Massachusetts Coastal Zone Management

MASSACHUSETTS COASTAL SUBMERGENCE PROGRAM

Passive Retreat of Massachusetts Coastal Upland Due to Relative Sea-Level Rise

Executive Summary

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Executive Summary

PASSIVE RETREAT OF MASSACHUSETTS COASTAL UPLAND DUE TO RELATIVE SEA-LEVEL RISE

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PASSIVE RETREAT OF MASSACHUSETTS COASTAL UPLAND DUE TO RELATIVE SEA-LEVEL RISE

INTRODUCTION

Shoreline recession is recognized widely as a major environmental management issue in Massachusetts as well as in many other parts of the United States and throughout the world (Bird, 1976). In considering this issue, it is essential to separate the retreat of coastal upland areas from the retreat of wetlands because of the differences between the processes involved. The retreat of a barrier beach, for example, may involve the landward translation of an entire feature without diminution in its size, but upland retreat always results in the loss of upland area. Although upland loss usually is accompanied by wetland gain, the upland lost is an irreversible loss of that area from those land uses for which wetlands are considered unfit. In Massachusetts these uses include, for example, human habitation, transportation and commerce.

Coastal upland retreat takes two distinct forms: active wave-produced erosion and passive loss resulting from relative sea-level rise. While a rise in relative sea level contributes to active wave-produced erosion, it is not possible at present to quantify the contribution to erosion made by sea-level rise. On the other hand, the recession of a passive shoreline as sea level rises can be estimated with reasonable accuracy.

Unfortunately, estimates of passive shoreline recession are seldom available, probably because upland loss due to this cause generally is considered to be small compared to that due to erosion. Relative sea-level rise along the Massachusetts coast over the past 40 years ranges between 2 and 3 mm. per year (Aubrey and Emery, 1983). Within recent years, however, a rapidly increasing body of data has appeared in support of the hypothesis that global climatic warming within the next century will cause increasing global sea level rises that can not be ignored. Hoffman (1984), for example, has projected global sea-level rises by the year 2100 ranging from 1.8 ft. ("low scenario") to 11.3 ft. ("high scenario").

Some emphasis in this report is placed on relative sea-level rise rather than absolute sea-level rise. Coastal submergence results not only from rise of ocean levels, but also from sinking of the land. In Massachusetts, nearly two-thirds of the submergence during the past century (documented by tide-gauge data) results from subsidence of the land. Only one-third of the submergence appears to be due to ocean rise (Aubrey and Emery, 1983; Braatz and Aubrey, in press). In quantitative terms, over the past sixty years Massachusetts has been sinking at a rate of 1.9 mm/yr (0.0062 ft/yr) while the ocean has been rising at 1 mm/yr (0.003 ft/yr) on average.

The estimates of magnitude of sea-level rise provided by Hoffman (1984) do not include the effect of land sinking. If the higher rate of rise scenarios (averaging 28 mm/yr) prove correct, the impact of land submergence is important only in the short term (the next 20-30 years). If the lowest rate-of-rise scenarios prove correct, however, then land subsidence will be a large fraction of the magnitude of sea-level rise (2 mm/yr versus 4-6 mm/yr).

The calculations based on hypsometric curves in the present study include the effect of land submergence but the color-coded maps do not.[1] The reader should be aware of this continental submergence, however, particularly if the low sea-level rise scenario is assumed to be true. Since the management implications for a lower rate of relative sea-level rise are less stringent than for the higher scenarios, the explicit neglect of land motions on the color-coded maps is justified.

The study reported here was designed to quantify the passive retreat of upland within the coastal communities of Massachusetts due to relative sea-level rise. The losses that presently occur annually, and those that will occur by the year 2025 given three specified projections of future relative sea-level rise, are presented for each community. Also presented are data that provide the means for predicting the rates and cumulative amounts of land area losses due to passive retreat that these communities will suffer in the future given any specified future relative sea-level rise or tidal range change scenario. Finally, color-coded maps are presented for the harbors of Hyannis, Westport and Gloucester that display the areas that would be lost by the year 2100 given any one of four different sea-level rise scenarios. An appendix contains tables, graphs and figures that present the results of the study. A detailed description of the data analysis methodology also is included in the appendix.[2]

The three sea-level rise scenarios presented here illustrate the potential magnitude of coastal flooding from global climate warming. These scenarios are based on predictions containing significant uncertainties, given the lack of precise understanding of complex atmosheric chemical exchanges, ocean/atmosphere interactions, and effects of land albedo, for example. Consequently, the three scenarios presented are not necessarily the most probable sea-level rise scenarios; however they are commonly cited scenarios widely thought to approximate the range of possible impacts. One advantage of the hypsometric data is the ease with which updated scenarios can be applied to a coastal town to obtain a first-order quantification of impacts on that town.

