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The Effect of Future Sea Level Rise Along the Southern Rhode Island Coast

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THE EFFECT OF FUTURE SEA LEVEL RISE ALONG THE SOUTHERN RHODE ISLAND COAST

BY

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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1990

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ABSTRACT

The barrier spit and headland shoreline of southern Rhode Island is presently migrating landward under the effects of storm-wave driven frontal erosion, while coastal lagoon and upland shorelines are being displaced landward by rising sea level. Relative sea level curves for southern Rhode Island projected to the year 2100 were constructed by adding a local isostasy rate of 0.15 ± 0.04 $cm \cdot yr^{-1}$ to the range of eustatic sea level predictions determined by the United States Environmental Protection Agency (EPA) (Hoffman, 1984). The EPA mid-range high scenario used in this study predicts a 216 cm global rise by 2100, and when local isostasy is added, a 235 cm rise by 2100 for southern Rhode Island.

Historic frontal erosion rates were extrapolated to the years 2020 and 2100 to map future barrier and headland shoreline position, while lagoon and upland shorelines for the same years were derived by inundating the present landscape with a 60 and 244 cm (2 and 8 ft) mean sea level rise. Frontal erosion will account for 49 ha of land loss by 2020 and 163 ha by 2100 between Watch Hill point and Point Judith. Inundation from a 60 cm (2 ft) mean sea level rise will submerge 87 ha of upland, while 645 ha will be submerged by a 244 cm (8 ft) relative sea level rise.

During the predicted relative sea level rise, Federal Emergency Management Agency (FEMA) V- and A-zones will expand in area and experience an increase in storm-surge water depth over present values. By 2020, map analysis indicates that the area flooded (FEMA A- and V-zones) along the south shore of Rhode Island by the 100-year event will be 2132 ha, an increase of 10% over the present area. Combined V- and A-zone area will expand to 2861 ha by 2100, a 47% increase in area over the present. Curves of storm-surge elevation versus return period, updated to reflect a 52 cm sea level rise by 2020 and a 235 cm rise by 2100, indicate a return period for a flood with an elevation of the present 100-year event (approximately 3.6 m) to be 26 years by 2020, and 0.6 years by 2100.

ACKNOWLEDGMENTS

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Y.J. Tsai of Stone and Webster Engineering Corporation, Boston, Massachusetts, provided base maps for the towns of Westerly, Charlestown and South Kingstown. The Dean of Arts and Sciences and the Office of the Director of Research provided funds for purchase of computer equipment.

I wish to thank Jon Boothroyd for the financial support he provided during my years at the University of Rhode Island, and for teaching me how to be a geologist.

To my wife Claudia, who through great personal sacrifice provided me with all forms of support during my years of study, I offer my gratitude and admiration.

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INTRODUCTION

Sea level is presently rising in Rhode Island at a rate of 27 ± 2 cm·100 yrs^{-1} (Hicks and Hickman, 1988; Lyles et al., 1987), and many climatologists predict that as a result of atmospheric warming, the rate of eustatic rise will accelerate during the next century (e.g. Schneider, 1989; Pirazzoli, 1989; Hoffman, 1984; Hansen, et al., 1984; Hoffman, et al., 1983; Revelle, 1983). The effects of a rising sea level on the south shore of the state include: changes in barrier morphology from erosion, inundation and migration; inundation of uplands and headlands bordering coastal lagoons; expansion of coastal areas flooded during storms accompanied by storm-surge, and an increased frequency of occurrence of floods of a given surge elevation.

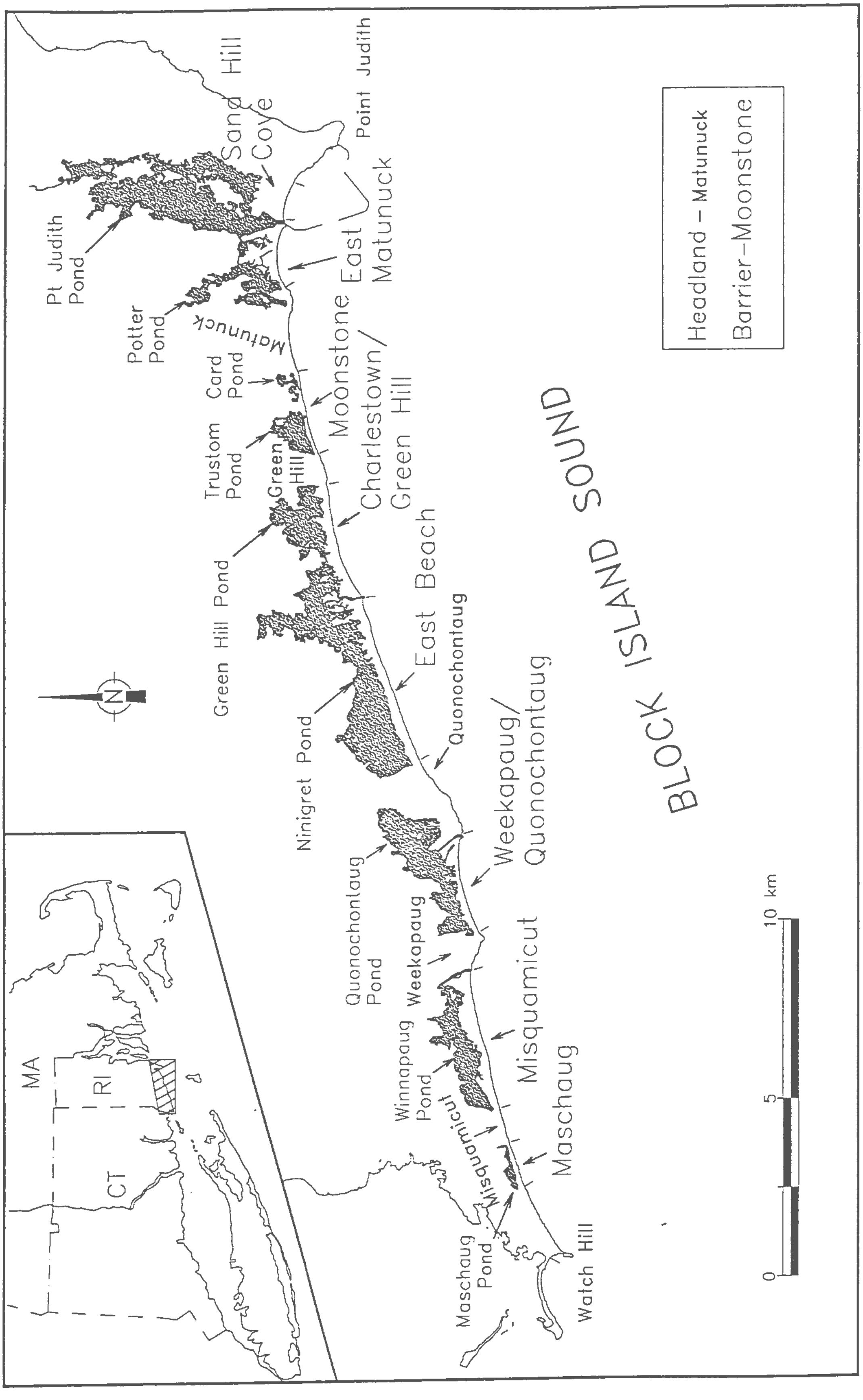
The primary intent of this study is to quantitatively predict future shoreline position and the inland expansion of storm-surge flooding given present predictions for sea level rise during the coming century. Shorelines and flood-zones are mapped for the years 2020 and 2100 based on projected sea level rise values established by the Environmental Protection Agency (Hoffman, 1984). The maps depict how south shore barriers, headlands, and lagoons will be changed by rising sea level in the next 100 years, and provide a graphic look at short-term barrier and headland evolution useful for coastal zone management.

PHYSICAL SETTING

The coastline of Rhode Island between Watch Hill Point and Point Judith is a 33 kilometer-long system of headlands and barrier spits facing south onto Block Island Sound (Fig. 1). The headlands are primarily eroding bluffs of Pleistocene till or glaciofluvial sand and gravel, fronted by sand or gravel beaches. The barrier spits are small relative to other Holocene age barriers of the U.S. east coast, ranging from 1 to 8 kilometers long and 200 to 300 meters wide. Tidal inlets, both natural and jetty-stabilized, maintain tidal exchange with the backing lagoons, providing sediment to well-developed flood-tidal deltas.

The southern Rhode Island shoreline is sediment starved, receiving little or no sediment input from fluvial sources. The barrier spits, headland beaches, and flood-tidal deltas receive sediment from erosion of Pleistocene material found in both headland bluffs and on the shoreface. Sediment is transported landward primarily by overwash of the barrier spits during tropical storms (hurricanes) and severe winter storms (Nor'easters), and by transport through inlets onto the lobes of flood-tidal deltas. Shore-parallel sediment transport occurs on the shoreface, driven by the longshore component of incident waves, while offshore movement of eroded sediment is by return flow. Sediment transported by these processes is deposited onto a topographically variable pre-Holocene

Figure 1. - Location map of the southern shore of Rhode Island indicating names of barriers, headlands, and coastal lagoons.


Sand Hill Cove
Point Judith
Pt Judith Pond
Potter Pond
Matunuck
East Matunuck
Card Pond
Moonstone
Trustom Pond
Green Hill
Charlestown/ Green Hill
Green Hill Pond
East Beach
Quonochontaug
Ninigret Pond
Weekapaug/ Quonochontaug
Quonochontaug Pond
Weekapaug
Misquamicut
Winnapaug Pond
Misquamicut
Maschaug
Maschaug Pond
Watch Hill
BLOCK ISLAND SOUND
Headland - Matunuck
Barrier-Moonstone
N
0
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10 km
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surface primarily made up of glaciofluvial, glaciolacustrine, and ice-marginal deposits. As in other barrier/lagoon shoreline settings, the antecedent topography is a major factor controlling present headland and barrier spit location, as well as lagoon bathymetry and shoreline configuration (e.g. Belknap and Kraft, 1985).

The southern Rhode Island shoreline is microtidal, with a mean tidal range of 1.1 meters and a mean spring range of 1.3 meters (NOAA, 1988). Mean wave height is 0.8 meters (Swanson and Spaulding, 1977). The rate of rise in relative sea level from the period 1931 to 1986 as measured at the Newport, Rhode Island tide gauge was 0.27 ± 0.02 $mm \cdot yr^{-1}$ (27 ± 2 $cm \cdot 100\ yrs^{-1}$) (Lyles, et al., 1987).

METHODOLOGY

Existing Map Information

Mylar topographic maps at scales of 1:4,800 and 1:1,200 used in the preparation of FEMA Flood Insurance Rate Maps were digitized on a Calcomp 9600 digitizing table using AutoCAD™ (Autodesk, 1988) software. These maps were constructed from aerial photography dated 1974 (1:1,200, town of Narragansett) and 1980 (1:4,800, towns of Westerly, Charlestown and South Kingstown). The maps were referenced to the state plane coordinate system grid, with all elevations measured relative to the 1929 National Geodetic Vertical Datum (NGVD). All topography and land-water boundaries, as well as selected roads and structures, were digitized from these maps into eleven separate data files. Topographic entities were assigned elevations (z values) within the files to allow three-dimensional analysis of the map data and to interpolate new contour lines intermediate to those on the base maps. The land-water boundary depicted on the work maps is the waterline at the time of photography, and does not represent mean sea level. Digitizing methods and data sources are described more fully in Boothroyd and Galagan (1990).

