concern to most shorefront property owners. Despite the complexity of the maps at this scale, major trends are still apparent.

Figure 4-9 is one of the 2025 map sets that show the baseline and high-scenario position of MSHW plotted against the present MSL shoreline. Figure 4-10 similarly illustrates the predicted position of MSHW for the 2075 baseline and all scenarios. These two maps illustrate the extremes in projected MSHW

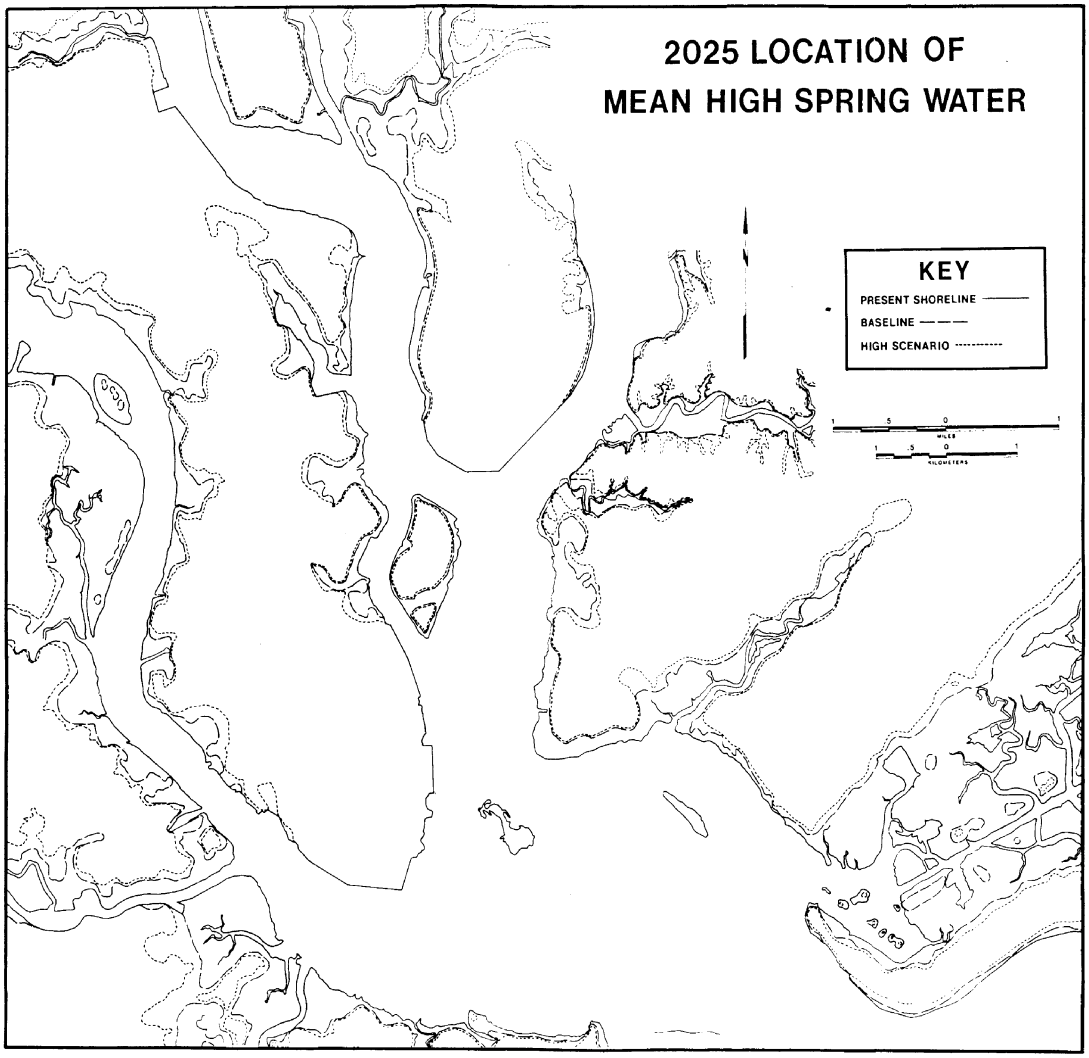

FIGURE 12.

Map showing the locations of MSHW for the 2025 baseline and High scenarios. The locations for the Low and Medium scenarios were fairly evenly spaced between the lines shown here.

Figure 4-9. Map showing the locations of MSHW for the 2025 baseline and high scenarios. The locations for the low and medium scenarios were farily evenly spaced between the lines shown here.

position for the present study. It should be obvious from a quick glance at the two maps that a very large zone of inundation would occur during the high scenario almost 100 years from now.

Figure 4-10 shows the trends in the position of MSHW for each scenario for the year 2075. On the southwestern tip of Charleston, the arrow labeled *A* represents the area of spring tidal inundation for the 2075 baseline scenario. The arrow labeled *B* represents additional areas of inundation for the low scenario; *C* represents the added area of inundation for the medium scenario; and *D* represents the additional area inundated under the high scenario.