Application of the results of this study to coastal zone management and policy is fraught with theoretical and practical questions. How might the Commonwealth, a coastal county, or a coastal town respond to these results, and incorporate them into a managment scheme? With the

[1] Color-coded maps are included in the full report, available at the Main Library and Planning Office of each coastal community. Additional copies may be viewed at the main CZM Office in Boston; regional CZM offices in Gloucester, Norwell, N.Dartmouth and Barnstable; and the Martha's Vineyard Commission in Oak Bluffs.

[2] Color-coded maps and appendices can be found in the full report.

considerable uncertainty in the scientific basis for predicting the details of global warming, how can these uncertainties be translated into an equitable planning or zoning process? That a global warming is in process and will continue is incontrovertible. What are not known precisely are the magnitude and timing of this global warming, and its exact impact on sea levels.

The appropriate response to these issues and results on local and state-wide levels is one of increasing awareness. Legislation and re-zoning may be premature. However, awareness by town planners, politicians, and Conservation Commissions, for instance, must be increased. Long-range planning could take these shoreline retreat data into account when making major land use decisions. Conservation Commissions could err on the side of caution in a coastal construction issue, mandating pile foundations in areas of critical concern. Public works could incorporate these data in siting wells or new sewer systems. In summary, some rational response to these sea-level rise issues are appropriate at this time. Major legislation and drastic changes in regulations, however, may be premature and might better await a clearer consensus from the scientific community before enactment.

Users of the data presented in this report must be aware that passive shoreline retreat via inundation is not the sole effect arising from global warming to which coastal communities must respond. Although the present study considers only the effect of passive retreat due to inundation, other impacts may be equally important. For example, rising sea levels will change the base level for river drainage and groundwater flow. Water quality deterioration may result from this impact. In addition, global warming will raise the ocean surface temperature, increasing the size of the "warm-pool" of water that is responsible for generating tropical cyclones. Although difficult to predict in detail because of the complexities of non-linear atmospheric physics, this ocean warming is certain to alter storm climates along the eastern seaboard and elsewhere. If the net product is an increase in tropical cyclones reaching the northeast, this could result in more severe short-term (order of decades) economic impact than that due to simple passive retreat. While the present study investigates an issue of fundamental importance, the user should be aware of these other significant impacts, and plan their rational response to global warming accordingly.

METHODS

Quantification of the passive retreat of coastal upland presents special problems due to the peculiar "fractal" nature of the passive shoreline (Mandelbrot, 1977). Simply stated, the problem is that the complex form of the passive shoreline does not simplify as smaller and smaller segments are examined, and thus the "tangible" shoreline always remains just out of reach of the investigator who would measure it. In order to skirt this problem, the present study deals not with the linear retreat of the shoreline, but rather with the areas that are lost as the shoreline recedes. Two separate approaches are used, each having special advantages and disadvantages. In the first, which treats entire coastal communities, the distribution of the area of the community with respect to its elevation is presented in the form of "hypsometric" curves, or cumulative frequency diagrams.

While this is a powerful tool for the analysis of such geographical units as a whole, the results give no information about the change at a specific point within that unit. The second approach makes use of color-coded maps of areas that are of special concern for the management of ports and harbors. For this purpose the harbors of Hyannis, Westport and Gloucester were chosen. While it is difficult to quantify the effects of small changes from these color-coded maps, the areas that will (and will not) be affected are displayed clearly.

Hypsometry [3]

As a tool for calculating the retreat of coastal upland resulting from relative sea-level rise, hypsometry has been discussed by Giese et al. (1985). Unlike previous work, however, the present study makes use of digital elevation data that permits the application of the hypsometric method to large areas. A separate hypsometric curve was calculated for each of 72 Massachusetts coastal communities.