The boundaries between FEMA V-and A-zones, and between A-and B-zones were digitized from Flood Insurance Rate Maps (FIRM's) obtained from the Federal Emergency Management Agency (FEMA). These maps are on paper at scales of 1:4,800 and 1:9,600, and depict all present flood zone boundaries based on the 100-year storm of record, which for southern Rhode Island, is the Great New England Hurricane of 1938. Although derived from the above work maps, the boundary lines between flood zones depicted on the Flood Insurance Rate Maps were generalized by FEMA when transferred to the final map format, and consequently did not fit the topography of the base maps. The generalized lines, and the instability inherent in paper maps required some flood zone lines be redrawn to be consistent with topography as digitized from the base maps.

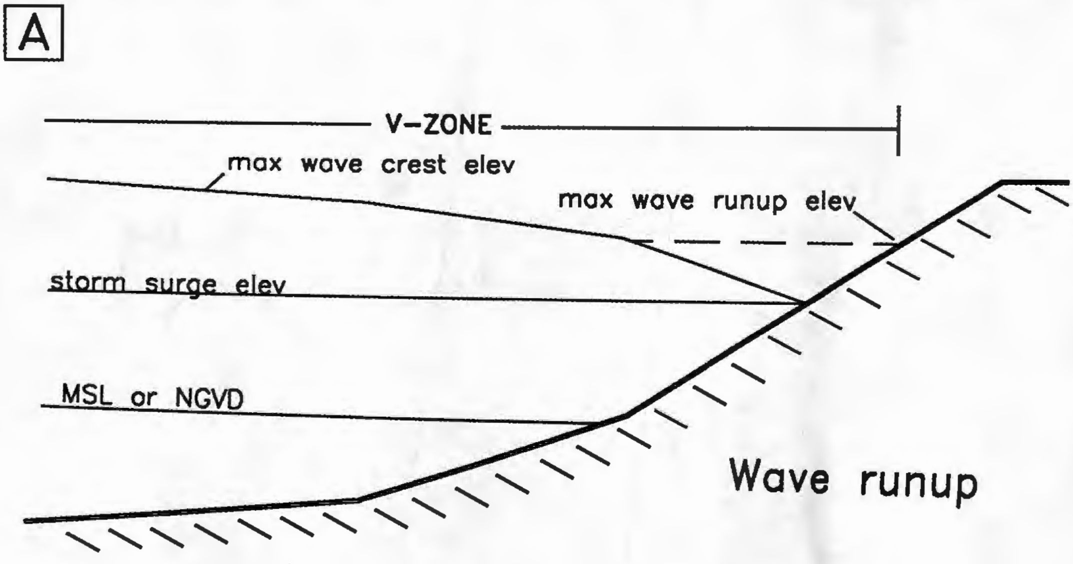
FEMA Flood Zone Designations

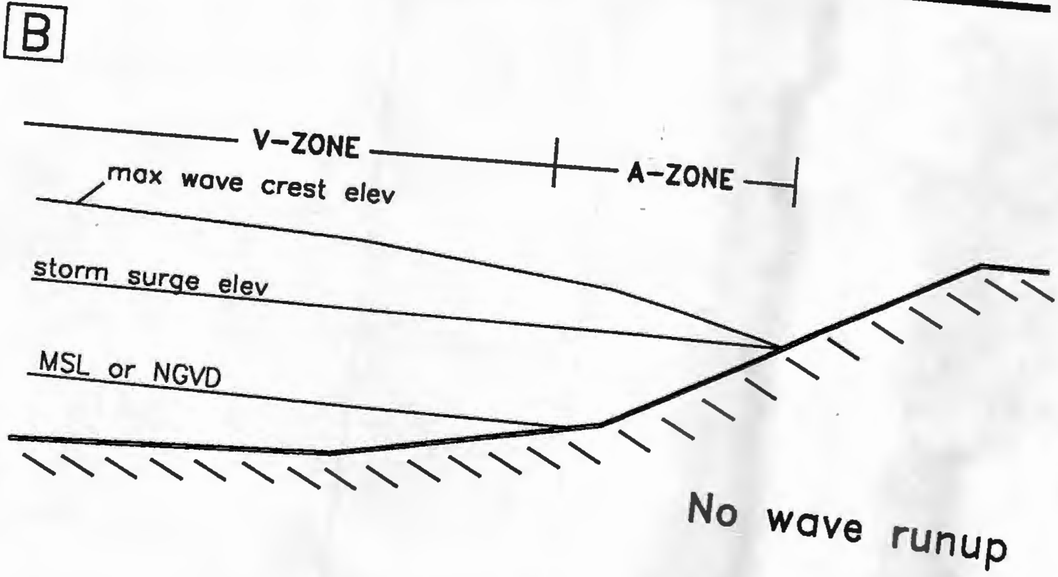
Storm-surge elevations within Block Island Sound were determined for flood insurance studies mandated by the National Flood Insurance Act of 1968, and the Flood Disaster Protection Act of 1973, for use by FEMA in determining coastal areas subject to flooding. For the coast of southern Rhode Island, the storm-surge elevation having a return period of 100 years is determined by fitting a Pearson type 3 curve through a series of annual peak tide levels recorded at Newport, R.I. and New London, CT., as well as high watermark elevations recorded after major storms along the south shore of Rhode Island (C.O.E., 1988). The surge elevation for the 100-year event ranges from 3.3 m above NGVD at Watch Hill Point to 4.2 m above NGVD at Point Judith (Corps of Engineers, 1988). Although FEMA flood-zones are based on the 100-year event, it should be kept in mind that the probability of occurrence of a surge elevation with a long return period is based on few actual data points. In addition, no two hurricane events are alike in the storm-surges they generate, and the flood elevation achieved by a future storm of a magnitude similar to the 1938 event may be greater or lesser.

Determination of flood zone boundaries is a complex process that requires combining accurate topographic and ground cover data with model-derived meteorologic and storm surge data to derive a measure of flood hazard for each area of the coast. Detailed methodology is found in numerous references, including: FEMA, 1986a, b, c, d; FEMA, 1981; Tsai, 1983; Stone and Webster, 1981. In brief, two water levels, or elevations above a vertical datum, are used to describe the inland extent of storm-induced flooding (Fig. 2). The first is the storm-surge or "still water" elevation measured during an event at local tide gauges or after the sea has subsided from watermarks. It is simply the sea surface elevation achieved during a given storm-surge, and does not include the effect of storm-generated waves (Fig. 2b). The second measurement of storm-induced inundation is a combination of wave height above the storm-surge elevation and the elevation of wave run-up on upland surfaces. Maximum trough-to-crest wave height (Hb) is related to water depth (d) by the coefficient 0.78 as expressed by the following equation (FEMA, 1986):

Figure 2. - Schematic cross-sections illustrating FEMA flood-zone determination criteria. See text for discussion.

FEMA Flood–Zone Determination





$$Hb = 0.78d$$

Wave crest elevation (Zw) above mean sea level (Se) is determined by the equation

$$Zw = Se + 0.7Hb$$

which simplifies to

$$Zw = Se + 0.55d$$

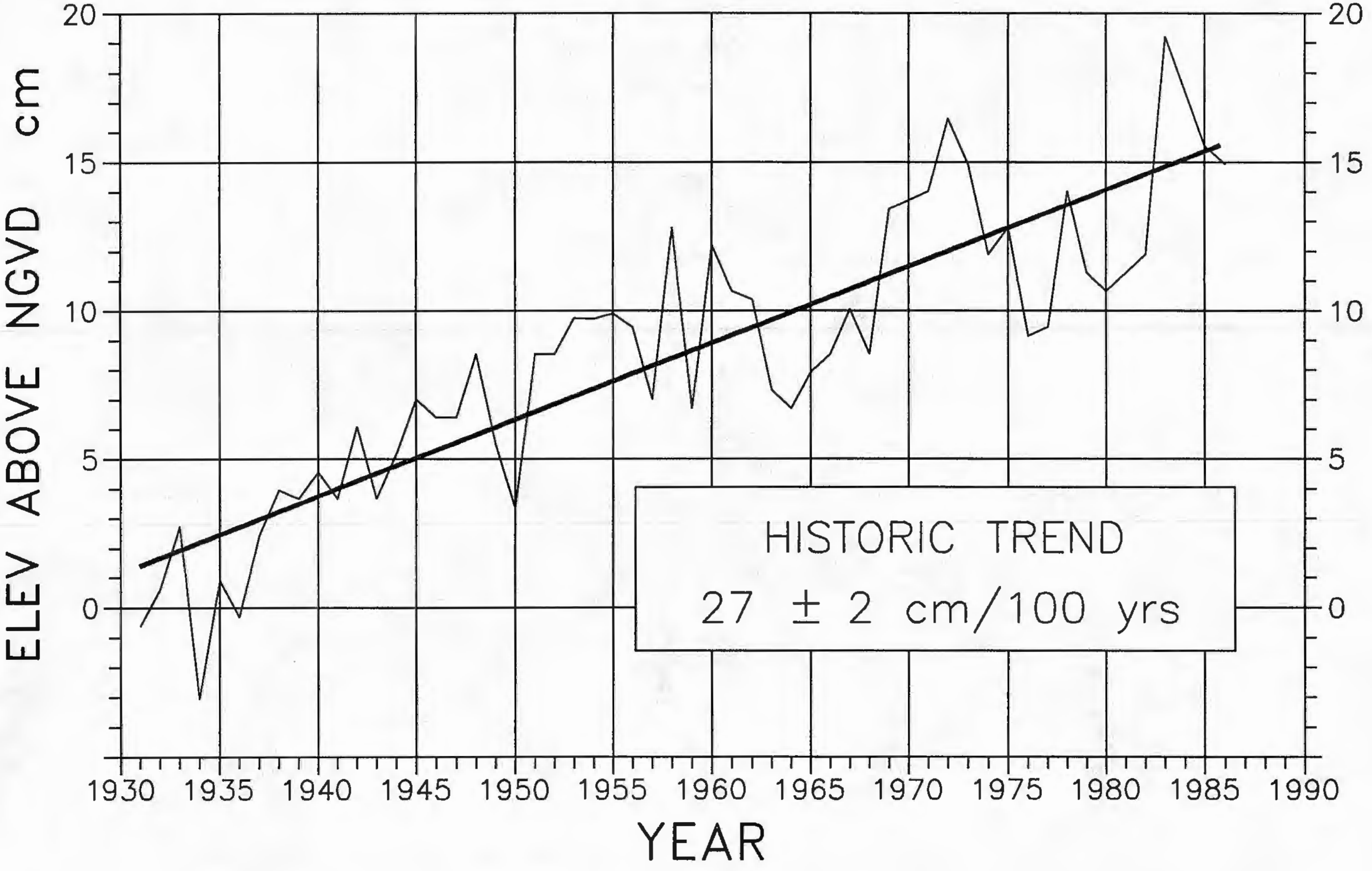
The coefficient 0.7 is that portion of the crest-to-trough distance that reaches above the storm-surge elevation or "still water" level. Wave runup elevation is that elevation attained by wave-driven water onto an upland surface. The additional height attained by the water surface above the storm-surge elevation due to these wave effects constitutes the wave envelope. The upper surface of the wave envelope is drawn (in vertical, shore-normal cross-section) landward along the wave crest elevation line to its intersection with the wave runup elevation line; it then follows the runup elevation line to its intersection with the land surface (Fig. 2a).