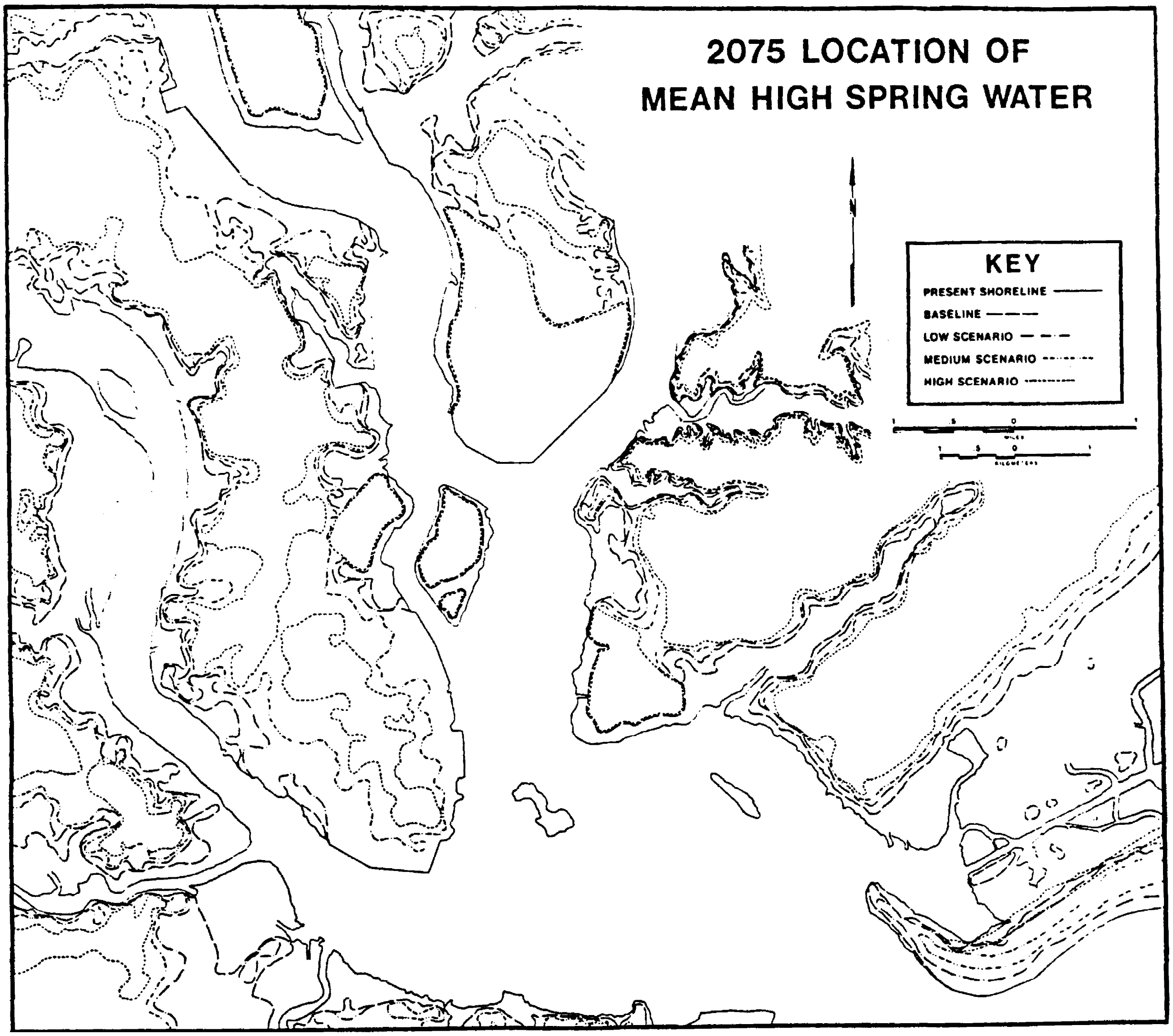

Figure 4-10. Map of the predicted locations of MSHW for the baseline, low, medium, and high scenarios for the year 2075. For diked areas, which always remained above MSHW, only the baseline and high lines are shown.

Baseline Map-Year 2025

The baseline map for 2025 (see Figure 4-9) was generated to represent the future shoreline and storm surge changes under current rates of sea level rise, which effected an 11 cm (0.4 ft) rise by 2025. When compared with existing (1980) conditions shown in Figure 4-8, there are few significant changes. An average of 30 m (100 ft) of inundation occurred along the western shore of the Ashley River, but the new MSHW was still within the astronomic tidal elevations and thus within high marsh vegetation. Along vertical seawalls and spoil dikes, the MSHW was already considered to be at the base of the structure; thus, there were no detectable changes along the man-made shorelines. The accretionary trends along the islandbeaches dominated over the small amount of inundation. The extensive marsh between Mount Pleasant and Sullivans Island was already mostly below MSHW, except for spoil islands along the Intracoastal Waterway and areas fringing the highland. In fact, considering the accuracy of the computer-plotted contours and the ± 15 m (50 ft) precision in measuring the changes between contours, there was essentially no change between present (1980) and the baseline for 2025 along interior shorelines. However, along shorelines which can be historically documented to be undergoing long-term deposition or erosion, the use of a baseline composed of a historical trend component is important. Inundation as a separate factor is not necessary because it is inherently included in the historical trend analysis.

The changes in shoreline and storm surge positions for the scenarios in 2025 were small and difficult to display at page-size scales. The shape of the study area is also difficult to illustrate in sections and still retain any sense of area-wide comparisons. Thus, the results for the 2025 high scenario only are shown in Figure 4-9. The low and medium scenario results are not shown but can be visually placed between the high and baseline positions. The results are described below; the reader should refer to Figure 4-9 during the following discussion.