The initial data for the upland hypsometric calculations were obtained from the U.S. Geological Survey's (USGS) National Cartographic Information Center (NCIC). They consist of two separate types of digital information, both of which are stored on magnetic tapes. The first type is elevation data that consists of land surface elevations to the nearest meter arranged in south-to-north profiles for entire one-degree latitude by one-degree longitude areas. The data points within the profiles, as well as the profiles themselves, are separated by intervals of three arc seconds, which is equivalent to a distance of about 92 m in a north-south direction and about 69 m in an east-west direction at a latitude of 42 degrees (the approximate mid-point of the study area).

The second type of digital data consists of land use and land cover codes arranged in west-to-east rows aligned along a Universal Transverse Mercator (UTM) grid and covering entire one-degree latitude by two-degree longitude areas. The UTM coordinate system is rotated slightly counterclockwise with respect to the geographic latitude-longitude coordinate system. The land use and land cover code data points, and the rows containing them, are separated by intervals of 200 m. The land use codes include the U.S. Bureau of the Census designation for each 200 m square; these data permit the assignment of each square to a specific town or city. The land cover classification codes are sufficient to permit exclusion of wetland and inland water areas.

A large part of the effort for this study consisted of the programming required to combine the raw digital data described above to produce a single data set consisting of elevation, census code and land-cover code for each 3-second box within one-degree blocks. A description of the programs and their use is included in Appendix B.

During the study, the accuracy of the census and land-cover codes was checked by reference to the appropriate U.S.G.S. 7.5-minute series topographic maps, as well as by comparing the total calculated upland area of individual communities with the known value of their total land area. No problems were encountered with either type of code. Unfortunately, the same was not true of the elevation data. Initial tests of these data were performed by comparing profiles derived from the digital data to profiles based on the 7.5-minute series maps. The results of these tests generally

[3] Hypsometric tables and graphs are included in Appendix A of the complete report. Appendix B covers the data base processing methodologies.

were satisfactory, particularly considering the fact that the entire elevation data set for each community was to be combined. However, when the cumulative distributions of elevation data were completed, it was evident that the USGS data were biased toward maxima in the vicinity of 3, 15, 30, 45 and higher multiples of 15 m. A program was written to smooth the distributions by redistributing the excessive values linearly to the depleted elevation categories between the maxima. A description of this procedure is included in Appendix B. The hypsometric curve thus calculated for one community (Barnstable) then was compared to the curve derived by a graphical method, and found to be acceptable. Nevertheless, it must be noted that cumulative hypsometric data presented in this report are less accurate than those that could be obtained using unbiased elevation data.

Color-coded Maps [4]

The three maps that accompany this report were prepared to illustrate the effect upon three harbors of the relative sea-level rise predicted by four different scenarios for the year 2100. The harbors of Hyannis, Westport and Gloucester were chosen for this purpose because of their contrasting geological settings and because of their distribution along the Massachusetts coast.

These maps were generated using data derived from the digitization of selected portions of the 7.5-minute series topographic maps for the three harbors. These maps have a contour interval of 10 feet, which is too great to resolve the flooding that was to be shown. Therefore, a surface was modelled to fit the digitized contours using a modified form of existing software. The levels of flooding characterizing the four scenarios then were applied to this modelled surface. Using color-plotting software and equipment, the flooded areas were displayed on color-coded maps. A detailed description of the methodology employed is included in Appendix B.

The four sea-level rise scenarios illustrated on the maps were presented by Hoffman(1984), and produce flooding of 1.8, 4.7, 7.1 and 11.3 feet by the year 2100. These values were added to the NGVD elevations of the mean high water shorelines shown on the 7.5 minute series maps. The shoreline elevations were assumed equal to the half-tidal range at each particular harbor plus 0.5 ft to account for relative sea-level rise since 1929, the date of the NGVD datum. Local variations between NGVD and mean sea level were ignored, although these data are available.

Two important differences between the hypsometric calculations and the color-coded maps should be noted. First, while the hyposometric calculations refer only to coastal uplands and wetland areas are entirely excluded, the color maps use as their basic reference level the present mean high water shoreline that, in many areas, borders on coastal wetlands. Therefore, the areas shown as being flooded according to the lowest rise scenario include wetland areas, many of which are salt marshes. The second difference, discussed in more detail below, is that the maps include a consideration of the ground water table rise that accompanies a rising relative sea level. This effect is excluded from the calculations based on hypsometry.