Sea Level Rise Projections for Rhode Island

An historic rate of relative sea level rise of 0.27 ± 0.02 $cm \cdot yr^{-1}$ has been determined by Lyles, et al., (1987) by linear regression through annual mean sea level values measured at Newport, RI from the years 1931 through 1986 (Fig. 3). By subtracting a global eustatic rise rate of 0.12 ± 0.03 $cm \cdot yr^{-1}$ (Gornitz and Lebedeff, 1987) from this local historic rate, a rate of local subsidence of 0.15 ±

Figure 3. - Historic trend of annual mean sea level at Newport, Rhode Island. Least squares regression line indicates a rise rate of 0.27 ± 0.02 $\mathrm{cm \cdot yr^{-1}}$ from 1931 to 1986. Data from Lyles, et al., 1987.

HISTORIC TREND OF ANNUAL MEAN SEA LEVEL
NEWPORT, RHODE ISLAND



0.04 $\text{cm}\cdot\text{yr}^{-1}$ is derived. Projected sea levels for this study (Fig. 4) were then calculated by adding a local subsidence value for the period being considered to the eustatic sea level predictions of Hoffman (1984) to arrive at predicted relative sea levels for Rhode Island to the year 2100. Predicted sea levels for the map analysis were taken from the mid-range high scenario curve (Fig. 4) for the years 2020 and 2100 and rounded to the nearest foot for ease of application to the maps. The elevations mapped are for a 60 cm rise by 2020 (2 ft) and a 244 cm (8 ft) rise by 2100. All projections begin at the 1980 sea level elevation above NGVD taken from the historic linear regression line. It should be noted that this 1980 relative "mean" sea level is approximately 14 cm above NGVD.

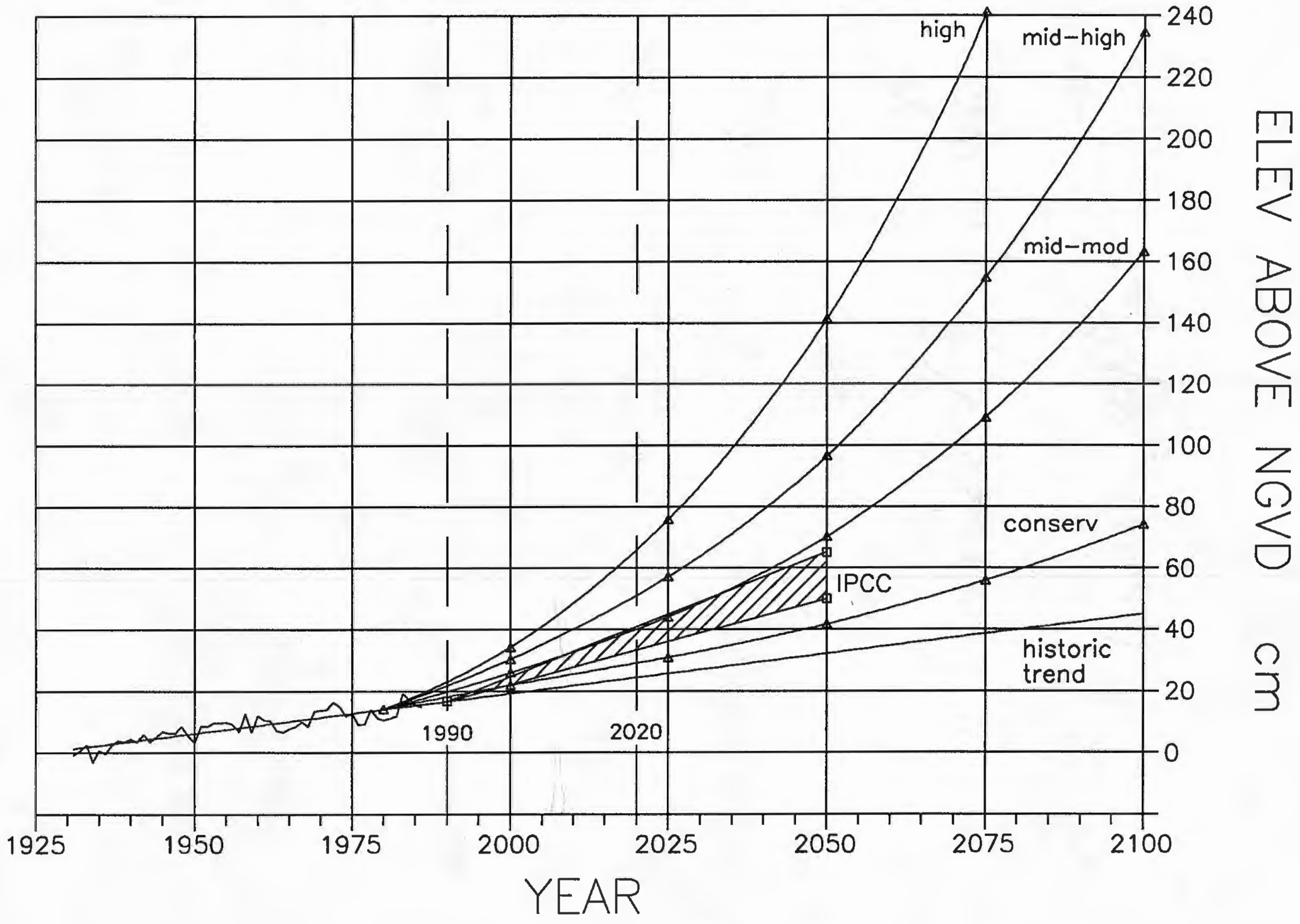
Shorelines Controlled by Frontal Erosion

Shoreline positions fronting barriers and headlands were derived by extrapolating the historic frontal erosion rates of Boothroyd, et. al., (1988) to the years 2020 and 2100. These annual rates of change were determined for 104 individual shoreline segments between Watch Hill Point and Point Judith. The 2020 and 2100 barrier and headland shorelines for a given segment were drawn on the maps by displacing the present waterline landward by an amount equal to 30 or 110 times the annual historic erosion rate for that segment. Projected shorelines to the year 2100

Figure 4. - Sea level rise scenarios derived using data of Hoffman (1984), and IPCC (1989). Historic exptrapolated trend of tide gauge data plus Hoffman's conservative, mid-range moderate, mid-range high and high scenarios plotted. Scenario values are plotted beginning at 1980 value on linear regression line through annual means at Newport, RI (see Fig. 3). Local isostasy of $0.15 \pm 0.04\ \mathrm{cm \cdot yr^{-1}}$ added.

PROJECTED SEA LEVEL RISE AT NEWPORT, RI

Data from Hoffman (1984) and IPCC (1989)



were not displaced far enough to encounter a change in sediment type thus lithofacies were considered to remain constant through the period of erosion, and rates of retreat were not adjusted through time.

Inundated Shorelines

As sea level rises, shorelines not subject to wave erosion, such as those inside Rhode Island coastal lagoons, retreat by inundation. For mean sea level rises of 60 and 244 cm (2 and 8 ft), future lagoon shorelines were drawn either by using existing contours (Narragansett), or generating new topographic contours at 60 and 244 cm (2 and 8 foot) elevations (Westerly, Charlestown and South Kingstown). New contours were generated from existing data using D.C.A. Digital Terrain Modelling software (D.C.A. Engineering Software Inc., 1989). This program creates a grid of points of known elevations and connects them by lines into a triangulated irregular network (TIN) using a triangulation method similar to that described by Davis (1986). In brief, elevation values between known elevations at grid points are interpolated along the lines of the TIN to create contours at any value intermediate to the original contour lines of the map.

Area Measurements

Area measurements of frontal erosion, upland inundation and FEMA flood-zones were obtained directly from the digitized maps. To measure map area, the lines depicting a feature were connected to form a closed polygon, and the area determined using an AutoCAD™ utility. This utility divides the area within the closed polygons into triangles and sums the areas of the triangles. The error contributed by the calculation method is orders of magnitude less than that from the systematic error in digitizing. The estimated systematic error was determined by digitizing a map feature of known area 31 times and then calculating the standard deviation about a sample mean. Three times the sample standard deviation resulted in a 0.3% error in the test area measurements.

Barrier Migration

For this study, barrier spits remained static and no attempt was made to depict migration either landward or upward. The position of projected barrier shorelines was determined for the ocean side by extrapolation of frontal erosion rates, and for the lagoon side by inundation from rising sea level. Barrier area was not included when projected upland inundation areas were measured.

Flood Zones

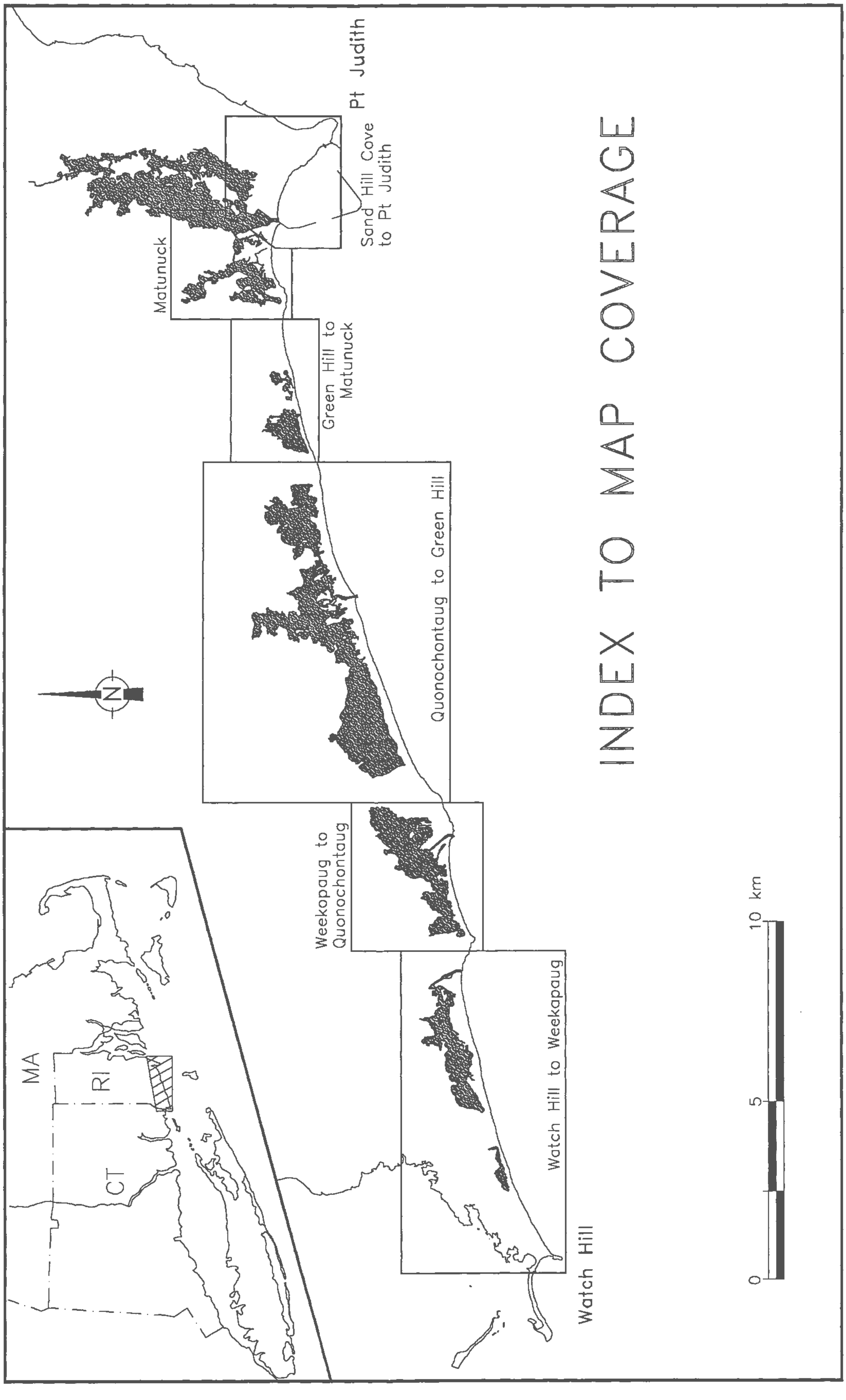
FEMA A-B boundaries for the years 2020 and 2100 were mapped by displacing the present A-B boundary line upslope by 60 and 244 cm (2 and 8 ft), the predicted sea levels from the mid-range high scenario. This resulted in a conservative landward displacement of the A-zone in a few areas where wave runup is significant, and either the A-zone boundary is displaced to an elevation higher than the storm-surge elevation by wave runup, or the present V-zone is the maximum extent of inland flooding, and no A-zone exists. Wave runup and wave height calculations needed to project future V-zone boundaries were not part of this study.