2025 Low Scenario

This scenario represented a total rise in sea level of 28 cm (0.9 ft) but only 17 cm (0.5 ft) above the baseline for 2025. The changes in the MSHW would be very small compared to the baseline. Inundation at the marsh stations ranged between 0 and 75 m (0-250 ft). As expected, changes in areas of narrow marshes that fringe developed highland, such as along James Island, would not be discernible because of greater slopes (and the limitations of computer interpolation). Mount Pleasant, formed on an old barrier island itself, rises sharply above the marsh fill behind Sullivans island; there would be little or no change in MSHW on all sides. Parts of Sullivans Island would become erosional, while the bulge in the lee of the jetties would slow its growth.

The changes in the 10- and 100-year storm surges would be small, generally less than 60 m (200 ft). A 28 cm (0.9 ft) rise obviously was not large enough to exceed any breaks in slope. The most significant change would occur on Sullivans Island, all of which is currently within the l00-year flood zone. The 10-year flood zone was predicted to dissect the island across contiguous low areas.

2025 Medium Scenario

The medium 2025 scenario of a 46 cm (1.5 ft) rise in sea level did not cause many changes in the shoreline position of consequence to developed property. At a total elevation of 1.4 m (4.6 ft) above present MSL, the new MSHW position was close to but below the 1.5 m (5 ft) contour, which is the practical lower limit for construction of permanent structures. Thus, while there would be no cases of complete structural property damage along the harbor shoreline, many structures would be placed in the zone of yearly astronomical flooding. This pattern was typical for the entire western shore of the Ashley River, which was primarily low density residential property.

Few structures would be included in the 10-year flood zone in this scenario, which ranged between 1.8 and 2.3 m (6.0-7.5 ft) above present MSL. Some new areas of residential property would be located in the 100-year flood zone, particularly between the Ashley River and Wappoo Creek (near station 11 on Figure 4-1).

The shoreline in the city of Charleston has areas that would lose up to 75 m (250 ft) due to erosion/inundation, particularly in the middle part of the peninsula. Although industrially developed, this

middle section has not been landfilled to the extent which occurred to the north (U.S. Navy facilities) and south (port facilities and residential). Therefore, a narrow neck of land with smaller areas above the 10- and 100-year storm surges occurred. North Charleston, up to 10 m (33 ft) above MSL, would show even fewer shoreline changes, except along the cutbank of the Ashley River. Most of the Cooper River shoreline is composed of bulkheads and docks for the U.S. Navy Reservation and would not be affected. This area also would show regular inland shifts in the 10- and 100-year flood zones of about 75m (250 ft). The historical district on the Charleston peninsula had no changes along the man-made shorelines. The seawalls range in elevation between 1.5 and 2.7 m (5-9 ft) above present MSL. Thus, increasing periodicity of flooding