[4] Color-coded maps are included in the complete report.

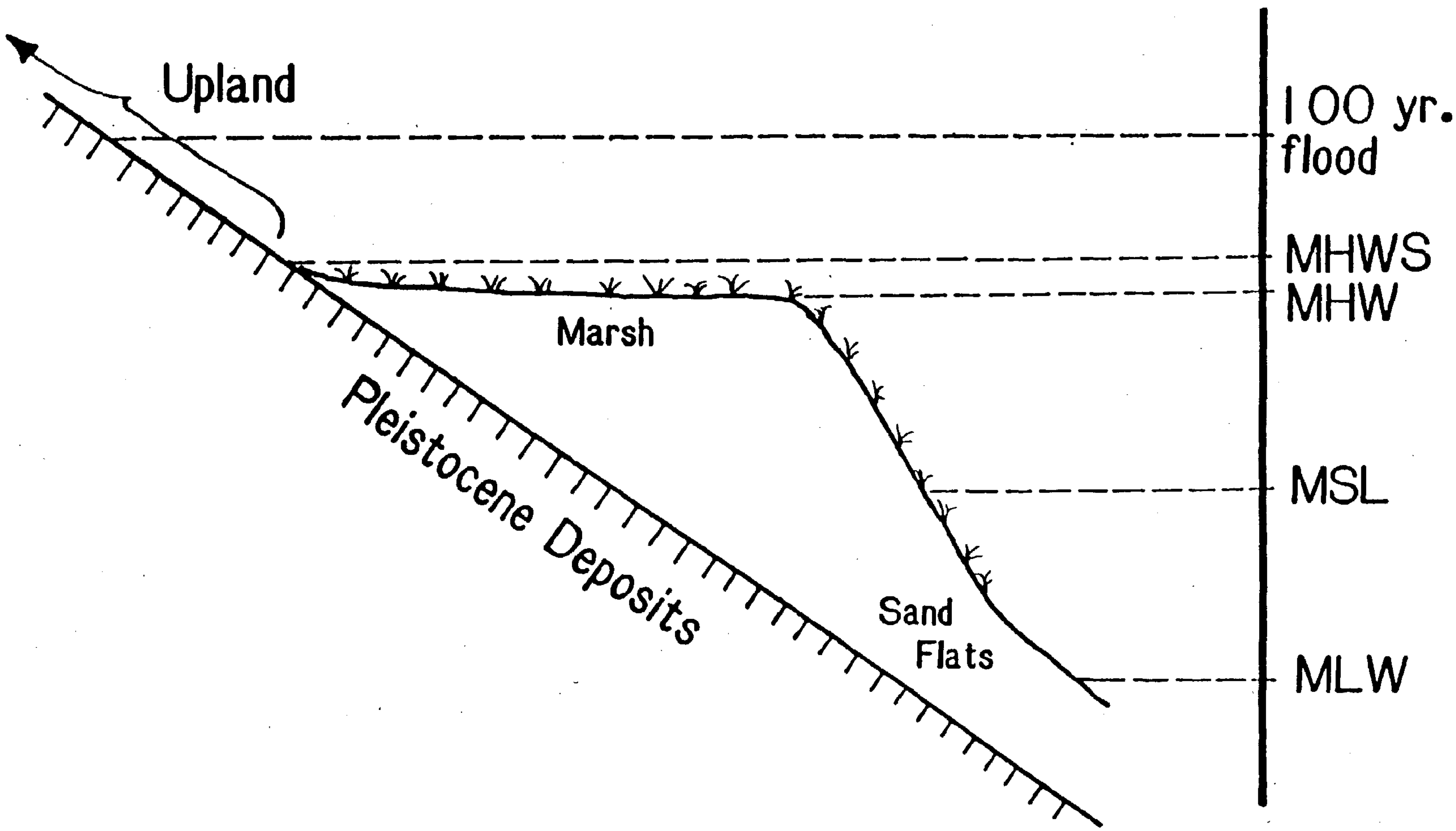

Figure 1: Schematic of datum planes selected for sea-level rise scenarios.