RESULTS

Six maps covering the area of study and depicting present and projected areas of frontal erosion, upland inundation, and FEMA A-zone expansion can be found in the pocket on the back cover. An additional mylar map set (1:10,00 scale) and the digital map data are archived in the Environmental Geology Data Center, Department of Geology, University of Rhode Island. The six maps depict: 1) the present ocean and lagoon shorelines; 2) projected ocean and lagoon shorelines for the years 2020 and 2100 assuming, respectively, a 60 and 244 cm (2 and 8 ft) rise in relative mean sea level; 3) present FEMA A- and V-zone areas; and 4) projected FEMA A-zone expansion under the above scenario. The index map in figure 5 shows the area of coverage of each of the larger maps.

The results of the map analysis are discussed in the following section by addressing each map area separately, beginning at Watch Hill Point and proceeding east to Point Judith (see Fig. 5). Measurements of area change from frontal erosion or upland inundation, and areas newly flooded by expanded FEMA A-zones derived from the maps are listed in tables 1 and 2. Table 1 gives values for the 2020 scenario which consists of 30 years of frontal erosion and 60 cm (2 ft) of relative mean sea level rise. Table 2 lists values for the 2100 scenario which assumes 110 years of frontal erosion accompanied by a 244 cm (8 ft) rise in relative mean sea level.

Figure 5. - Map showing location and coverage of 6 map sheets discussed. Maps can be found in back pocket.



INDEX TO MAP COVERAGE

TABLE 1 - Areas of frontal erosion, inundation, and FEMA flood-zone expansion derived from map analysis. - 2020

MAP	FRONTAL EROSION (ha)	UPLAND INUNDATION (ha)	PRESENT A+V-ZONE (ha)	2020 A+V-ZONE (ha)	% CHANGE A+V-ZONE AREA
Watch Hill to Weekapaug	12	19	430	470	+9 %
Weekapaug to Quonochontaug	6	12	245	265	+8 %
Quonochontaug to Green Hill	24	45	737	804	+9 %
Green Hill to Matunuck	3	NA	139	162	+17 %
Matunuck to Narragansett	4	9	187	213	+14 %
Sand Hill Cove to Pt Judith	1	2	204	218	+7 %
TOTAL	50	87	1942	2132	+10 %

NOTE: 1) A+V-zone areas represent land areas only, and do not include coastal lagoons or inland water bodies. 2) Measurement of map areas determined accurate to +/- 0.3%.

TABLE 2 - Areas of frontal erosion, inundation, and FEMA flood-zone expansion derived from map analysis. - 2100

MAP	FRONTAL EROSION (ha)	UPLAND INUNDATION (ha)	PRESENT A+V-ZONE (ha)	2100 A+V-ZONE (ha)	% CHANGE A+V-ZONE AREA
Watch Hill to Weekapaug	37	138	430	585	+36 %
Weekapaug to Quonochontaug	21	85	245	320	+31 %
Quonochontaug to Green Hill	75	307	737	1145	+55 %
Green Hill to Matunuck	12	37	139	281	+102 %
Matunuck to Narragansett	15	69	187	263	+41 %
Sand Hill Cove to Pt Judith	4	9	204	267	+31 %
TOTAL	164	645	1942	2861	+47 %

NOTE: 1) A+V-zone areas represent land areas only, and do not include coastal lagoons or inland water bodies. 2) Measurement of map areas determined accurate to +/- 0.3%.

Watch Hill Headland to Weekapaug Headland - Plate 1

Watch Hill headland extends eastward from Watch Hill point, where the topography of the Charlestown end moraine is expressed, to the west end of Maschaug barrier, a small barrier backed by the Maschaug Ponds. Further east, Misquamicut headland fronts a low, gently sloping outwash fan extending from the base of the northeast trending Charlestown end moraine. From this headland east to Weekapaug breachway, the Misquamicut barrier spit encloses Winnapaug Pond, a coastal lagoon open to Block Island Sound through the jetty-stabilized Weekapaug inlet. Weekapaug headland is composed of till and has an eroding bluff fronted by a gravel beach.

Rates of frontal erosion range from 20 to 71 $cm \cdot yr^{-1}$ along this section of shoreline, (Boothroyd, et al., 1988) and 30 years of erosional retreat would remove 12 hectares (ha) of headland and barrier sediment from between Watch Hill Point and Weekapaug headland. The effect of a 60 cm (2 ft) mean sea level rise are seen only around the shore of Winnapaug Pond where 19 ha of upland would be inundated. The Maschaug Ponds mapped at an elevation of 1.5 m above NGVD, are not presently open to Block Island Sound and would not necessarily respond to a 60 cm relative sea-level rise. A storm-surge of the magnitude of the present 100-year storm occurring after a 60 cm sea-level rise would expand the present A-zone in this area by 39 ha, flooding a total area of 470 ha. The area most affected by this expanded flood zone would be the glaciolacustrine outwash fan backing Misquamicut headland and the western half of Winnapaug Pond. The steeper terrain of the Charlestown end moraine prevents much expansion of the A-zone along Watch Hill headland.

Extrapolating historic erosion rates to the year 2100 results in 37 ha of frontal erosion, much of which would occur just east of the sea wall protecting the light house compound at Watch Hill point. Projecting historic retreat rates to 2100 would displace the shoreline adjacent to the sea wall up to 100 meters landward.

Inundation by a sea level rise of 244 cm (8 ft) during this time would have a significant effect on the area, inundating 138 ha of upland, including large areas of the Misquamicut headland, and linking Winnapaug and the Maschaug Ponds across the back side of the headland. Watch Hill headland would be affected little by even this amount of sea level rise due to its steeper terrain and higher elevation.

A storm-surge elevation of the magnitude of the present 100-year event occurring after a 244 cm (8 ft) relative sea level rise would flood everything in this area up to the base of the Charlestown end moraine, a total of 585 ha, and an increase in area of 36% over the combined present A- and V-zones. Most of this A-zone expansion would occur across Misquamicut headland and the back side of Winnapaug Pond.

Weekapaug Headland to Quonochontaug Headland - Plate 2

Weekapaug headland is primarily till and fronted by a 2 to 4 meter high till bluff, with one small outcrop of Narragansett Pier granite within the headland. The till of the headland continues east, backing Quonochontaug Pond with a steep shoreline. Small outcrops of Narragansett Pier granite are also found at the back edge of the lagoon. The pond is enclosed by the Weekapaug-Quonochontaug barrier spit where dune elevations increase in height from 3 to 4.5 m (10 to 15 ft) at the west end, to 4.5 to 6 m in height (15 to 20 ft) at the eastern terminus. The east end of the barrier fronts a flood-tidal delta fed by the Quonochontaug inlet. Quonochontaug headland is backed by glacial ice-marginal fluvial sand and gravel.

Frontal erosion of the Weekapaug/Quonochontaug barrier increases from 0.31 $m \cdot yr^{-1}$ at the west end to 0.76 $m \cdot yr^{-1}$ in the east (Boothroyd, et al., 1988). Extrapolation of the historic retreat rates to 2020 would remove 6 ha from this section of shoreline. This west-to-east increase in erosion rate is seen on other south shore barrier spits.

The upland area surrounding the relatively steep Quonochontaug Pond shoreline inundated by a 60 cm (2 ft) sea level rise would be 12 ha, approximately one-half the area lost from frontal erosion along this shoreline segment during the same time period. The general configuration of the lagoon shoreline would change little under this scenario.

The present FEMA A-B boundary surrounding Quonochontaug Pond is a discontinuous line broken in areas where wave runup onto the steep glacial till topography displaces it beyond the storm-surge elevation, creating a FEMA V-to-B boundary where the wave envelope intersects the land. Since recalculation of wave runup was not a part of this study, expansion of the A-zone in this and other areas where wave runup is significant, is conservative. The area surrounding Quonochontaug Pond flooded within the combined present A- and V-zones is 245 ha. This would expand to 265 ha by 2020, an increase of 8% that is evenly distributed within a thin strip around the lagoon shoreline.

Extrapolating frontal erosion rates to the year 2100 along this headland/barrier section of shoreline removes 21 ha of sediment, primarily from the Weekapaug/Quonochontaug barrier. The shoreline at the east end of the barrier would erode landward approximately 100 meters by this time. A 244 cm (8 ft) rise in relative mean sea level would inundate a relatively small 85 ha around the shore of Quonochontaug Pond, most of this occurring as an expansion of the east end of Quonochontaug Pond onto the back side of Quonochontaug headland.

A storm-surge of the depth of the 100-year storm after a 244 cm (8 ft) rise in mean sea level would flood 320 ha of upland around the lagoon shore, expanding the present A-zone by 31%. No new large areas would be included in this expanded A-zone, the expansion occurring equally around the edge of the pond.

Quonochontaug Headland to Green Hill Headland - Plate 3

Ninigret Pond is the largest coastal lagoon on the south shore, covering approximately 690 ha. It is fronted by the East Beach barrier spit which extends 4.9 km east from Quonochontaug headland, and by the Charlestown/Green Hill barrier extending west from the Green Hill headland. The two spits are separated by the Charlestown Breachway, a jetty-stabilized inlet. Green Hill Pond is an adjacent coastal lagoon to the east of Ninigret, and connected to it by a narrow channel just east of the Ninigret flood-tidal delta. The deposits flanking both ponds are primarily glaciofluvial, some portions of which are gently sloping plains, while others contain large ice-block depressions and areas of till. Green Hill headland is composed of glacial till and fronted by a sandy beach. The headland is eroding at a rate similar to south shore barriers (Boothroyd, et al., 1988) and has a small seaward expression.

Thirty years of frontal erosion would remove 24 ha from the shoreline reach between Quonochontaug Headland and Green Hill headland, with most of this loss coming from the two barrier spits. An accompanying 60 cm (2 ft) mean sea level rise would inundate a relatively small area of upland (45 ha), expanding Ninigret and Green Hill Ponds slightly landward, but leaving their general shoreline configurations unchanged. The effects from a storm-surge of the magnitude of the present 100-year event occurring after a 60 cm (2 ft) relative sea level rise would expand the present A- and V-zones from 737 ha to 804 ha, a 9% increase. The area most affected by upland inundation and A-zone expansion is within Ninigret Park on the glacial outwash fan surface behind Ninigret Pond.