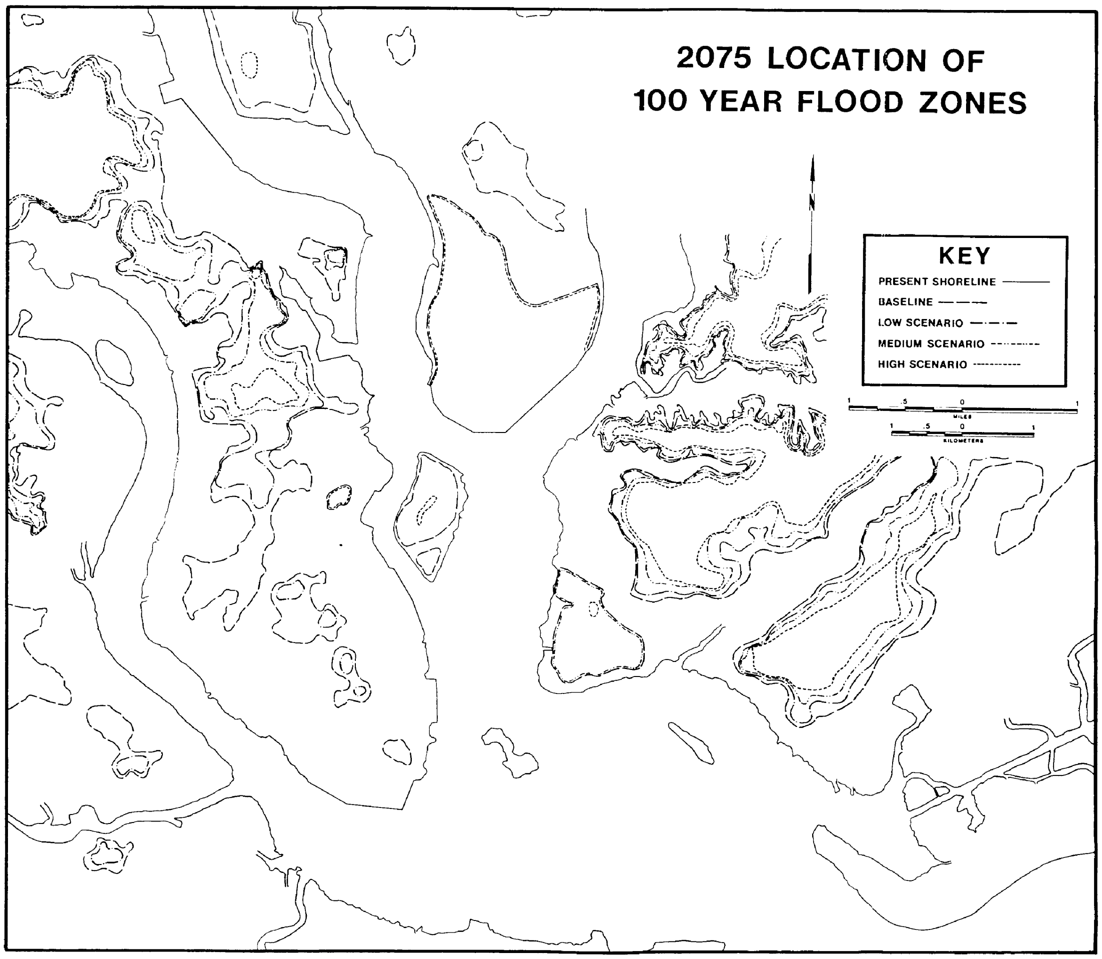

Figure 4-11. Map of the predicted locations of the 100-year storm surge for the baseline, low, medium, and high scenarios for the year 2075. For diked areas, which always remained above the 100-year surge, only the baseline and high lines were shown. Some of the diked spoil areas were affected under the medium and high scenarios.

was of more concern than inundation for this scenario. Of great importance is the projection that some of the key arteries of the city would be regularly flooded. The 10-year flood zone moved inland about 75 m (250 ft) in densely populated areas on the west side. The 100-year flood zone became scattered islands of high ground down the center of the peninsula.

Sullivans Island was the area of most serious impact. The causeway connecting the island to the mainland would be barely above spring tidal elevations. Any storm or unusual astronomical tides would regularly cut off access to and from the island. The projected position of MSHW was landward of the first row of houses in the middle section of the island. Erosion of this section would supply sediment to the western end of the island, parts of which were still accreting. Wave refraction caused by the jetties would continue to cause accretion near station 50 (Figure 4-1). Areas above the 10-year flood would be limited to a narrow strip of land down the center of the island [the only part higher than 2.3 m (7.5ft) MSL]. Further accretion into the harbor would be limited by the deep channel and strong ebb currents, which would carry sand back out the jetties.

2025 High Scenario

There would be few additional changes in the shoreline inundation/erosion trends for this scenario, with some notable exceptions. Large movement in the MSHW position occurred on both sides of Wappoo Creek, west of the Ashley River. The scenario elevation of MSHW at 1.6 m (5.2 ft) above present MSL barely exceeded the present 1.5 m (5 ft) contour. The maps showed shoreline positions behind some existing structures and several islands of highland would be isolated in the southwestern part of the study area. Although the 10-year flood zone would get progressively larger, most of the areas above the 100-year flood west of the Ashley would now be in the flood zone.

On the peninsula, there would still be few serious shoreline problems. The newly filled and developed commercial area north of the Ashley River bridge (station 8, Figure 4-1) would be within the new intertidal zone. Otherwise, existing seawalls were high enough to prevent daily inundation. The 10-year flood would have moved 90 m (300 ft) inland of the present position. Only small areas would be above the 100-year flood along the historic district.

Currently, the town of Mount Pleasant is divided in half by a small water body (Shem Creek), which separates two highland areas. As old barrier islands, both sections are relatively high and flat. Shoreline and flood position changes would be generally small and regular, even along the convoluted areas.

Few if any structures in Mount Pleasant would be affected by shoreline movement for this scenario. The largest changes would be along the mainland facing Sullivans Island (Figure 4-9); MSHW shifted up to 225 m (750 ft) inland of its baseline position.

The causeway to Sullivans Island would be regularly flooded during spring tides, that is, every 14 days. Sullivans Island itself would have continued to narrow from both shorelines. There would no longer be any accretion on the southern end and the western tip was barely maintained by a seawall. A second row of houses would be threatened by erosion and storm waves. The 10-year flood lines would have changed little; there would still be a narrow corridor barely above the 2.5m (8.1 ft) elevation.

Even at the highest rise for 2025, there would be no effects on the diked spoil areas throughout the harbor. Dike elevations range between 4.3 and 7,3 m (14-24 ft) above present MSL and thus would protect the spoil areas from even the 100-year storm surge.

Baseline Map-Year 2075

Projections of historical trends in shoreline position and sea level rise were used to create the 2075 baseline maps (Figure 4-10). The sea level rise of 24 cm (0.8 ft) was practically the same as the 2025 low scenario, which had a 28 cm (0.9 ft) rise. There were few areas of significant change. The new MSHW, at 1.2 m (3.9 ft), would still be below normal astronomical tides, and there would have been a gradual landward shift in marsh vegetation of a few tens of meters at the most. The only structural loss along the shoreline would have occurred in scattered locations along the seaward row of homes on Sullivans Island. Expansion of the 10- and 100-yea r flood zones would be highly variable but would average some 60m (200 ft).

The changes due to sea level rise for each scenario were so large that separate maps were made for each type of coastal response. Figure 4-10 shows new shoreline positions, and Figure 4-11 shows the 100-year flood zones. Each map shows the baseline for determination of accelerated sea level rise effects.