RESULTS AND DISCUSSION

The hypsometric curves for each community, together with tables giving the cumulative distribution of upland area with respect to elevation for each, are presented in Appendix A. The first area value presented in each table and graph (that for 3 m) represents the upland area that lies between 2.5 and 3.5 m. This interval was chosen because at lower elevations it is impossible to distinguish between upland and wetland in the source data, and does not imply that there is no upland below 2.5 m. in the community. The assumption is made throughout this study that the areal frequency of upland below 2.5 m. is equal to that at 3 m. No assumption is made, however, about the elevations of the wetland/upland boundaries within the community, other than that these boundaries, whatever their elevations, rise at the same rate as relative sea level (figure 1). It also should be noted that the data terminate at an elevation of 60 m., even when higher land exists within a community, in order to limit the size of the figures.

There is a striking variation between communities in the shape of their hypsometric curves, reflecting variation in the geological processes that formed them. For example, communities on glacial outwash plains, such as Yarmouth, have curves with flatter slopes at low elevations as compared to those, such as Brewster, that lie on glacial moraines. Certain well-known local topographic features, such as the "Wellfleet Plains", also show up clearly on the figures.

Making use of these hypsometric data, calculations have been made of the upland areas that each community would lose given particular changes in relative sea level. The results of these calculations are presented in Table 1. The first column in Table 1 lists the names of the coastal communities of Massachusetts, and the second column gives the upland area, in acres, of each community. The third column lists the percentage of upland area - and the fourth column the actual area measured in acres - that each community looses in response to a relative sea-level rise of 0.01 ft. (3 mm), considered here to be the historical mean annual rate of rise (Aubrey and Emery, 1983). The following three pairs of columns give the amount of retreat, first in percent of total upland area and then in acres, that will occur between 1980 and 2025 given three different sea-level rise scenarios. The first scenario, case 1, calls for a continuation of the historical mean annual relative sea-level rise rate of 0.01 ft/yr, giving a total rise of 0.45 ft over the 45 year period. Case 2 assumes that global sea level will rise 0.86 ft over the 45 year period (as given by Hoffman's "mid-range low" scenario) and that the local coastal subsidence rate will remain at 0.0062 ft/yr, giving a total relative rise of 1.14 ft by 2025. Case 3 is based on the same assumption about local subsidence, but uses Hoffman's "mid-range high" global sea-level rise estimate of 1.29 ft by 2025, yielding a total relative rise of 1.57 ft.

The total Massachusetts upland loss at the historical relative sea-level rise rate is 65.4 acres per year. Averaged among the 72 communities, this works out to be 0.9 acres per year per community. However, the variation between communities is great, covering two orders of magnitude: Nantucket loses 6.1 acres per year, while Winthrop loses only 0.06 acres. After Nantucket, other communities having large annual losses are: Wareham, 4.7 acres; Falmouth, 3.8

TABLE 1

CALCULATED UPLAND RETREAT

(Areas are in acres, % represents percent of upland submerged)