Frontal erosion during the coming 110 years would remove 75 ha of sediment from this shoreline reach. Because the barrier shorelines are retreating at a greater rate than the adjacent headlands, and since the retreat rate increases away from the headlands, the effects of this erosion would be an increase in the concavity of the shoreline reach between Quonochontaug and Green Hill Headlands.

Upland inundation in the area surrounding Ninigret and Green Hill Ponds after a 244 cm (8 ft) relative mean sea level rise would submerge 307 ha. Three areas would be most affected: 1) the eastern portion of Quonochontaug headland would be flooded from the east by an expanded Ninigret Pond, and from the west by Quonochontaug Pond; 2) the Ninigret Pond shoreline along the outwash plain would be displaced up to 700 meters landward, inundating portions of Ninigret Park; and 3) the relatively low glacial outwash plain directly behind Green Hill Pond would be inundated.

Expansion of the A-zone in the year 2100 after a 244 cm (8ft) relative sea level rise occurs in the areas of the gently sloping glacial outwash plains. Combined A- plus V-zone area would be a total of 1145 ha by 2100, a 55% increase from the present area. This expanded flood-zone includes an area of U.S. Route 1 in the northern part of the map.

Green Hill Headland to Matunuck Headland - Plate 4

The surface of the sandy glacial till of Green Hill headland is approximately at the elevation of present mean low water, thus allowing formation of eolian dunes and washover fans on this till headland (Boothroyd, et al., 1986). This low headland composed of sediment of high sand content erodes at rates similar to south shore barriers (Boothroyd, et al., 1988), and responds similarly to barriers during major storms. Moonstone barrier extends east from the headland, and fronts Trustom Pond, a small (72 ha) coastal lagoon open periodically to Block Island Sound through a nonstabilized inlet. Card Ponds, also fronted by Moonstone barrier, are a series of small (24 hectares total) coastal lagoons, also periodically open through a temporary inlet. (When the base maps were made, the inlets to Trustom and Card Ponds were closed and the water elevations in the ponds were mapped at 160 cm above NGVD.) Till deposits surround the west half of Trustom Pond forming a topographically irregular surface resulting in a steep lagoon shoreline. The eastern half of Trustom and all of Card Ponds, as well as the eastern portion of Matunuck headland, consist of a sand and gravel glacial outwash plain.

Thirty years of frontal erosion between Green Hill and Matunuck headlands would remove 3 ha of sediment. The relatively high rate of erosion along Green Hill headland (equal to many barrier spits) indicates that it will retain its present configuration relative to the adjacent barriers as it retreats landward.

(Upland inundation from a 60 cm (2 ft) rise in relative mean sea level can not be evaluated for this area because of the high water elevation (160 cm) mapped in Trustom and Card Ponds.)

Storm-surge flooding from an event of the magnitude of the present 100-year storm following a 60 cm (2 ft) mean sea level rise would flood 162 ha, increasing the present A- plus V-zone area by 17%. The increase occurs primarily in the area of glacial outwash plain between the two ponds.

Frontal erosion rates extrapolated to 2100 would remove 12 ha along this shoreline segment. Green hill headland and the western portion of Matunuck headland, eroding at approximately the same rate as Moonstone barrier, would maintain the present relationship with the barrier, and not protrude further seaward.

Inundation of the upland surrounding Trustom and Card Ponds after a 244 cm (8 ft) rise in relative mean sea level would combine the two ponds into a single coastal lagoon, submerging 37 ha. Most of this submergence would occur in the area between the two ponds with little change elsewhere. Storm-surge flooding of the glacial outwash plain backing this single, enlarged lagoon after a 244 cm (8 ft) relative sea level rise would inundate an area 102% larger than that flooded by the current 100-year event, a 142 ha expansion. This flood zone expansion would occur largely behind the present Card Ponds, as well as over large portions of the Matunuck headland.

Matunuck Headland to East Matunuck Barrier - Plate 5

The eastern portion of Matunuck headland is a 4- to 6-meter high bluff of ice-marginal glaciofluvial gravel of the Saugatucket system. Seaweed Cove and other small ponds within this part of the headland are flooded ice-block depressions. This contrasts with the eastern portion of the headland (Plate 4) which consists of a glaciofluvial sand and gravel outwash plain. The bluff of the eastern part of the headland is fronted by a boulder beach and a intertidal erosional gravel terrace up to 100 m wide (Boothroyd, et al., 1986). The East Matunuck barrier extends 1.8 km east from the headland, its western end fronted by a gravel beach, which becomes sandy at its eastern terminus at the Point Judith inlet. Landward of the East Matunuck barrier, Potter and Point Judith Ponds occupy ice-block depressions within the glaciofluvial deposits of the Saugatucket and Pettaquamscutt systems

(Kaye, 1960; Schafer, 1961).

Historic frontal erosion rates for the east-facing portion of Matunuck headland are as high as many erosion rates for south shore barriers, ranging from 94 to 101 $cm \cdot yr^{-1}$ (Boothroyd, et al., 1988). When projected to the year 2020, 4 ha of sediment are removed from this part of the Matunuck headland and the East Matunuck barrier spit.

Inundation of the upland surrounding Potter and Point Judith Ponds by a 60 cm (2 ft) mean sea level rise submerges a relatively small 9 ha. This small amount of inundation is because lagoon shoreline slopes are as great as 18° in many parts of the two ponds. The present lagoon shorelines would be changed very little under this scenario.

Storm-surge elevation inside Potter Pond during the present 100-year storm of record is 3.6 m (11.7 ft), and the combined FEMA A- and V-zones cover an area of 187 ha. This area would expand to 213 ha for the same event occurring after a 60 cm (2 ft) mean sea level rise, an increase of 14%. This expansion would mean a small landward displacement of the present A- to B-zone boundary due to the steep terrain, but since this displacement occurs over a relatively long lagoon shoreline, the total increase in area is large.

Extrapolating historic frontal erosion rates to the year 2100 shows a continued rapid retreat of the eastern end of Matunuck Headland, and when combined with a 244 cm

(8 ft) mean sea level rise, a drowning of large portions of the headland. Frontal erosion during the next 110 years would remove 15 ha from the headland and barrier, while an additional 69 ha of upland would be inundated. This amount of sea level rise would cause Potter Pond to expand, inundating large portions of the eastern half of Matunuck headland, and leaving islands of glacial till separated from the mainland.

A storm surge occurring after a 244 cm (8 ft) mean sea-level rise would flood 263 ha of land in this area, expanding the area presently flooded by the 100-year event by 41%. As with the scenario for storm-surge flooding in the 2020 scenario, expansion of the A-zone would not occur in one single area, but would creep landward a small distance around the perimeter of the lagoons.

Sand Hill Cove Barrier to Point Judith Headland - Plate 6

This map area includes the eastern tip of the East Matunuck barrier (from the Narragansett town line to the Point Judith inlet) to the Point Judith headland. Base maps from which this area was mapped cover only the town of Narragansett and topography and FEMA lines depicted therein do not agree with those of the adjacent South Kingstown map along the boundary between the two towns.

The Sand Hill Cove barrier extends east 1.4 km from the Point Judith inlet to Point Judith headland, and is wholly contained within the Harbor of Refuge. The barrier is fronted by a sandy beach and topped by a 4.5 to 6 m high (15- to 20-ft) foredune zone. A relict flood-tidal delta occupies the area directly behind the barrier, large portions of which have been modified to accommodate the fishing port and state pier at Galilee. Point Judith headland forms a 3 to 6 meter (10- to 20-ft) high bluff composed of silt- and clay-rich till of the Point Judith end moraine (Boothroyd, et al., 1986). The seaward tip of the headland is armored by a seawall.

Frontal erosion along this barrier and headland segment would remove 1 ha of sediment when extrapolated to the year 2020. Within the harbor of refuge, erosion predominates along the Sand Hill Cove barrier to the headland approximately 1 km from the east jetty of the harbor. From this point east to the east jetty, the historic trend shows deposition to be the predominate mode, accreting sediment at rates from 0.3 to 1.5 $m \cdot yr^{-1}$ (Regan, 1976). The result of this alongshore change from long-term erosion to deposition is a realignment or clockwise "rotation" of the shoreline through time within the Harbor of Refuge.

Upland inundation of the Point Judith end moraine after a 60 cm (2 ft) rise in mean sea level will submerge 1.9 ha, mostly along the natural or non-engineered portions of the Point Judith Pond shoreline. The west end of Sand Hill Cove barrier is entirely engineered with sea walls and pier facilities, and pier elevation at the mapped waterline ranges from 1.5 to 2.4 m (5 to 8 ft) above NGVD.

The present 100-year base flood elevation ranges from 3.8 m (12.6 ft) within the Harbor of Refuge to 3.0 m (9.8 ft) inside Point Judith Pond (FEMA, 1986c). Adding a relative mean sea level rise of 60 cm (2 ft) to this storm surge elevation would result in flooding of 204 ha within this map area, an increase of 7% over the present 100-year flood area.

Frontal erosion and accretion rates extrapolated to 2100 show a continued realignment of the shoreline within the Harbor of Refuge and result in a total sediment loss of 4 ha. The shoreline continues its realignment as accretion occurs along the eastern segment of shoreline within the Harbor of Refuge.

Inundation by a relative mean sea level 244 cm (8 ft) higher than present would flood 9 ha of upland along the Point Judith end moraine.

The base flood elevation accompanied by the 100-year event after a 244 cm (8 ft) sea level rise would flood a total of 267 ha of upland and barrier, a 31% increase over present FEMA A plus V flood area.

Watch Hill Point to Point Judith

Frontal erosion along the entire 33 km shoreline reach would remove a total of 49 ha of material by the year 2020, and 163 ha by 2100. A 60 cm (2 ft) rise in relative mean sea level would submerge 87 ha of upland within the same area. For a 244 cm (8 ft) rise in relative sea level, 645 ha of upland would be inundated.

The storm surge occurring during a storm of the magnitude of the present 100-year storm for Rhode Island would flood 1941 ha of coastal land within the study area. When a mean sea level rise of 60 cm (2 ft) is added to this surge elevation, the area flooded increases 10% to 2132 ha. Adding a 244 cm (8 ft) sea level rise to the same storm-surge would flood 2861 ha, a 47% increase from the present.

DISCUSSION

Sea Level Rise Projections

Projections of future sea level rise are based on complex climate models that contain the assumption that the atmospheric concentration of CO_2 and other "greenhouse" gases will double within the next century (Charney, 1979; Smagorinsky, 1982). CO_2, along with water vapor, methane, nitrous oxide and chlorofluorocarbons, absorb terrestrial infrared radiation emitted from the surface of the earth, preventing its escape to space. The energy absorbed is then reradiated from the atmosphere to the surface, enhancing surface warming. This warming may in turn create positive feedback mechanisms within the global climate system to further increase surface warming. Models run without the effect of positive feedback show that a doubling of CO_2 would result in a 1.2° C increase in average global surface temperature (Hoffman, 1984). When feedback mechanisms are accounted for, some models predict an average global temperature increase for 2100 as high as 4.5° C (Hoffman, 1984; Charney, 1979).