2075 Shoreline Changes

Figure 4-10 shows the position of MSHW for the baseline, low, medium, and high scenarios for 2075. Accelerated sea level rises ranged from 0.9 to 2.3 m (2.9-7.6 ft). With an MSHW range of 0.9 m (3.1 ft), the worst-case scenario reflects an intertidal zone beginning at 3.2 m (10.7 ft) above present MSL. The low scenario exceeded in rise the highest scenario considered for 2025.

The position of MSHW for the low scenario [at 1.8 m (6 ft) above present MSL] would be inland of property along several sections of shoreline, particularly Wappoo Creek and the west shore of peninsular Charleston. Other areas of Charleston would still be protected by existing coastal structures. Sullivans Island would begin to lose a second row of houses, with 67-120 m (220-400 ft) of shoreline retreat. Under the 2075 medium scenario, the western tip of Suilivans Island would have retreated by over 600 m (2,000 ft), and the island's width would have decreased from a baseline of about 670 m (2,200 ft) to 150 m (500 ft). The island was predicted to shift to a washover mode of shoreline retreat at MSHW elevation of 2.3 m (7.5 ft). Washover islands are a flat terrace of sand which is periodically overwashed during high tides and storms. They move by landward transport of sand as opposed to alongshore transport, Dunes generally do not have time to form.

Using the 2075 high scenario, the island would have maintained its 150 mm (500 ft) width and moved landward at 6 m/yr (20 ft/yr) with up to 790 m (2,600 ft) of retreat recorded. The Mount Pleasant area would show steady shoreline inundation, with an average shift of 250 m (800 ft) in the MSHW level for the high scenario. The Charleston peninsula would have experienced the most dramatic changes in shoreline position. Under the medium and high scenarios, all existing seawalls would be overtopped, and large areas would be subsequently inundated up to 550 m (1,850 ft) for the medium scenario and 1,200 m (4,000 ft) for the high scenario. Only the central part of the peninsula would be above the intertidal zone. The entire Navy Reservation would be inundated even for the medium scenario. The spoil island dikes would still be above MSHW. Daniel Island (station 27, Figure 4-1) would become several smaller marsh islands. Highland areas west of the Ashley River would have shrunk considerably in very irregular patterns, with up to 900 m (3,000 ft) loss of land.

In summary, the areas of greatest impact would be on Sullivans Island (which became a washover island) and the Charleston peninsula (where a highly developed area underwent extensive inundation). Mount Pleasant and the spoil islands would be the least affected.

Storm Surge Elevations

With accelerated sea level rise, the 100-year flood zones would have changed dramatically. For the low scenario, only a few small patches of land would have remained above the 100-year flood west of the Ashley, on the lower peninsula, and on Daniel Island. The 100-year storm would inundate hundreds of meters of North Charleston and Mount Pleasant. For the medium scenario, the only areas above the 100-year storm surge would be slivers of land west of the Ashley, small islands of highland in North Charleston, and two slightly smaller ridges in Mount Pleasant.

For the high scenario, the only areas above the 100-year flood elevation would be restricted to the northeastern part of North Charleston and to significantly reduced ridges in Mount Pleasant. For the first time, the diked spoil areas would show some impact-a wide part of the spoil surface would be flooded by the 100-year storm.

GROUNDWATER IMPACTS

The present position of the freshwater/saltwater interface in the water table aquifer is unknown, but it is suspected to be very close to the existing shorelines. Using the Ghyben-Herzberg relationship, the new interface was predicted to occur about 60 m (200 ft) inland of the new shoreline position. The slope of the interface should be nearly vertical because the water table aquifer is only 10-20 m (33-66 ft) deep. Therefore, the interface would eventually shift inland proportionally to the distance of shoreline inundated or eroded for each scenario. The rate of response of the interface for the water table aquifer should be close to the rate of sea level rise.

Saltwater intrusion was found to not threaten existing public water supply wells (in Mount Pleasant) until the high scenario for 2075, when the saltwater/freshwater interface was predicted to move inland 150-450 *m* (500-1,500 ft). The ultimate impact of sea level rise may be negligible, considering the long-term trend for shallow coastal aquifers for the last 50 years, which has been toward a declining use and reliance on shallow groundwater. Even without accelerated sea level rise, the shallow aquifers will be overpumped, resulting in much more severe saltwater intrusion than predicted here. In 50 years, saltwater intruded up to 13 km (8 mi) in the shallow aquifer near Miami because of construction of drainage canals and heavy utilization (Kohout, 1960). On Long Island, New York, the freshwater/saltwater interface advances 3-60 m (10-200 ft) per year, depending on local pumping conditions (Todd, 1980). In the study area, Mount Pleasant pumps many of its shallow wells dry in the summer and will eventually be forced to drill more deep wells long before sea level rise becomes a factor. Additionally, shallow coastal aquifers are very prone to contamination by septic tanks, tile fields, agricultural practices, and other disposal problems. Thus, as the coastal areas become more populated, the shallow aquifers will be frequently abandoned as sources of potable water. Therefore, it is concluded that there will be no discernible effects on shallow groundwater from accelerated sea level rises in the Charleston study area. This is not to say there is no groundwater problem, only that it has a cause not related to sea level rise. In addition, there will not be any effects on confined aquifers because the time periods necessary to reestablish equilibrium are on the order of tens of thousands of years.