TOWN NAME	UPLAND AREA (ACRES)	HISTORICAL ANNUAL RETREAT 0.01 ft/yr RISE %	HISTORICAL ANNUAL RETREAT 0.01 ft/yr RISE AREA	TOTAL RETREAT: 1980-2025 Case 1 0.45 ft RISE %	Case 1 AREA	Case 2 1.14 ft RISE %	Case 2 AREA	Case 3 1.57 ft RISE %	Case 3 AREA
ACUSHNET	11520	0.002	0.22	0.09	9.8	0.22	25.0	0.30	34.4
AMESBURY	8052	0.002	0.13	0.07	5.8	0.18	14.7	0.25	20.2
BARNSTABLE	30709	0.012	3.72	0.54	167.2	1.38	423.6	1.90	583.4
BERKLEY	9582	0.005	0.43	0.20	19.4	0.51	49.2	0.71	67.7
BEVERLY	9748	0.003	0.28	0.13	12.7	0.33	32.2	0.46	44.4
BOSTON	24264	0.009	2.16	0.40	97.2	1.01	246.2	1.40	339.0
BOURNE	23935	0.006	1.53	0.29	68.9	0.73	174.6	1.00	240.5
BREWSTER	14110	0.005	0.72	0.23	32.4	0.58	82.0	0.80	113.0
CHATHAM	5250	0.020	1.04	0.89	46.8	2.26	118.5	3.11	163.2
CHELSEA	1217	0.010	0.12	0.44	5.4	1.12	13.6	1.54	18.7
CHILMARK	7196	0.007	0.50	0.32	22.7	0.80	57.4	1.10	79.1
COHASSET	3505	0.003	0.11	0.14	4.7	0.34	12.0	0.47	16.5
DANVERS	7866	0.003	0.25	0.14	11.3	0.36	28.7	0.50	39.5
DARTMOUTH	34785	0.006	2.05	0.27	92.4	0.67	234.0	0.93	322.2
DENNIS	10622	0.024	2.51	1.06	112.8	2.69	285.8	3.71	393.6
DIGHTON	13208	0.006	0.77	0.26	34.5	0.66	87.3	0.91	120.3
DUXBURY	12725	0.002	0.25	0.09	11.5	0.23	29.0	0.31	40.0
EASTHAM	6628	0.014	0.91	0.62	41.2	1.57	104.3	2.17	143.6
EDGARTOWN	9964	0.025	2.44	1.10	109.9	2.79	278.3	3.85	383.3
ESSEX	6227	0.003	0.22	0.16	9.8	0.40	24.8	0.55	34.2
EVERETT	1696	0.008	0.14	0.37	6.3	0.93	15.9	1.29	21.8
FAIRHAVEN	6765	0.020	1.35	0.90	60.9	2.28	154.2	3.14	212.4
FALL RIVER	20708	0.001	0.19	0.04	8.4	0.10	21.2	0.14	29.3
FALMOUTH	24340	0.016	3.82	0.71	172.0	1.79	435.6	2.46	600.0
FREETOWN	19862	0.002	0.34	0.08	15.2	0.19	38.5	0.27	53.0
GAY HEAD	1933	0.012	0.24	0.55	10.7	1.40	27.1	1.93	37.3
GLOUCESTER	15009	0.003	0.48	0.14	21.6	0.36	54.8	0.50	75.4
GOSNOLD	4327	0.013	0.58	0.60	26.1	1.53	66.1	2.10	91.0
HARWICH	11825	0.016	1.92	0.73	86.2	1.85	218.4	2.54	300.8
HINGHAM	8772	0.002	0.17	0.09	7.5	0.22	19.0	0.30	26.2
HULL	624	0.026	0.16	1.18	7.4	3.00	18.7	4.13	25.8
IPSWICH	14516	0.006	0.83	0.26	37.2	0.65	94.3	0.89	129.9
KINGSTON	11415	0.003	0.35	0.14	15.9	0.35	40.3	0.49	55.6
LYNN	6336	0.004	0.26	0.18	11.7	0.47	29.6	0.64	40.8
MANCHESTER	4793	0.002	0.12	0.11	5.2	0.27	13.1	0.38	18.1
MARBLEHEAD	2353	0.007	0.16	0.30	7.1	0.76	18.0	1.05	24.8
MARION	6883	0.031	2.13	1.39	96.0	3.53	243.2	4.87	335.0
MARSHFIELD	14332	0.004	0.60	0.19	27.1	0.48	68.6	0.66	94.5
MASHPEE	13386	0.010	1.35	0.45	60.8	1.15	154.1	1.59	212.3
MATTAPOISETT	5647	0.012	0.69	0.55	31.3	1.40	79.2	1.93	109.0

TABLE 1 (continued)

CALCULATED UPLAND RETREAT

(Areas are in acres, % represents percent of upland submerged)