By comparison, the range in global mean temperature during the last 1-million years has been approximately 5° C. During the time of peak warming of the present interglacial period, 5,000 to 8,000 YBP, mean temperature is estimated to have been 0.5 to 1.0° C warmer than present (Hansen, et al., 1981). The Cretaceous Period, (135 to 65 million YBP) possibly the warmest time during the

Phanerozoic, was a time when average global surface temperatures were an estimated 6 to 14° C warmer than present (Barron, 1983).

The range in global temperature increase suggested by climate models from a doubling of CO_2 was used by the Environmental Protection Agency (EPA) (Hoffman, et al., 1983) to calculate a range of corresponding sea level rise scenarios. Three models were used interactively by the EPA to derive sea-level rise projections to the year 2100 (Hoffman, et al., 1983). The first, a world-energy and CO_2-emissions model, used as its input, energy demand, energy prices, and energy supplies in the following six categories: oil, gas, coal, hydroelectric, solar and nuclear. The model output was an estimate of global CO_2 emissions to the year 2100. Factors affecting this model include economic growth rate and the future production costs for nuclear energy. If for example, nuclear fusion is made available as an affordable energy source in the next half century, a significant decrease in CO_2 emissions could result.

The second model used by the EPA traced the global transfer of carbon between terrestrial and oceanic reservoirs. Model input was the estimate of global fossil-fuel carbon emissions from the world energy and CO_2 emissions model described above. Output was atmospheric CO_2 concentrations on a five year interval for the period 1980 to 2100. The carbon cycle model incorporates assumptions about the fraction of the total CO_2 budget that is retained in the atmosphere as opposed to that retained in the oceans, since it is atmospheric concentration, not terrestrial or oceanic concentration that controls the degree of greenhouse warming taking place.

The third component of the sea level projections is the atmospheric temperature model. This part of the model estimates the temperature increases associated with atmospheric CO_2 increases, translates these temperature increases in the atmosphere to ocean water temperature increases, which in turn are translated into thermal expansion of sea water and finally into sea-level rise. The model assumes that sea-surface temperature will be the same as atmospheric temperature at the ocean surface, and ocean-surface water temperatures are derived from a time versus atmospheric temperature relationship established by the model. Sea level rise estimates were derived by calculating thermal expansion of ocean water due to heat flux from the atmosphere into the worlds oceans.

Added to the thermal expansion effects were the results of a general circulation model that predict a contribution to sea level by glacial ice of 13.5 $mm \cdot yr^{-1}$ as a result of atmospheric CO_2 doubling (Hoffman, et al.; 1983).

The resulting global sea level rise estimates for approximately the next one-hundred years (to the year 2100) range from a conservative 56.2 cm above the 1980 level, to a high projection of 345.0 cm (Hoffman, et al., 1983; Hoffman, 1984). For this study, the EPA (Hoffman, 1984) mid-range high scenario was chosen (216 cm rise to 2100). Both mid-range scenarios are based on a 3° C rise in mean global surface temperature by 2100. Hoffman (1984) states that future sea level rise is "most likely" to fall in the area of the mid-range estimates (144 to 216 cm by 2100). For the Rhode Island shore, the mid-range high scenario would result in a seven-fold increase in the rate of sea level rise over historic rise rates (see Fig. 4).

Clearly there are many uncertainties in the current projections of future sea level rise, and the models are being continually refined to produce better estimates of the probability of a specific rise. Estimates coming from work presented at two recent meetings (IPCC, 1989; Kerr, 1989) suggest that global sea level rise values in the range of 25 to 40 cm's by 2050 may be more realistic. At this time it would be prudent to be aware of the potential impacts from any amount of sea level rise, and to prepare for it to a degree commensurate with the probability of its occurrence. As the estimates are refined, the response can be adjusted accordingly.

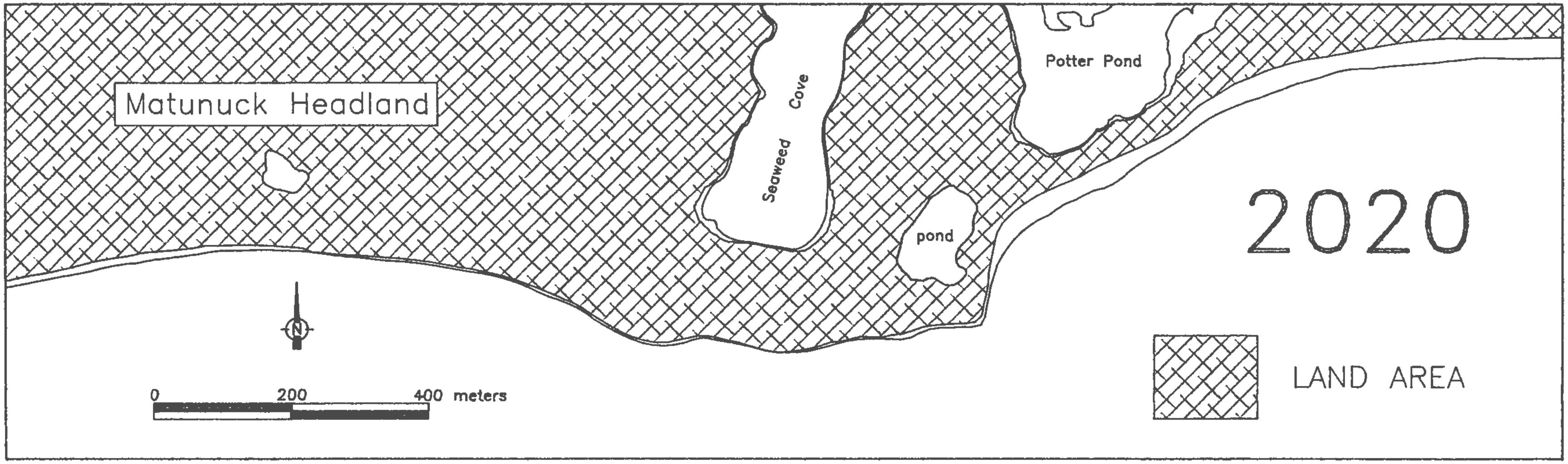
Frontal Erosion

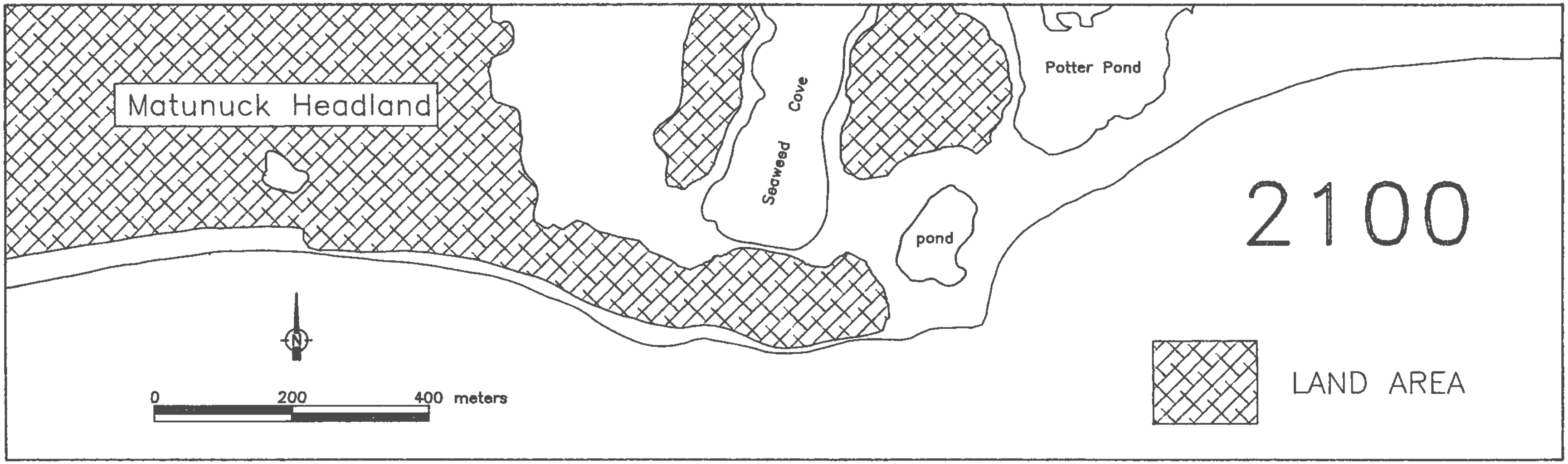
Extrapolation of historic erosion rates defines a future barrier and headland shoreline configuration not markedly different from that of the present. Weekapaug, Quonochontaug, and the eastern portion of Matunuck headland, currently the most prominent headlands in terms of seaward expression, will become more prominent as they continue being left behind by adjacent barriers. In contrast, the Misquamicut and Green Hill headlands will continue their present relationship to adjacent barriers, eroding at rates as high as those barriers, and allowing sediment to bypass.

Figure 6 is a map of a portion of the Matunuck headland in its present configuration with the 2020 and 2100 land areas superimposed. Extrapolated erosion to 2020 erodes up to 30 m of shoreline on the east-facing side of the headland, accentuating its protrusion from the adjacent barrier shoreline. When 110 years of frontal erosion is combined with a 244 cm (8 ft) rise in sea level, portions of the headland are cut off from the mainland by inundation from the lagoon side over much of the eastern part of the headland, flooding much of the lower portions and creating islands of glacial till. Much of Matunuck headland is armored with engineering structures and rip-rap meant to protect it from frontal erosion, yet the map analysis shows that this area is subject to significant change by inundation from Potter Pond.

Frontal erosion along the entire south shore study area is predicted to account for 49 ha of land loss when projected to 2020, and 163 ha by the year 2100 (Tables 1 & 2). When compared with land lost by upland inundation from

Figure 6. - Map of the eastern part of Matunuck headland illustrating 2020 and 2100 land areas relative to present area. 2020 land area is after a 60 cm (2 ft) mean sea level rise and 30 years of frontal erosion. 2100 land area is after 244 cm (8 ft) mean sea level rise and 110 years of frontal erosion. See text for discussion.


Matunuck Headland
Seaweed Cove
Potter Pond
pond
2020
N
0
200
400 meters
LAND AREA


Matunuck Headland
Seaweed Cove
Potter Pond
pond
2100
N
0
200
400 meters
LAND AREA

a rising sea level, loss through frontal erosion is approximately 57% of the inundation losses for 2020 and 25% of the projected 2100 inundation loss.

As stated earlier, erosion rates used are from the historic record, and sea level rise rate during the period of record was considerably slower than that projected by the EPA for the coming century. Presently, no direct correlation between sea level rise rate and the rate of shoreline erosion has been established for Rhode Island headlands and barriers. The underlying assumption is that shoreline retreat proceeds by "permanent" removal of sediment from dunes and headland bluffs by wave energy from middle latitude and tropical cyclones passing within proximity of the Rhode Island shore. This storm-wave energy is expended within a finite area of the dune and bluff system, and when considered over long time spans, rising sea level controls the position and rate of landward translation of this high-energy area, but storm frequency and intensity control the amount of erosion taking place. It is assumed that an increased rate of sea level rise will increase erosion along the south shore, but it is not known at what rate this increase will occur.