ANALYSIS OF METHODOLOGY

Precision of Results

The computer-generated contour maps used in this study were made from high concentrations of digital elevation data from which contours could be plotted for specific elevations. This procedure was superior to hand interpolation between the normal 5 ft contours on the standard 7.5 minute USGS topographic maps. Even so, frequent corrections were necessary during construction of the baseline and sea level rise maps to make them conform to the USGS maps. For instance, the computer generated maps were unable to plot accurately straight stretches of shorelines where seawalls occurred. These corrections were easily made and were not significant sources of error. The areas of greatest concern were marsh elevations, which are important for evaluation of the small sea level rises. The addition of spot elevations from large-scale maps for the marshes was critical in the generation of accurate contours between 0 and 5 ft. Even with this added detail, many manual corrections were required. To generate accurate maps at the requested detail used in this study in a routine fashion, alternative methods were necessary. The smaller sea level rises considered here were at the limit of the technique used. The digital data base needs to be even more precise than that used by the USGS to construct the base maps for accurate interpretation.

The uncertainty in the position of the predicted shorelines for the maps was at best ±15 m (±50 ft), based solely on errors due to manual transfer and line thickness. Much larger errors are possible from determination of historical trends from aerial photographs, criteria used to apply or modify the historical shoreline change rates, and interpolation of the shoreline between stations. These errors are impossible to quantify; they are a function of the data base and the judgment of the user.

Evaluation of Groundwater Analysis

The long time period for impact on confined aquifers eliminates them from consideration in this study. However, the water table aquifers are susceptible to increased saltwater intrusion. The methods used to analyze the effects of sea level rise on the water table aquifers were simple approximations of complex systems. The more precise methods, such as numerical models, require much data that are not generally available or accurately known. Even the USGS models to simulate the movement of the freshwater/saltwater interface during Pleistocene sea level fluctuations in a region with an extensive data base, have been extremely difficult to calibrate.

The shallow aquifer in the study area was only 10-20 m (33-66 ft) thick; thus, the Ghyben-Herzberg principle predicted 60 m (200 ft) of saltwater intrusion beyond the new shoreline position for each scenario. In thicker aquifers, the Ghyben-Herzberg principle works well as a conservative estimate. The main uncertainties in its application are the degree to which the freshwater system equilibrates with the rise in saltwater head and the net effect of increased discharge. Since little is known about how these two processes affect the response of the water table, they have not been incorporated into this study. However, groundwater effects from sea level rises up to 200 cm (6.5 ft) appear to be minor compared with other processes that are causing more rapid and extreme saltwater intrusion. Studies should be made to test the impact of sea level rise on large water table aquifers that are well understood, such as the Long Island glacial aquifer, to determine if groundwater effects are an important consideration to evaluate.

General Applicability

The methods developed in this pilot study used data that are readily available for most coastal regions (i.e., various scales of topographic maps, aerial photographs, flood-hazard boundary maps) and widely applicable. The methods used to predict the position of the shoreline for the baseline and scenario maps have been described in detail in this report. They are based on general principles of coastal geology and can be applied to almost any shoreline type or location. The general applicability of this method should be tested in other areas, especially to test for differences in geomorphology, tide regime, and local effects such as high subsidence rates. The coastal geomorphology and physical setting of the Chesapeake area, for example, may require a very different ordering of the dominant processes. The tidal range is smaller, and it borders a major estuary. The sediment flux will be smaller for both fine-grained, suspended sediments and littoral sediments eroding from the headlands
in the bay and at the entrance capes.

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APPENDIX

Shoreline Locations by Scenario for 2025 and 2075

Table 4-A. Shoreline Location by Scenario for the Year 2025

Station	Change in Shoreline Scenario (ft)																
	Baseline			Low				Medium					High				
Number	tr	in	bc	in	er	nc	tc	bc	in	er	nc	tc	bc	in	er	nc	tc
1	0	-100	-100	-250	0	-250	-350	-100	-250	0	-250	-350	-100	-350	0	-350	-450
2	-150	0	-150	0	0	0	-150	-150	0	0	0	-150	-150	-50	0	-50	-200
3	0	0	0	-100	0	-100	-100	0	-100	0	-100	-100	0	-100	0	-100	-100
4	-100	0	-100	0	0	0	-100	-100	0	0	0	-100	-100	-50	0	-50	-150
5	0	-50	-50	-50	0	-50	-100	-50	-150	0	-150	-200	-50	-150	0	-150	-200
6	0	-50	-50	-50	0	-50	-100	-50	-50	0	-50	-100	-50	-100	0	-100	-150
7	0	0	0	-200	0	-200	-200	0	-250	0	-250	-250	0	-350	0	-350	-350
8	0	0	0	0	0	0	0	0	0	0	0	0	0	-50	0	-50	-50
9	0	-100	-100	0	0	0	-100	-100	-150	0	-150	250	-100	-950	0	-950	-1050
10	0	0	0	0	0	0	0	0	0	0	0	0	0	-150	0	-150	-150
11	0	50	-50	-100	0	-100	-150	-50	-150	0	-150	200	-50	-200	0	-200	-250
12	0	50	-50	-200	0	-200	250	-50	-400	0	-400	-450	-50	-450	0	-450	-500
13	0	-150	-150	-50	0	-50	-200	-150	100	0	-100	-250	-150	-100	0	-100	-250
14	14	-100	-114	50	0	50	164	-114	100	0	-100	214	114	-100	0	-100	-214
15	0	-100	-100	0	0	0	100	-100	50	0	-50	150	-100	-50	0	50	150
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	-100	0	-100	100	0	100	0	-100	100