TOWN NAME	UPLAND AREA (ACRES)	HISTORICAL ANNUAL RETREAT 0.01 ft/yr RISE %	AREA	TOTAL RETREAT: 1980-2025 Case 1 0.45 ft RISE %	AREA	Case 2 1.14 ft RISE %	AREA	Case 3 1.57 ft RISE %	AREA
NAHANT	465	0.019	0.09	0.83	3.9	2.11	9.8	2.90	13.5
NANTUCKET	23225	0.027	6.15	1.19	277.0	3.02	701.6	4.16	966.3
NEW BEDFORD	10410	0.006	0.60	0.26	27.2	0.66	68.8	0.91	94.8
NEWBURY	9442	0.009	0.81	0.39	36.5	0.98	92.6	1.35	127.5
NEWBURYPORT	4705	0.005	0.22	0.21	9.7	0.52	24.7	0.72	34.0
OAK BLUFFS	4288	0.014	0.59	0.62	26.4	1.56	67.0	2.15	92.2
0RLEANS	6211	0.017	1.07	0.78	48.4	1.97	122.7	2.72	168.7
PLYMOUTH	59264	0.001	0.77	0.06	34.7	0.15	87.8	0.20	121.0
PROVINCETOWN	1173	0.018	0.21	0.81	9.5	2.05	24.1	2.83	33.1
QUINCY	8062	0.010	0.84	0.47	37.7	1.19	95.6	1.63	131.6
REHOBOTH	27701	0.003	0.78	0.13	34.9	0.32	88.4	0.44	121.8
REVERE	2595	0.009	0.24	0.41	10.7	1.05	27.2	1.44	37.5
ROCKPORT	3715	0.004	0.14	0.18	6.5	0.44	16.5	0.61	22.7
ROWLEY	9184	0.002	0.17	0.08	7.4	0.21	18.8	0.28	26.0
SALEM	3956	0.007	0.29	0.33	13.0	0.83	32.9	1.15	45.3
SALISBURY	6167	0.013	0.82	0.60	36.9	1.52	93.5	2.09	128.8
SANDWICH1	24469	0.005	1.20	0.22	54.0	0.56	136.7	0.77	188.2
SAUGUS	5859	0.002	0.13	0.10	6.1	0.26	15.4	0.36	21.2
SCITUATE	8745	0.004	0.38	0.20	17.3	0.50	43.9	0.69	60.4
SEEKONK	11433	0.001	0.09	0.04	4.1	0.09	10.4	0.13	14.4
SOMERSET	4184	0.011	0.46	0.50	20.7	1.25	52.5	1.73	72.3
SWAMPSCOTT	1931	0.006	0.11	0.25	4.8	0.63	12.1	0.86	16.7
SWANSEA	12599	0.007	0.86	0.31	38.6	0.78	97.7	1.07	134.5
TISBURY	3539	0.012	0.41	0.52	18.5	1.32	46.8	1.82	64.5
TRURO	10734	0.006	0.61	0.26	27.5	0.65	69.7	0.89	96.1
WAREHAM	19822	0.024	4.70	1.07	211.4	2.70	535.6	3.72	737.6
WELLFLEET	9127	0.011	1.01	0.50	45.6	1.27	115.5	1.74	159.1
WESTPORT	27340	0.004	1.12	0.18	50.4	0.47	127.8	0.64	176.0
WEST TISBURY	14466	0.006	0.90	0.28	40.4	0.71	102.2	0.97	140.8
WEYMOUTH	9944	0.001	0.14	0.06	6.3	0.16	15.9	0.22	21.9
WINTHROP	300	0.021	0.06	0.94	2.8	2.37	7.1	3.27	9.8
YARMOUTH	12556	0.026	3.21	1.15	144.6	2.92	366.4	4.02	504.7
TOTALS	804246		65.4		2945.		7459.		10273.

The following coastal towns loose less than 0.001% of their total upland area annually as the result the historical mean sea-level rise rate of 0.01 ft/yr, and therefore were omitted from this table: Braintree, Hanover, Milton, Norwell, Peabody and Pembroke.

acres; Barnstable, 3.7 acres; and Yarmouth, 3.2 acres. In terms of annual percentage of total upland lost per year, the communities most affected are: Marion, which loses 0.031 % per year, followed by Nantucket which looses 0.027 % per year, and Hull and Yarmouth, which loose 0.026% per year.

Looking forward to the year 2025, if the historical rate of relative sea-level rise were to remain unchanged (case 1), the total Massachusetts upland loss would be 2,945 acres. A relative sea-level rise of 1.14 ft, as projected in case 2, would be accompanied by an upland loss of 7,459 acres, and a rise of 1.57 ft (case 3) would cost the commonwealth 10,273 acres of upland.

When considering these figures, it is important to realize that they do not include the upland losses that would result from the response of ground water levels to sea-level rise. In those communities where bedrock is absent and the terrain consists of unconsolidated sediments, the water table level over geological time periods is controlled by relative sea level. As sea level rises, the water table level rises with it, increasing the size of existing streams, ponds and bogs, and creating new ones. This effect has not been included in the hypsometric analysis discussed above, although it was taken into account in the construction of the color-coded maps.

The reader also should bear in mind that the calculated upland retreat rates are based on the assumption that the coastal uplands have a natural form and are not protected by engineering structures. Particularly in urban coastal areas where seawalls, riprap and fill are prevalent, the actual losses will be less than those predicted here. As the color-coded maps indicate, however, when large values of sea-level rise are considered, these structures are overwhelmed.