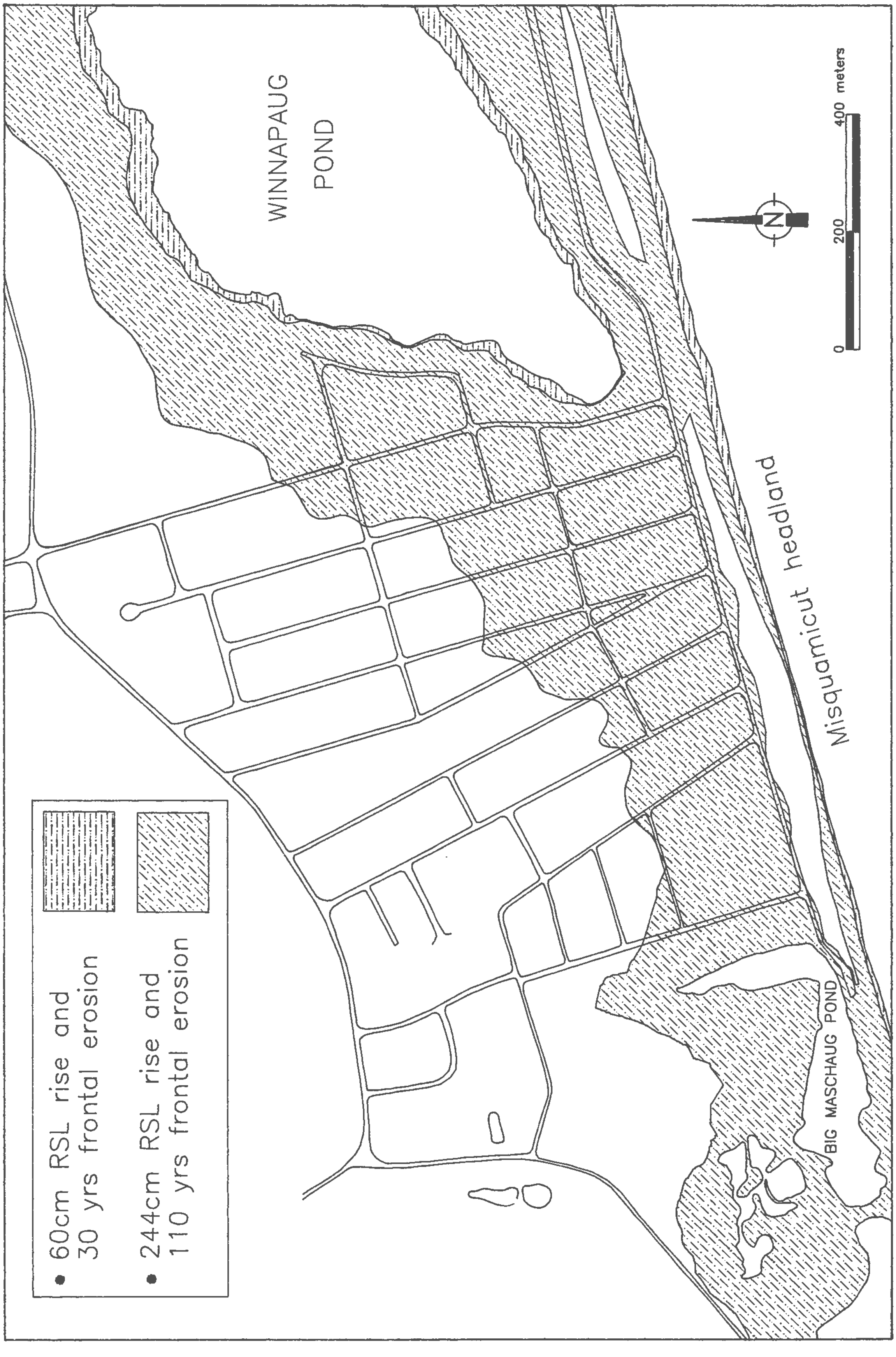
The significance of a comparison between land area lost to erosion with that lost to inundation is that future upland submergence will become as serious a problem as frontal erosion has been historically. To date, erosion has been the perceived problem for south shore barriers and headlands, and retreat rates are incorporated into the state Coastal Resources Management Council's (CRMC) Coastal Resources Management Program (CRMC, 1990). Given the predictions for upland inundation, it seems that future CRMC programs should consider appropriate additional setback requirements for inundation.

Upland Inundation

Upland inundation during rising sea level is a function of the rate of rise and the slope of the upland terrain. Map analysis shows that the largest areas of submergence will occur in places of lowest slope, in this case glacial outwash plains, and that in areas of glacial till and ice-block depressions, inundation will be minimal. Slopes of glacial outwash plains are 0.5° (Misquamicut headland) and 0.6° (Green Hill headland), while slopes in areas of ice-block depressions such as surrounds Potter Pond are as high as 18°. At Misquamicut, for every 10 cm of sea level rise, 12 m of linear shoreline displacement will occur, while the same rise will displace the 18° Potter Pond shoreline only 0.3 m. Thus the effects of inundation are localized and each area should be addressed individually.

Figure 7 is a map of the Misquamicut area depicting the land inundated by a 60 and 244 cm (2 and 8 ft) rise in relative mean sea level. The changes from a 60 cm rise are limited to a slight expansion of Winnapaug Pond, however the submergence from a 244 cm (8 ft) rise would cover large

Figure 7. - Map of Misquamicut, RI area depicting land inundated by a 60 cm (2 ft) mean sea level rise and 30 years of frontal erosion, and by a 244 cm (8 ft) mean sea level rise and 110 years of frontal erosion. See text for discussion.


• 60cm RSL rise and 30 yrs frontal erosion
• 244cm RSL rise and 110 yrs frontal erosion
WINNAPAUG POND
Misquamicut headland
BIG MASCHAUG POND
N
0
200
400 meters

portions of the headland, joining Maschaug and Winnapaug ponds. The Misquamicut headland is unique in that the headland area is of a lower elevation than the fronting dunes, and subsequently it responds much like a barrier, including being subject to overwash from storm-surge. Overwash during the 1938 hurricane deposited sediment in washover fans up to 200 meters inland of the waterline along Misquamicut headland. Yet, since this area is a headland by definition, it is subject to different, less stringent land-use regulations than barriers. This situation is compounded by the presence of developed residential and commercial properties in the area, something that has occurred possibly through the false sense that headlands are safer places to build than barriers. It is clear that the Misquamicut area will become an even less-safe place to build in the future, and that regulations concerning construction need to be revised.

Storm-Surge Flooding

Storm-surge is the elevation of the ocean surface above a given astronomical tide level resulting from the effect of a storm. It is measured as the difference between actual sea-surface elevation during a storm, and the sea-surface elevation associated with the astronomical tide at the time. Storm surges result from several factors, but are primarily a function of the high wind stress and reduced atmospheric pressure associated with extratropical and tropical storms. The exchange of momentum between onshore storm winds and the surface waters of the coastal ocean creates an onshore flow that "sets up" a water mass against the coast; while reduced atmospheric pressure, or inverse barometer effect, can cause a 1 cm rise in the sea surface for each 1 millibar drop in local atmospheric pressure (Tsai, 1983). While set-up and the inverse barometer effect are the primary forces causing elevated water levels during storms, probably the most important factor in the peak elevation attained by any individual surge event is the time and phase of the tide relative to the time of storm passage. The severity of flooding in Rhode Island during the September 21, 1938 hurricane was in part because the storm came onshore at approximately spring high tide (Nichols and Marston, 1939). Wind speeds of 195 to 242 kph (121 to 150 mph) accompanied by a barometric pressure drop of approximately 56 mb at the storm center combined to create a storm surge along the south shore of 3.0 to 4.6 m (10 to 15 ft) (Nichols and Marston, 1939).

Flood-zone Expansion

One result of a higher sea level on present flood zones will simply be to increase the elevation achieved by any given storm-surge by the amount of sea level rise. This will increase the predicted floodwater depth in the current A- and V-zones and expand the current A-zone into new areas. This A-zone expansion will place many areas that are presently outside the range of the 100-year storm inside the newly enlarged A-zone. As with upland inundation, those areas affected most by this expansion will be the gently sloping glacial outwash plains.

Figure 8 is a map of the Misquamicut area which illustrates FEMA A-zone expansion. The area within the present V- and A-zones and the area of expansion of the A-zone for the two sea level rise scenarios are shown. The 60 cm (2 ft) relative sea level rise extends the A-zone as much as 150 meters landward, while the 244 cm (8 ft) rise scenario expands the present A-zone area by one-third. The present A-zone boundaries depicted on the Flood Insurance Rate Maps (FIRM) will become out of date quickly in this and other areas as sea level rises, and properties not within the present A-zone will become subject to A-zone minimum elevation regulations, requiring that the FIRM's be updated.

Increased Storm-surge Frequency

A second result of rising sea level on storm-surge flooding is the increase in frequency of occurrence of a flood attaining the elevation of the present 100-year storm. Figure 9 is a graph of storm-surge elevations plotted as a function of return period in years. The bottom curve is based on present values for the central part of the south shore of the state and includes water elevations for mean spring high water (MSHW), the 10-, 50-,

Figure 8. - Map of Misquamicut, RI area depicting area flooded by storm-surge of the elevation of the present 100-year event, plus expansion of FEMA A-zone after a 60 and 244 cm (2 and 8 ft) rise in mean sea level. See text for discussion.