(continued)

Table 4-A. *(continued)*

Station Number	Change in Shoreline Scenario (ft)																		
	Baseline			*Low*				*Medium*					*High*						
	tr	*in*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*		
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
24	0	50	50	−100	0	100	−150	50	−100	0	−100	150	−50	−150	0	−150	−200		
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
26	0	0	0	−100	0	100	100	0	−100	0	−100	−100	0	−150	0	−150	−150		
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
28	0	50	50	0	0	0	50	−50	−50	0	−50	−100	−50	−100	0	−100	−150		
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

(continued)

Note: Erosion is designated by negative numbers. Accretion is designated as positive numbers, without a sign. See Figure 4-1 for station locations and Table 4-2 for station descriptions.

tr = change caused by extrapolation of past shoreline trends
in = change caused by inundation due to projected sea level rise
bc = total change in baseline from 1980, equal to tr + in
er = change caused by erosion due to accelerated sea level rise
nc = net change caused by accelerated sea level rise equal to in + er
tc = total change equal to bc + in + er

Table 4-A. *(continued)*

Station Number	Baseline			Change in Shoreline Scenario (ft): Low				Medium					High				
	tr	*in*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*
40	0	50	50	0	0	0	50	−50	−100	0	−100	−150	−50	−100	0	−100	−150
41	0	0	0	150	0	150	150	0	−200	0	−200	−200	0	−250	0	−250	−250
42	230	0	230	0	0	0	−230	−230	0	0	0	−230	−230	0	0	0	−230
43	0	50	50	0	0	0	−50	−50	0	0	0	−50	−50	0	0	0	−50
44	0	50	50	200	0	−200	−250	−50	−400	0	−400	−450	−50	−550	0	−550	−600
45	0	50	50	−50	0	−50	−100	−50	−50	0	−50	−100	−50	−50	0	−50	−100
46	0	0	0	−50	0	−50	−50	0	−100	0	−100	−100	0	−150	0	−150	−150
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	50	50	0	0	0	−50	−50	−250	0	−250	−300	−50	−250	0	−250	−300
49	20	−20	0	0	−45	−45	−45	0	−75	−75	−150	−150	0	−100	−105	−205	−205
50	475	−20	455	−50	−45	−95	360	455	−75	−75	−150	305	455	−400	−105	−505	−50
51	70	−20	50	−50	−45	−95	−45	50	−75	−75	−150	−100	50	−150	−105	−255	−205
52	45	−20	25	−50	−45	−95	−70	25	−75	−75	−150	−125	25	−100	−105	−205	−180
53	255	−20	235	−50	−45	−95	140	235	75	75	−150	85	235	−200	−105	−305	−70

Note: Erosion is designated by negative numbers. Accretion is designated as positive numbers, without a sign. See Figure 4-1 for station locations and Table 4-2 for station descriptions.

tr = change caused by extrapolation of past shoreline trends
in = change caused by inundation due to projected sea level rise
bc = total change in baseline from 1980, equal to tr + in
er = change caused by erosion due to accelerated sea level rise
nc = net change caused by accelerated sea level rise equal to in + er
tc = total change equal to bc + in + er

Table 4-B. Shoreline Location by Scenario for the Year 2075

Station Number	Baseline			Low				Change in Shoreline Scenario (ft) Medium					High				
	tr	*in*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*
1	0	−250	−250	−350	0	−350	−600	−250	−450	0	−450	−700	−250	−1050	0	−1050	−1300
2	−320	−100	−450	−100	0	−100	−520	−420	−250	0	−250	−670	−420	−250	0	−250	−700
3	0	0	−200	−250	0	−250	−250	0	−700	0	−700	−700	0	−900	0	−900	−900
4	170	−50	−220	−150	0	−150	−370	−220	−400	0	−400	−620	−220	−800	0	−800	−1020
5	0	−50	−50	−350	0	−350	−400	−50	−350	0	−350	−400	−50	−1050	0	−1050	−1100
6	0	−50	−50	−200	0	−200	−250	−50	−450	0	−450	−500	−50	−1100	0	−1100	−1150
7	0	−200	−200	−350	0	−350	−550	−200	−650	0	−650	−850	−200	−950	0	−950	−1150
8	0	0	0	−450	0	−450	−450	0	−1900	0	−1900	−1900	0	−3300	0	−3300	−3300
9	0	0	0	−1300	0	−1300	−1300	0	−1400	0	−1400	−1400	0	−1850	0	−1850	−1850
10	0	0	0	−150	0	−150	−150	0	−2300	0	−2300	−2300	0	−5450	0	−5450	−5450
11	0	−100	−100	−900	0	−900	−1000	−100	−950	0	−950	−1050	−100	−1350	0	−1350	−1450
12	0	−200	−200	−450	0	−450	−650	−200	−650	0	−650	−850	−200	−2100	0	−2100	−2300
13	0	−50	−50	−400	0	−400	−450	−50	–[a]	0	–[a]	–[a]	−50	–[a]	0	–[a]	–[a]
14	−20	−50	−70	−100	0	−100	−170	−70	–[a]	0	–[a]	–[a]	−70	–[a]	0	–[a]	–[a]
15	0	0	0	−50	0	−50	−50	0	−100	0	−100	−100	0	–[a]	0	–[a]	–[a]

(continued)

Note: Erosion is designated by negative numbers. Accretion is designated as positive numbers, without a sign.

tr = change caused by extrapolation of past shoreline trends
in = change caused by inundation a due to projected sea level rise for baseline or scenario
bc = total change in baseline from 1980
er = change caused by accelerated sea level rise
nc = net change caused by accelerated sea level rise equal to in + er
tc = total change equal to bc + in + er

[a]Shoreline completely inundated/eroded on map.
[b]Beaches now in washover mode; inundation not a factor.