It is of interest that the presently existing rate of upland retreat due to the passive effects of relative sea-level rise is much greater than the upland retreat rate due to active wave-produced erosion. This may be illustrated by a consideration of the Cape Cod coast, which is well-known as a region of rapid erosion. While detailed estimates for cliff retreat do not exist for the entire region, the rate of erosion of the outer coast is well-known (e.g., Zeigler et al., 1964), and reasonable estimates can be made for the remaining and more slowly retreating cliff areas. Using such existing information and reasonable estimates, the annual upland loss experienced by Cape Cod as the result of active wave-produced erosion is about 9 acres per year. On the other hand, the annual loss due to the passive effects of relative sea-level rise, calculated from the figures for each Cape Cod town listed in Table 1, is about 24 acres per year. Thus it is seen that even considering a region of rapid erosion, and excluding the effects ground water table rise, passive retreat accounts for 73% of coastal upland loss under present conditions.

Figures 2, 3, and 4[5] present the color-coded maps depicting the submergence patterns of Hyannis, Gloucester, and Westport harbors that would accompany each of the four Hoffman (1984) sea-level rise scenarios for the year 2100. The maps show in red the land areas that would be lost given the low scenario rise of 1.8 ft, in yellow the submerged areas given the mid-range low scenario rise of 4.7 ft, and in green and blue the areas submerged by the mid-range high scenario rise of 7.1 ft and the high range scenario rise of 11.3 ft respectively. The low scenario changes are

[5] Included in the complete report. See footnote[1].

extensive only in wetland areas, such as the salt marshes northwest of Gloucester Harbor, the sand spit southwest of Hyannis Harbor, and fringing marshes in Westport Harbor. While the upland lost given this scenario is not extensive, the increased potential for storm wave and flooding damage should be of concern.

The submergence that would accompany the other scenarios is extensive and would impact severely operations of harbor facilities. In addition, the maps show locally significant flooding of inland areas for these scenarios resulting from elevated ground water levels. As has been discussed above, it should be kept in mind that the levels used in applying these scenarios do not include the effects of coastal subsidence, and that for the lower rise rates the increases would be significant were they to be included.

CONCLUSIONS

Major conclusions of the present study are:

1. Relative sea-level rise is the major process responsible for upland loss in Massachusetts. Neglecting coastal erosion and fresh water table changes, Massachusetts presently looses about 65 acres of upland each year due to passive submergence.
2. The rate of upland loss due to passive submergence varies widely from town to town, and depends upon the geology of the region in which the town lies.
3. The hypsometric curves of the towns provide important basic information that permits the calculation of the upland areas which those towns will lose to passive submergence as the result of any given increase in relative sea-level.
4. The total land loss by the year 2025 has been calculated for several relative sea-level rise scenarios. At the present rate of rise, Massachusetts will have lost about 3,000 acres of upland between 1980 and 2025. This is the same upland loss that occurred between 1935 and 1980, an equal length of time. For a rise of 1.14 ft, about 7,500 acres would be lost; and for a rise of 1.57 ft, the maximum likely, over 10,000 acres would be lost. Given a nominal value of ocean-front property of $1,000,000 per acre, the economic impact of this retreat is substantial.
5. Color-coded maps are a useful device for depicting the specific areas that will be submerged as the result of specified increases in relative sea level. These maps could be developed for each coastal town in the future, to provide guidance for land use, public works, and conservation decisions.
6. These data can be used immediately to help provide a rational basis for local response to global climate warming. Data from this report, although representing hypothetical scenarios, remove the quantification of the impacts of passive retreat from the realm of speculation, placing them on a firmer basis. Although enactment of legislation and major revision of regulations may be premature, local communities must increase their awareness of these impacts, and begin to incorporate these data in planning, design, and conservation issues.

7. Although the present study has shown that passive retreat is an important element of the shoreline response to anticipated global climate change, this inundation is certainly not the sole impact. Future research is mandated for other impacts on the coast of Massachusetts, including but not limited to:

- Effects of relative sea-level rise on groundwater resources.
- Effects of relative sea-level rise on marshes and other biotopes.
- Possible global climate change impact on storm climatology of Massachusetts waters.

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