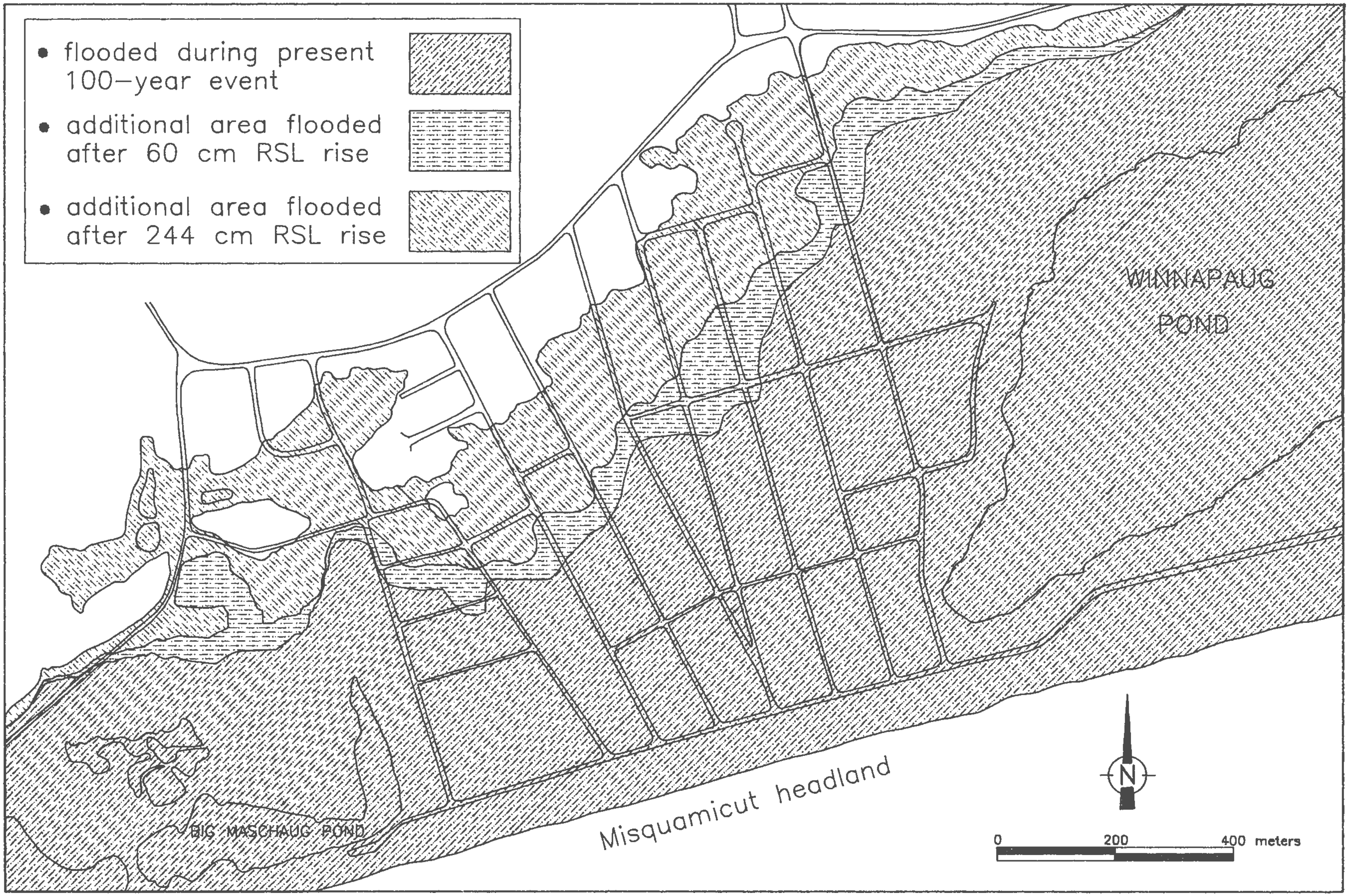
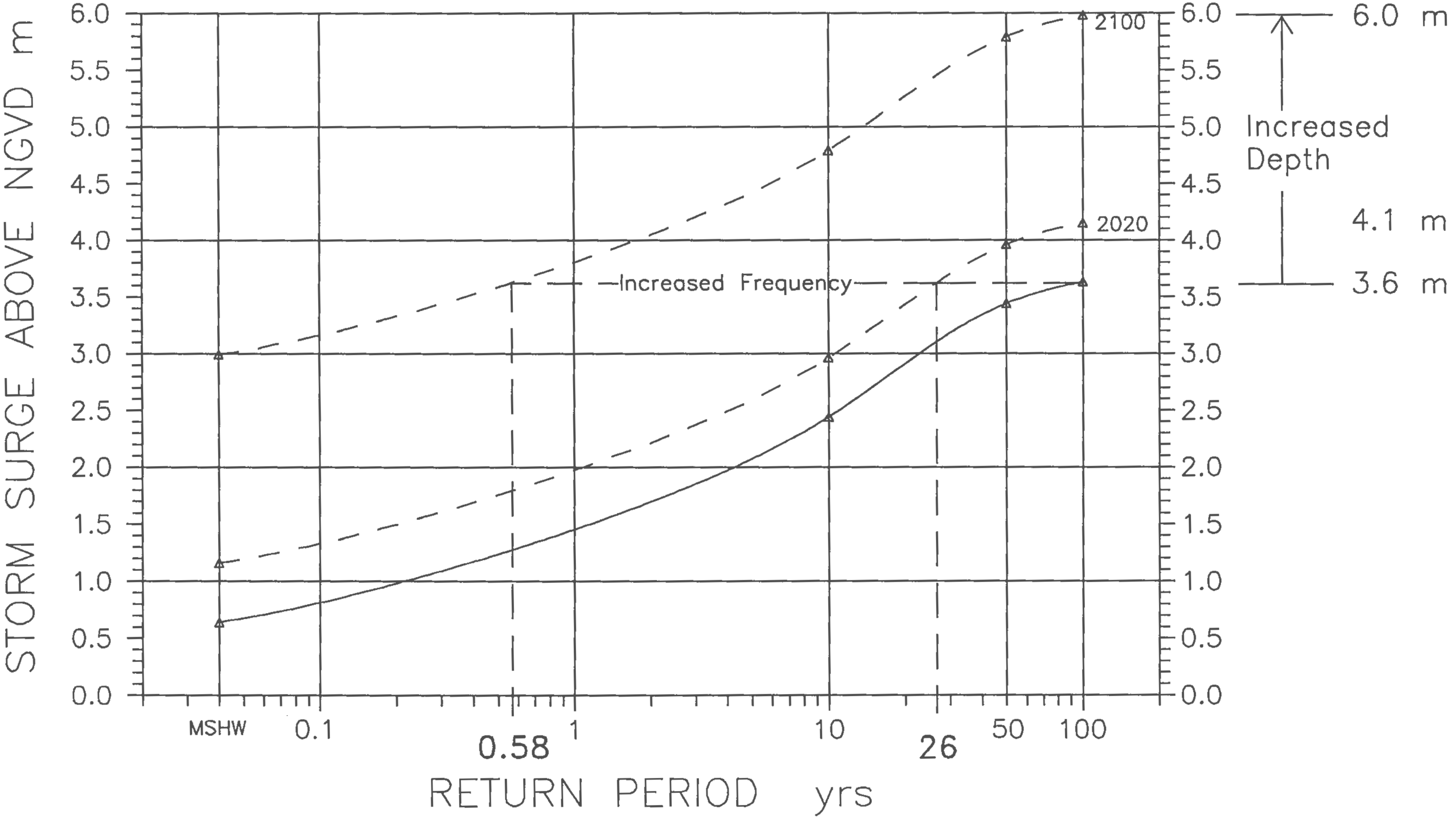

flooded during present 100–year event
additional area flooded after 60 cm RSL rise
additional area flooded after 244 cm RSL rise
WINNAPAUG POND
BIG MASCHAUG POND
Misquamicut headland
N
0
200
400 meters

Figure 9. - Graph of storm surge elevations above NGVD for East Beach barrier, southern Rhode Island. Surge elevations are plotted as a function of their return period in years. Solid curve shows present elevations, dashed curves incorporate mid-range high sea level rise to 2020 and 2100. Curves were drawn using a cubic spline fit so as to pass through all data points. Flood elevations from U.S. Army Corps of Engineers (1988). See text for discussion.

PROJECTED STORM-SURGE RETURN PERIOD
SOUTHERN RHODE ISLAND



and 100-year frequency tidal flood events (Corps of Engineers, 1988). The middle and top curves are the present curve elevated by 52 and 235 cm (1.7 and 7.7 ft) respectively. What the projected curves show is that given a sea level rise of 52 cm, storm-surge flooding to the elevation of the present 100-year storm (3.6 m, 11.9 ft) would occur with a return period of approximately 26 years. (Alternatively, the 100-year storm in 2020 after a 52 cm (1.7 ft) sea level rise would have a flood elevation of 4.1 m (13.5 ft)). The return period for a storm-surge of the present 100-year storm elevation after a 235 cm (7.7 ft) sea level rise would be 0.6 years. The result of a higher sea level on storm-surge will be an increased probability of severe flood occurrence within an expanding A-zone.

Management Strategies

Present management strategies for determining erosional setbacks, minimum building elevation requirements, and construction design standards are based on historical sea-level rise and storm-surge occurrence data, yet projections of future sea-level rise (Fig. 4) and storm-surge occurrence (Fig. 9) indicate a need for additional setback criteria in areas of rapid inundation and revised minimum building elevations in FEMA V- and A-zones. Present policy (CRMC, 1990) defines portions of the south shore as critical erosion areas within which the setback from the coastal feature for new construction is 30 times the annual erosion rate. Critical inundation areas could be similarly established where the setback distance is based upon a future rate of sea level rise translated into an inundation rate given the topographic slope within each area. These areas can be easily identified on the maps generated for this study (back pocket).

Present minimum construction elevation criteria require that the elevation of the lowest portion of the lowest floor of new or substantially improved structures be above the wave envelope in V-zones and above the storm-surge elevation in A-zones. These flood elevations are measured relative to NGVD and do not reflect the amount of sea level rise that has occurred since this datum was established in 1929. In order to keep the minimum construction elevation criteria up to date as sea level rises, the Flood Insurance Rate Maps need to be periodically revised to account for both the amount of historic sea level rise that has occurred to date, plus an amount of rise predicted to occur 30 to 50 years after construction. As written, the regulations (CRMC, 1990) would not need changing, only the flood elevations upon which they are based.

In addition to the changes suggested above, the most effective strategy for properly managing the coastal zone of the state of Rhode Island is a strict enforcement of the regulations concerning building and development therein. Regulations are ineffectual without enforcement, and the effort put toward formulating a coherent plan for the coastal zone will only be rewarded through adherence by all individuals to the precepts of the State and the Coastal Resources Management Council.

CONCLUSIONS

Frontal Erosion

Frontal erosion along the entire south shore of the state is projected to remove 49 ha by 2020 and 163 ha by 2100. The predicted results of erosion on the configuration of the present ocean shoreline include: 1) accentuation in the seaward expression of Weekapaug, Quonochontaug and Matunuck headlands as faster retreating barriers leave them behind; 2) an increase in seaward concavity of the waterline between these headlands; 3) continued rapid erosion of Misquamicut and Green Hill headlands, maintaining their present small seaward expression relative to adjacent barriers; and 4) a west-to-east trend of erosion to accretion inside the Harbor of Refuge causing a clockwise rotation of the waterline.

Upland Inundation

Upland inundation within the study area is projected to submerge 87 ha by 2020 and 645 ha by 2100. The consequences of inundation will be seen mostly in areas of glacial outwash where slopes are as low as 0.5°. Headland areas will be submerged by lateral inundation from adjacent lagoons, e.g., Winnapaug Pond will expand across the back side of Misquamicut headland forming one lagoon with the Maschaug Ponds; and Potter Pond will inundate large portions of the Matunuck headland, creating islands of glacial till.

Storm-surge Flooding

The base flood elevation of the 100-year event will increase as sea level rises, flooding the present A-zone in increasingly deeper water, and expanding into areas of low topographic relief. Total A-zone expansion within the area of study is calculated to be 190 ha by 2020, and 919 ha by 2100, an increase in total flood-zone area (FEMA A and V) of 10% by 2020 and 47% by 2100.

As sea level rises, flood events attaining a storm-surge elevation equal to the present 100-year event will occur with increased frequency. In the year 2020, this surge elevation will have a return period of approximately 26 years, almost four times the present annual probability of occurrence, and in 2100, the return period for a storm-surge of this elevation is reduced to 0.6 years.

Management Strategies

Frontal erosion will continue to be a problem along the south shore of Rhode Island, and Setbacks in critical erosion areas as defined by the CRMC should be updated as new shoreline change measurements are made. In the future, the threat of upland inundation should be considered equally with frontal erosion, and areas where shoreline displacement due to inundation will be large should have setback criteria established based upon projected sea level rise and topographic slope. These areas are easily identified on the maps generated for this study.

The FEMA Flood Insurance Rate Maps do not reflect the approximately 14 centimeters of local relative sea level rise that has occurred since establishment of the National Geodetic Vertical Datum of 1929, nor do they account for projected future sea-level increases. The FIRM maps should be revised to reflect historic sea level rise to date, and they should incorporate 30 to 50 years of projected sea level rise to ensure that future construction complies with the goals of flood insurance legislation.

Finally, the most effective strategy for managing the coastal zone of Rhode Island is one involving strict enforcement of construction and development regulations therein. All coastal-zone residents should adhere to the laws of the state and to the precepts of the Coastal Resources Management Council, or take an active part to enact changes deemed necessary.

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