Table 4-B. *(continued)*

Station Number	Baseline tr	Baseline in	Baseline bc	Low in	Low er	Low nc	Low tc	Medium bc	Medium in	Medium er	Medium nc	Medium tc	High bc	High in	High er	High nc	High tc
								Change in Shoreline Scenario (ft)									
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	1400	0	1400	1400	0	2100	0	2100	2100
19	0	0	0	0	0	0	0	0	500	0	500	500	0	600	0	600	600
20	0	0	0	0	0	0	0	0	1850	0	1850	1850	0	2150	0	2150	2150
21	0	0	0	0	0	0	0	0	1100	0	1100	1100	0	3350	0	3350	3350
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	100	100	300	0	-300	400	100	550	0	550	650	100	-1800	0	1800	1900
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	100	100	150	0	150	250	-100	200	0	200	300	100	500	0	500	600
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	150	0	150	150	0	650	0	650	650	0	2050	0	2050	2050
29	0	0	0	0	0	0	0	0	1600	0	1600	1600	0	2100	0	2100	2100
30	0	0	0	0	0	0	0	0	1250	0	1250	1250	0	3750	0	3750	3750

(continued)

Table 4-B. *(continued)*

Station Number	Baseline			Change in Shoreline Scenario (ft) Low				Medium					High				
	tr	*in*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*	*bc*	*in*	*er*	*nc*	*tc*
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	1950	0	-1950	1950	0	-2250	0	-2250	-2250
34	0	0	0	0	0	0	0	0	-1000	0	1000	1000	0	-2300	0	2300	-2300
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	-100	0	-100	-100	0	-100	0	-150	-150
37	0	0	0	0	0	0	0	0	-100	0	-100	-100	0	-150	0	-150	-150
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	-50	0	-50	-50	0	-100	0	-100	-100	0	-150	0	150	-150
40	0	-50	-50	250	0	-250	-300	-50	-600	0	-600	-650	50	-3000	0	3000	-3050
41	0	-150	150	-600	0	-600	-750	-150	-1050	0	1050	-1200	-150	-1300	0	1300	-1450
42	370	0	-370	0	0	0	-370	-370	0	0	0	-370	-370	0	0	-370	-370
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	-200	200	-550	0	-550	-750	-200	-650	0	-650	-850	-200	-1200	0	-1200	-1400
45	0	-50	50	-100	0	-100	-150	-50	-250	0	250	-300	-50	-500	0	-500	-550

(continued)

Note: Erosion is designated by negative numbers. Accretion is designated as positive numbers, without a sign.

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er = change caused by accelerated sea level rise
nc = net change caused by accelerated sea level rise equal to in + er
tc = total change equal to bc + in + er

[a]Shoreline completely inundated/eroded on map.
[b]Beaches now in washover mode; inundation not a factor.

Table 4-B. *(continued)*

Station Number	Baseline *tr*	Baseline *in*	Baseline *bc*	Low *in*	Low *er*	Low *nc*	Low *tc*	Medium *bc*	Medium *in*	Medium *er*	Medium *nc*	Medium *tc*	High *bc*	High *in*	High *er*	High *nc*	High *tc*
								Change in Shoreline Scenario (ft)									
46	0	−50	−50	−250	0	−250	−300	−50	−400	0	−400	−450	−50	−650	0	−650	−700
47	0	0	0	0	0	0	0	0	–[b]	−2100	−2100	−2100	0	–[b]	−4250	−4250	−4250
48	0	0	0	−300	0	−300	−300	0	–[b]	–[a]	–[a]	–[a]	0	–[b]	–[a]	–[a]	–[a]
49	30	0	30	−100	−150	−250	−220	30	–[b]	−550	−550	−520	30	–[b]	−1500	−1500	−1470
50	600	−50	550	−800	−150	−950	−400	750	–[b]	−1650	−1650	−900	750	–[b]	−2100	−2100	−1350
51	120	−50	70	−200	−150	−350	−280	70	–[b]	−800	−800	−730	70	–[b]	−2000	−2000	−1930
52	75	−50	25	−150	−150	−300	−275	25	–[b]	−650	−650	−625	25	–[b]	−2000	−2000	−1975
53	425	−50	375	−450	−150	−600	−225	375	–[b]	−1000	−1000	−625	375	–[b]	−2600	−2600	−2225

Note: Erosion is designated by negative numbers. Accretion is designated as positive numbers, without a sign.

tr = change caused by extrapolation of past shoreline trends
in = change caused by inundation a due to projected sea level rise for baseline or scenario
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[a]Shoreline completely inundated/eroded on map.
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